University of California, Berkeley
CAL-Rover Final Technical Report
2016 RASC-AL Robo-Ops Competition

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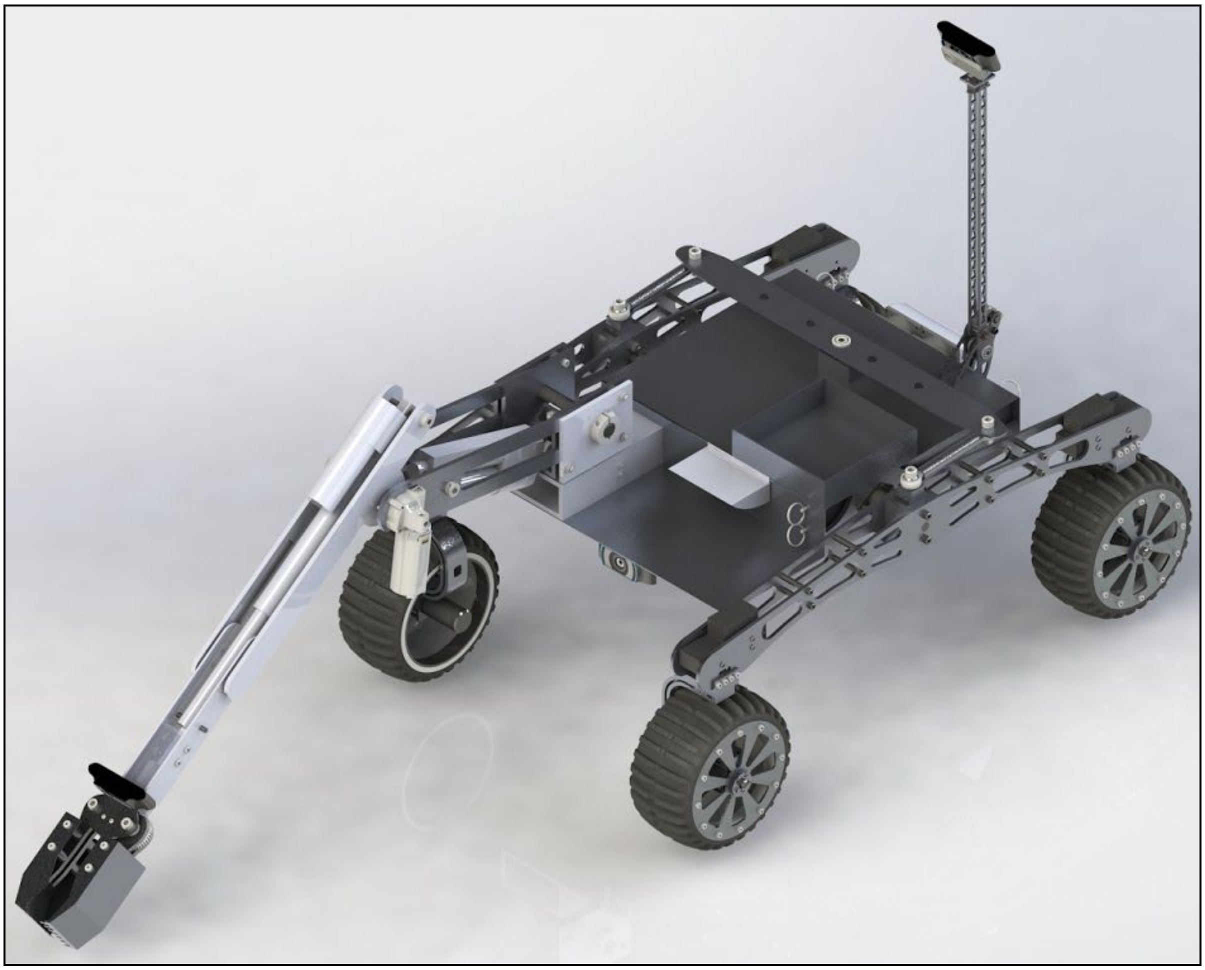

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INTRODUCTION

CAL-Rover is the University of California, Berkeley's entry into NASA's 2016 RASC-AL Robo-Ops competition. Fully loaded, including a weight buffer of 15%, it weighs in at 31.8 kg. Its instrument suite features three cameras and a 5-DOF manipulator arm. In its stowed configuration, the rover fits within a 87.6 cm by 60.3 cm by 49.5 cm box , which fits within the maximum delivery envelope.

