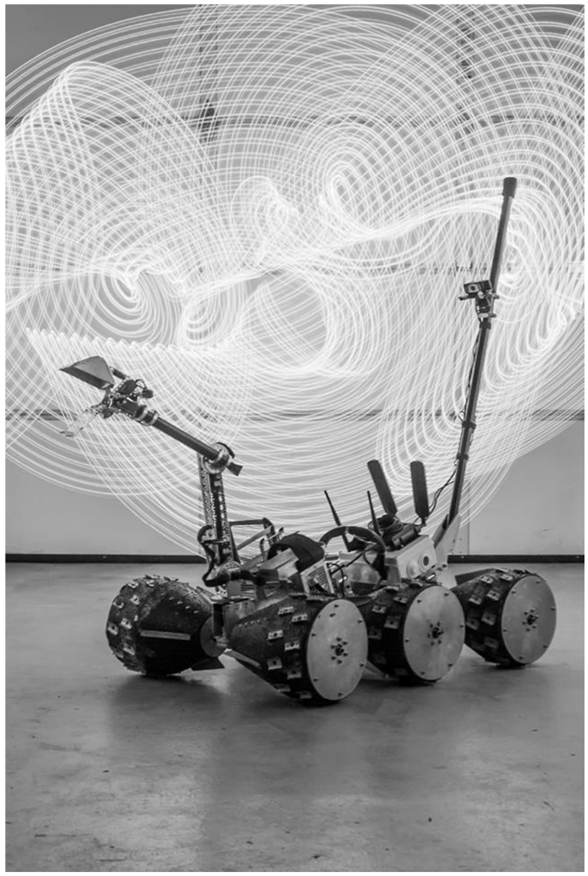


“Rovie McRoverface: A Foray into Teleoperations”

Final Technical Report
NASA RASC-AL Robo-Ops 2016
University of Oklahoma

Project Advisor: Dr. David Miller

Project Leads: Dane Schoelen – Project Manager
Nathan Justus – Chief Engineer
Bill Doyle – Electrical Lead
Brent Wolf – Mechanical Lead
Jacob Jordan – Software Lead
Alex Borgerding – Mission Control Manager

Team Members: Kevin Cotrone, Janella Clary, Ashley Findley
Oskar Paredes, Matthew Solcher, Aaron Condreay

Introduction

The University of Oklahoma is very pleased and excited to participate in the sixth annual RASC-AL Robo-Ops Competition for the first time, and submits this report in order to officially document the development and creation of its rover. Because this is the University of Oklahoma's first attempt at competing in this competition, there was very little infrastructure available at the beginning of the design process other than the equipment in the university machine shop. In addition, the team had no design from previous years of competition to rely on to ease the design process. However, the team has worked tirelessly to overcome these hurdles and to climb the steep learning curve in order to build this entire system from scratch. The University of Oklahoma team believes that it has developed an incredibly competitive vehicle for submission, and looks forward to the challenges to be faced on competition day. Enter Rovie McRoverface.

System Description

The rover was designed in general form to resemble the