The mission goal for CAL-Rover is to traverse the Johnson Space Center (henceforth to be referred to as JSC) Rockyard and acquire as many colored rock samples as possible within the one-hour allotted time frame. This document will explain the technical systems implemented on CAL-Rover for the 2016 competition. It will also elaborate on our planned strategy for the competition in order to score as many points as possible. All physical dimensions are given in MKS units, but since most domestic parts and materials suppliers list their products in imperial units, these dimensions will be displayed where appropriate.

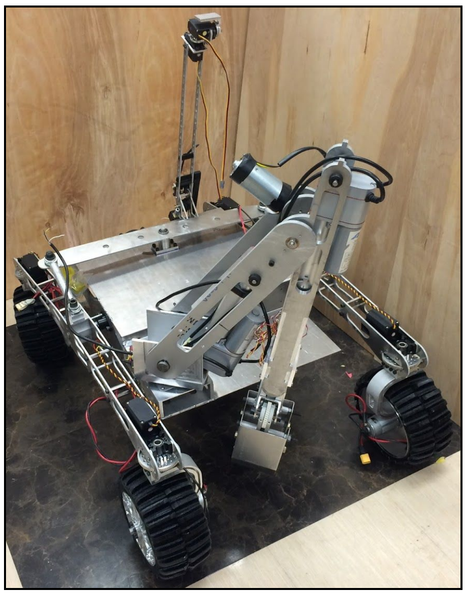


Figure 1: Cal Rover Assembled for Testing & Debugging

CHASSIS & SUSPENSION DESIGN

Our chassis design is based on reducing the size and weight of the rover while creating a sturdy platform that allows for easy maintenance. This was done by creating a frame with a removable electrical box within. We utilized CAD blocks of the electrical components when designing the frame and electrical box in order to optimize the space. The individual components of the chassis were first waterjetted from 0.063" thick 5052 Aluminum and then TiG welded to create the frame and electrical box. The camera mast and arm base are both welded to the frame and made from 6061 Aluminum. The final dimensions of the chassis are 49.1cm x 38.9cm x 6.9cm, much smaller than the previous year's design.

The suspension is unique from previous iterations, aiming for a much more light and sleek design. Previous generations were quite large and square in their truss design, using far more material to connect the chassis and electronics to the drive system. A past version of the suspension included a six-wheel rocker-bogie differential that pushed that device close to the weight limit. Following with this year's goal to minimize weight, the first major change we made to this suspension was to drop back to a simplified four-wheeled rocker differential design. After research on four-wheel differential designs, we settled on a one point attachment to the chassis with a differential bar to connect both drive legs together mechanically. The differential bar is similar to the previous year's design, but the old, boxy suspension was redesigned to two suspension plates in wishbone shapes that connect both to the chassis and the two wheels. Although the suspension was originally designed as one solid structure, it made more sense to abrasive waterjet two ⅛ inch Aluminum 6061 plates for each rocker arm and fortify the structure with standoffs at measured increments. The two-plate design creates a light but rigid structure; it benefits from the increased bending moment of inertia of a wide beam while also being lightweight due to the large reduction of material.

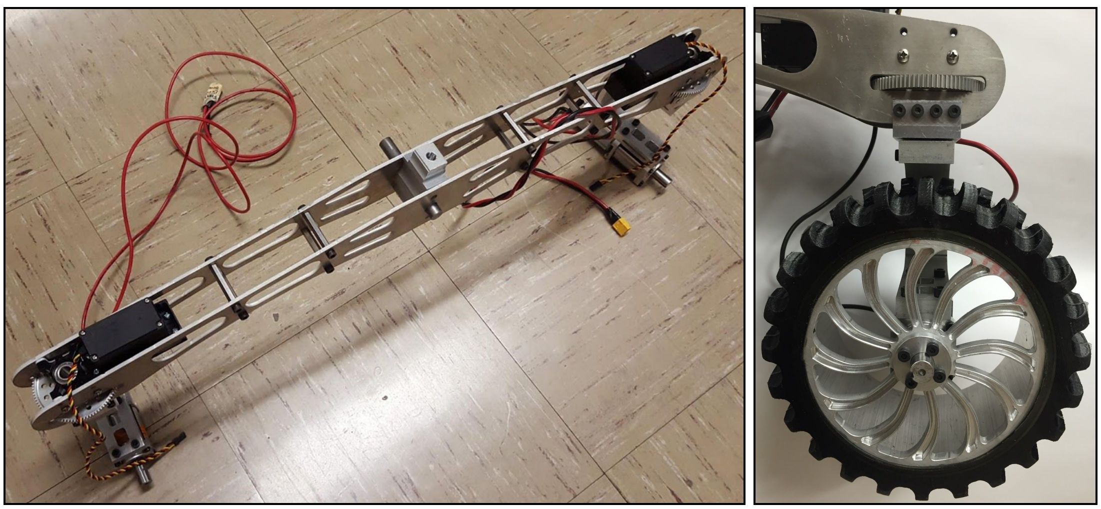


Figure 2: a) Single sided suspension bar & b) Swerve drive module attached to the suspension bar

DRIVE SYSTEM DESIGN

Since switching from a tank drive system in 2013, the CAL-Rover team has continually made improvements to the swerve drivetrain. A swerve drivetrain allows for refined maneuverability of the rover, allowing it to rotate without linear movement when trying to reach its final destination. The goals for the 2015-2016 drivetrain were to reduce complexity and bulk size, while increasing machinability.

The 2016 CAL-Rover boasts four swerve modules, each of which are individually operable in both heading and speed. SPG785-CM Servos control the individual module headings, while Banebot PDX104 motors drive the wheels. The motors are housed inside the hub of each wheel and are attached to the aluminum drive legs which carry the load of the rover. The PDX104 motors are capable of propelling the rover at a max tested speed of 8 kph on flat ground, utilizing our two Roboclaw dual 60A motor controllers. We have not fully maxed out our capable speed on ground because we believe CAL-Rover will never need to travel at the maximum speed that the Roboclaws can drive the wheels. Instead, we have chosen to electronically limit the max speed of the rover to allow better driver control.

WHEELS

In previous years, our wheels were designed as machined steel and aluminum pipe caps. However, the machining process left the thin pipe caps too deformed to use properly. For the 2016 CAL-Rover, we initially proposed a multi-part wheel rim assembly that included an aluminum wheel hub bolted to a 3D printed ABS rim with an interior steel ring to provide the ABS structural strength. A silicone rubber tire would be molded around the rim assembly. After initial concept testing of the wheel assembly in the late fall, we decided to reevaluate the wheels for a stronger structure.

Taking inspiration from UC Berkeley's Formula SAE team's custom machine wheel centers, we redesigned our wheels to be made of lightweight 6061 Aluminum. Iterative design optimization with basic FEA was used to remove material weight from the wheel assembly, while ensuring a 5x yielding factor of safety and minimal deflection. The rim assembly is made up of two pieces. The first piece (*figure* 3a)) is initially cut from ¼" thick plate using the waterjet, then the contour cutouts are made using an ⅛" rounded ball end mill on a 3-Axis CNC mill. The second part (see *figure* 3b)) was fabricated from a stock of 6.25" OD aluminum which was pipe turned and lightened on the lathe. The two pieces were then press fitted together and locked into place with six #4-40 screws in case the press fit came loose. Our wheels are 9.1cm wide and 19.7cm in diameter at their largest point.

Figure 3 a) Initial wheel center & b) Machined outer wheel

The most challenging part of the wheel assembly was creating a mold for the tire. We utilized Series 1 Type-A 3D printers to create the molds out of PLA. After multiple iterations, we settled for a custom 6-piece mold that would allow easy assembly and disassembly with our tread design (see figure 4). The tread design utilizes 1.15cm high grousers staggered down the centerline of the width of the wheel. These grousers are deep enough to provide a scooping action in loose sand, but also strong enough to provide grip needed to climb over rocky surfaces.

Figure 4: a) Pieces of the wheel mold & b) pouring urethane around the aluminum wheel assembly

After testing multiple hardnesses of pourable urethane rubbers, 60A Shore hardness was chosen for it's ability to be both rigid and flexible on different surfaces. Smooth-On PMC-746 two-part Urethane rubber was molded around the aluminum hubs. In order to ensure adhesion, both radial and circumferential grooves were cut into the aluminum rim to provide variable surface area that the rubber could adhere to. The final wheels are very sturdy, capable of withstanding a 1.5m drop and bouncing back nearly to the original height. A single completed wheel assembly weighs in at just over 1kg.

Figure 5: A single completed wheel assembly mounted onto the gearbox shaft

WEIGHT

The assembled rover weighed in at 31.8 kg total. This weight includes the assembled rover, batteries and electronics, and a built in weight buffer of 15% for potential last minute additions such as extra wiring circuits. In designing the 2016 CAL-Rover, we extensively used the abrasive waterjet machining process to cut plate material, which made weight saving additions such a truss structure cutouts easy when compared to the CNC machining in our previous design. The plate and standoff design also helped to significantly reduce weight, since the majority of the structure is open air.

Table 1: Breakdown of mass by component

Components	Mass (kg)
Chassis	18.3
Batteries	3.4
Wheel Assembly	4.2
Electronics	1.7
Weight Buffer (15%)	4.1

POWER

Cal-Rover uses four 14.8 V and one 11.1 V Lithium Polymer batteries to power all the electrical systems on the rover. The 14.8 V batteries are fed into the Roboclaw Dual motor controllers, which regulate the voltage and power multiple motors and actuators. These include the BaneBots PDX 104 Geared Motors used to drive the wheels, the shoulder joint and base rotation geared motors on the arm, and linear actuators used to actuate the arm. The 11.1 V battery is fed into two Turnigy 8-15A UBECs to act as 5V and 6V power rails. The 5V rail is used to power the Raspberry Pi and camera mast servo. The 6V rails are used to power the SPG785-CM swerve drive servos and the RioRand motor controller for the manipulator claw.

VIDEO & AUDIO

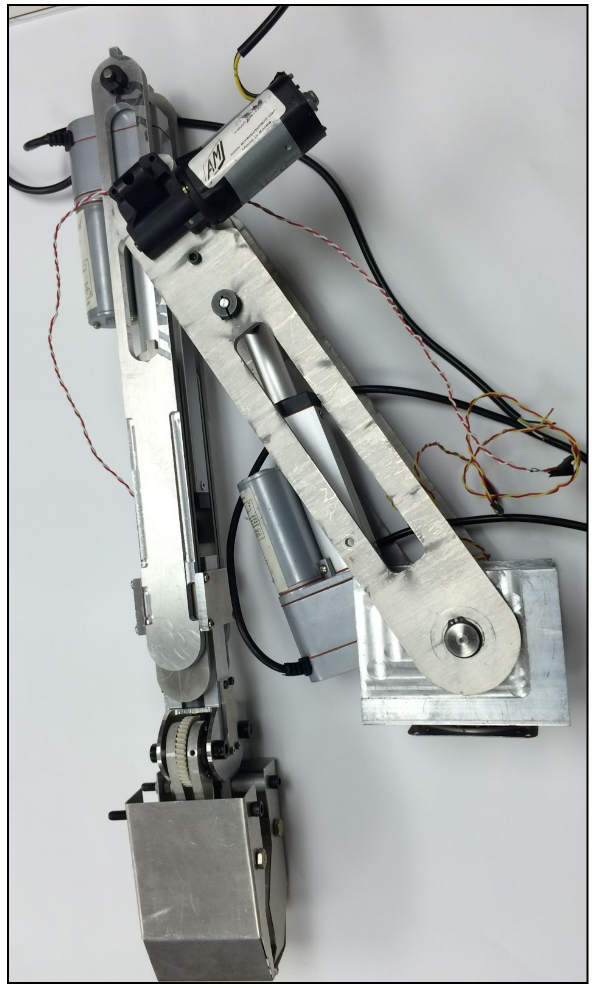
CAL-Rover will utilize three different cameras to complete its mission, though at any point in time, only a maximum of two cameras will be streaming. The main camera we are using is the 1080p HD Logitech C920, which will sit atop the camera mast. The mast extends the camera 80cm above the ground and provides both pan and tilt capabilities. This camera will be used to capture 15MP high definition photos of the course to look for rocks. The other two cameras are 720p Logitech C270s. One will be placed on the arm where it can provide a bird's eye view of the gripper's target. The second is mounted under the front of the chassis to see the ground immediately in front of the rover and to provide another angle of the gripper.

We will use the stereo microphones included in the Logitech C920 to capture stereo audio from the rover. This audio will be live streamed along with the video on our YouTube Live stream on the day of the competition.

To broadcast the video streams from the cameras, we are using a program called Motion on the Raspberry Pi. By editing the default configurations files we are able to use the Pi's multiple cores to pick up the video stream from each camera and broadcast it to a port reachable via the Pi's local IP address. At this stage, the command interface navigates to the starting predefined URL's for each main camera feed and displays them to the URL controlling the rover as well as to the YouTube Live stream. In the event that we switch into arm mode, the screen hosting the camera mast is switched to the camera right above the gripper. This gives us an up close view as we manipulate the arm to acquire our targets. Upon successful retrieval, we simply switch modes again and the Control window reverts back to the overwatching camera.

MANIPULATOR & SAMPLE ACQUISITION STRATEGY

Full Technical Specifications



For our sample acquisition strategy we are using a five degree of freedom manipulator that is designed to maximize our workspace for picking up rocks. The manipulator arm rests on a base that is welded directly into the chassis. This base provides the first degree of freedom and allows the arm to rotate a full 360 degrees around the rover. The base rotation is powered by a 12V brushed DC motor, and a worm gear drive helps provide the required torque. The next degree of freedom is rotation at the "shoulder" joint that moves the first boom. This joint is driven by a heavy-duty linear actuator that can output up to 150 lbs of force, which can easily lift the rest of the arm. It can also rotate the boom between 0 and 60 degrees to easily reach both the ground and the rock box for sample acquisition and up to the rock box for sample storage. The next degree of freedom is the "elbow" joint that links the first boom to the telescoping section. This DOF is powered by a right angle motor with a built in worm drive. The section can swing between 30 degrees and 180 degrees relative to the first boom, which allows the manipulator to reach a wide area along the ground and easily move into the stored position. The fourth degree of freedom is the telescoping section of the second boom. It is driven by a linear actuator that provides 6 inches of extension. We chose to use a telescoping section instead of a more traditional wrist joint because this gave the arm a much larger workspace, while still allowing it to reach a stowed position that was within the size limit. We determined the loss of the additional positional flexibility offered by a wrist joint to be an acceptable tradeoff. A gripper driven by a worm and two worm gears is attached to the end of the telescoping section. The end effector is made of bent sheet metal, and can open wide enough to clamp around the 8 cm maximum diameter of the largest potential samples. In its fully extended position, the arm can reach samples that are 86 centimeters from the front of the rover. This allows the rover to potentially reach many rocks from one position. During our testing, the arm could lift well over 200 grams, which is sufficient to handle the largest samples in the competition.

Improvements Since Mid-Year Review

Since our mid year review, we were able to fully assemble the manipulator with all of its intended functionality and complete some revisions and improvements. The additional plates we added to the telescoping boom section greatly increased the rigidity and stability of the telescoping action. These plates also provided a convenient mounting point for the camera on the arm. The additional degrees of freedom presented no issues during assembly. One change that we did not implement from the mid-year review was a redesign of the end effector shovels. While the reasoning behind using a smaller and more customizable 3D printed design was sound, after initial testing, we determined that the current shovels could sufficiently pick up the rocks, so we prioritized other improvements. After full assembly, we noted that the arm was quite heavy, so we modified parts to save weight. The large slots that were cut into the telescoping boom plates reduced their weight by nearly 30 percent. We also removed material from the heavy steel shaft at the elbow joint and replaced the shaft collars with much lighter external retaining rings.

TECHNICAL SPECIFICATIONS

A Summary of CAL-Rover's technical specs is listed below in the table 2.

Table 2: Technical Specifications

Technical Specification	Value
Main Drive Power	(4x) 8000mAh @ 14.8v
Computer System Power (Voltage Regulated)	(1x) 5000mAh @ 11.1v
Propulsion Drive	(4x) Banebots PDX 104 Geared Motors
Rover Heading	(4x) SPG785-CM 7:1 Servos
On Board Computing	(1x) Raspberry Pi 2
Operating System	Raspbian Jessie Lite (Minimal Debian OS)
Motor Controllers	(2x) Roboclaw Dual 60A (1x) Roboclaw Dual 30A (1x) Roboclaw Dual 5A (1x) RioRand 15A motor controller
Wireless Connectivity	Verizon Ellipsis Jetpack MHS800I 4G LTE Hotspot
Mission Controller	Saitek X52 Flight System
Max Speed (electronically limited)	8 kph
Max Obstacle Size (Vertical Climb)	12.5cm
Tested Payload	500g

TESTING STRATEGY

Rover testing began with testing of each individual system during the month of April. The main focus was placed upon testing the manipulator and swerve drive systems separately while developing the control code in parallel. This allowed us to ensure the individual mechanical components were working correctly before assembly for quick repairs.

After placing each component of the system onto our chassis and beginning the testing for the swerve drive system, the maximum height we have been able to traverse is a 12.5 cm tall, vertical box. We have noticed areas in need of improvement once assembling the chassis, namely the stiffness of the chassis itself. Currently, the chassis/suspension interface has significant amounts of compliance, resulting in the reduction of the overall stiffness of the chassis. Another interfacing issue we found is between the manipulator arm and the chassis. The arm was found to not always drop objects into the original rock box location. In order to ensure placement of rocks in the rock box, our original location of the rock box will be replaced with a rock box attached to the rear of the chassis.

Due to unforeseeable setbacks, our testing has not been fully completed as of the submission of this report. However, we aim to test a fully integrated chassis until departing for the competition. We will focus on getting every system working satisfactorily to be able to last the hour necessary for the competition. We are in the process of stiffening the chassis by replacing the current half axle design with a full axle that spans both sides of the rover. Additional compliance will be reduced by replacing the plate differential bar with a U-channel. A timeline of our fixes and testing time is in the following section.

TIMELINE TO COMPETITION

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
8	**9 (Finals)** - Revision workshop with advisor & machine shop	**10 (Finals)** - Machine axle bearing support	**11 (Finals)** - Replacement motors arrives - Machine chassis axles	**12 (Finals)** - Reassembled motors on arm and drivetrain - Machine axles	**13 (Finals)** - Continue Testing - Machine axle support - Machine diff bar	**14 (Graduation)** - Graduation
15 - Simulate mission control - Finish wiring	**16 (Graduation)** - Machine new rockbox location	**17** - Attach rockbox - Continue Testing	**18** - Continue Testing	**19** - Continue Testing (Take to Berkeley Marina)	**20** - Continue Testing (Take to beach volleyball court)	**21** - Continue Testing
22 (Depart CA) - Depart for Texas - Long distance command	**23 (Arrive TX)** - final testing - assembly & part check from trip	**24 (Competition)**	**25 (Competition)**	**26 (Competition)**	**27 (Depart TX)**	**28 (Return CA)**

OVERALL COMPETITION STRATEGY

The overall strategy for the competition will be to keep the rover running for as long as possible in order to maximize the amount of rocks found. This means that we will initially stay in the less dangerous areas - away from the Rock Field, for example. While this means we will likely be able to pick up lower valued rocks, we hope to pick up a substantial amount to amass a large point total.

Our designs reflect this general objective. With the four swerve drives, we created the rover to be maneuverable enough to navigate the rock yard. If necessary, we will be able to turn in place in order to avoid unforeseen obstacles without requiring us to retrace our steps. Additionally, motor selection prioritized acquiring motors strong enough to allow us to climb the steep gradients on Mars Hill. On flatter ground, this will let us speed through the terrain to find the target samples.

Coupled with our drivetrain, the rocker suspension system was selected to improve the maneuverability over obstacles. Movement over rocks 10 cm in diameter will not result in large displacements of the camera. Thus, maintaining a stable and constant viewing angle will let us continue planning our path while moving past obstacles, reducing travel time significantly. We hope that the efficiencies in traversing the rock yard will result in more opportunities for points.

We selected the specific manipulator type to ensure the retrieval of samples. Our shovel concept allows us to pick up rocks without requiring incredible precision. The size of the shovel allows us to pick up larger rocks, which will be useful in scenarios where removal of obstacles to the manipulator's range is necessary, in order to excavate some of the samples. The maneuverability of the arm additionally allows us to reach difficult spots when necessary. With the quick travel and a robust manipulator, we believe we will be able to pursue our strategy of amassing low difficulty samples.

When it comes to the potential bonus points, we will attempt to accomplish as many tasks as possible, provided the tasks do not conflict with the above strategy. For instance, we will aim to collect rocks from all four districts, with the caveat of saving higher risk regions such as the Rock Field for last. The same provision holds for the contingency task, as well as capturing the "alien life form". If any of these tasks should require further exploration into higher risk regions, we will save such tasks until the end of the hour, when we will allow those controlling to evaluate the situation to decide whether they feel comfortable with progressing. The final bonus scenario, maneuvering the rover back to the top of the Mars Hill at the end of the hour, is one in which our group has decided to attempt to accomplish. After an hour of roving, we expect to easily get the maximum fifteen bonus points for five of the rocks we have already collected. With the exception of our hesitation on behalf of our chassis in its current state, we are confident in the capabilities of our rover and should have no issues getting the rover back atop the hill. Our only concern is that if we are in the middle of the contingency task (worth the same amount of bonus points) or excessively far away from the Mars Hill, it may do our team better to let this opportunity pass. Much like before, such a decision will be reserved for those controlling the rover to evaluate as time winds down.

BUDGET

The CAL-Rover team has efficiently utilized the funds that we have been granted in order to build a cost effective rover. The total available budget for the 2016 CAL-Rover was $13,900, which includes funds from the Mechanical Engineering Department, Engineering Student Council, Boeing, and the National Institute of Aerospace. To manufacture the rover, we have spent around $5,400. Of this amount, $3800 was spent on raw materials, hardware, and other components, with $1600 spent on manufacturing expendable costs associated with waterjet machining and chassis welding. We were able to significantly reduce our manufacturing costs due to the heavily subsidized resources available through the new Jacobs Institute of Design at UC Berkeley. We expect around $4000 in costs associated with competition registration, transportation and lodging for the team.

We would like to thank our monetary sponsors mentioned above as well as our sponsors that donated supplies, ServoCity and SolidWorks, for supporting the 2016 CAL-Rover team on our mission!

MISSION CONTROL CENTER

Mission control will exist at either Etcheverry Hall or Cory Hall, pending our ability to find a suitable room with a projector and enough room to house all present members of the team. Our fall back mission control will be 120 Bechtel, an engineering facilities room for engineering student groups, with a portable projector we can use. During mission control operations, team members will be split into two different units, each focusing on a different functional area.

The most important will be the drive unit, which will focus on controlling the rover and manipulator arm via the live feed. Using high resolution pictures and the live feed from the rover, they will be able to navigate throughout the course quickly and efficiently. Once a target is found, the drive team will be responsible for determining the most optimal route and navigating the rover to the objective. Once the object has entered the range of our manipulator, they will switch from drive mode to arm mode and guide the claw to the target using the same controller. We have assembled the manipulator onto the rover, and as the motion and degrees of freedom are functioning we are confident in the sample acquisition capabilities. Once a target has been successfully collected, the drive team will either continue on to other potential targets in the area or return to the hill as directed by the command unit.

The second unit, the command unit, will be involved with strategizing and high level control of the rover (i.e. directing the drive unit's movements). This unit will be responsible for taking into account the current state and position of the rover, and using the information to map out the best course of action to maximize the points obtained. The rationale here is that by separating the strategic aspect from the driving, a full unit's attention may be devoted to optimal path planning, leaving the drive unit free to handle the precise control of the rover's systems.

The personnel requirement for such a system will be well within our ability. We require at minimum 1 person per unit, but would be most efficient with 2 or 3 persons per unit. Up until the day of the competition, we will practice mission control along with continued rover testing.

CONTROLS & COMMUNICATIONS

Starting on command side, we will be reading the inputs from Saitek X52 Flight Joystick. We chose this joystick because it allows us a wide range of programmable buttons and axes for a complete representation of the desired drive mode. This allows us to map the rover controls to extremely intuitive motions (i.e. forward/backward, side to side, extend/retract the arm). These simple mappings will increase the speed at which we are able to traverse the course to obtain our targets, and expedite learning of the controls. Furthermore, to minimize our command transmission size, we utilized a default layout that is assembled and sanitized on the command computer side, and parsed for the necessary commands by the rover. This layout contains a list of comma separated values (CSV's) that currently have the capacity to control eight individual motors and eight servos. By doing this we were able to save a lot of time, because adding new motor controllers and servos is as simple as mapping a new command to an input from the joystick and then assigning an action to that item's position in the command transmission list.

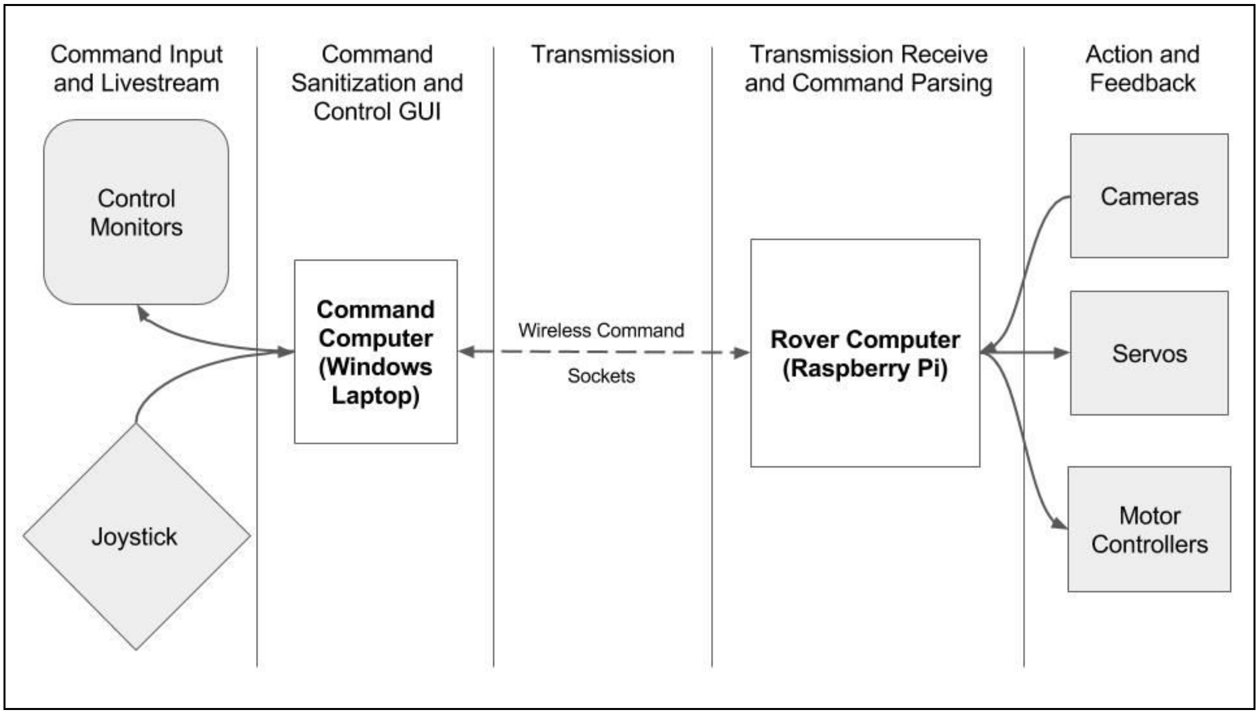


Figure 6: Rover Control Block Diagram

As mapped out by figure 6, controls will be sent from mission command to the rover through a stream socket setup using Transmission Control Protocol (TCP). We choose TCP since the protocol ensures that data arrives sequentially and error-free. Our other option for this was a datagram socket, which, although faster, does not preserve order because it is sent via the User Datagram Protocol (UDP). Both host and client are written in C++ and have been tested with a data buffer of up to 1024 bytes, although our typical message will be at most 64. In our configuration, the rover computer takes on the role of "server" in the sense that it listens on a specified port (port 8080) for the command computers' initial connection and predefined startup sequence. We chose this configuration since it allows the rover to revert back to a listening state in the event of any untimely connection terminations. Thus, we are able to ensure that we can easily connect or reconnect to the rover when ready. Additionally, the timeout enforced on a client side connection socket proved difficult to implement as it makes the startup handshake harder to sync.

Both the command computer and the rover computer are written in C++. We chose C++ since it offers many low level libraries that make talking directly to hardware very easy. This was especially the case with the Saitek Joystick on the command side and the UART on the Raspberry Pi. Unfortunately, we have to use the Raspberry Pi 2 as opposed to our original hopes of utilizing the Pi 3's increased power and onboard wifi chip. This is due to how the Pi 3 maps the UART Serial Pins which we found out after successfully implementing our motor control code on the Pi 2 and then trying to run it on the Pi 3. Essentially, the hardware clock on the Pi 3 has been delegated to the new bluetooth module, which runs on the unstable CPU clock, instead of the UART Serial Pins. By "unstable" we mean that the CPU clock frequency is free to vary as more and less power are required which results in a noisy PWM signal. This noisy signal is then either outright rejected by the Roboclaw (our motor controller connected to the TX/RX pins) or is mapped to random, uncontrollable actions. Furthermore, we found that in order to control all the servo's we couldn't just use the 5V and Ground pins on the Pi as this required too much current and resulted in an impromptu shutdown of the Pi as the CPU was starved of power. We quickly righted this problem by powering the Pi, servos and a couple of the lower power motors through a designated 5V rail. Additionally, we found that a common ground between the Pi, servos and batteries was necessary, otherwise the servos became unresponsive and continuously spin. We believe this was due to the Pi sending garbage signals as there was no common ground to base everything off of.

PUBLIC/STAKEHOLDER ENGAGEMENTS

The social media component of our public engagement is through the Cal AIAA Robo Ops Facebook page. We use the page to give weekly updates on the progress for the rover, highlighting creative design choices and innovative procedures on behalf of members of the team. We created a weekly update and hashtag called #MarsRoverMonday to better engage with our followers. Through this page we advertise the competition and our build team to hundreds of students, with the post that gained our largest public engagement reaching over two thousand students.

Our major public engagement event was Cal Day. Cal Day attracts 40k-50k visitors each year as they check out what Berkeley and its hundreds of student groups have to offer. On Cal Day, we tabled in front of the Mechanical Engineering building, showcasing our wheel molds, manipulator, and swerve drivetrain to current/incoming students and the visiting general public. Our display was very popular, and many people of all ages asked "is it really going to Mars?"

Figure 7: CAL-Rover (on the right) tabling at the 2016 Cal Day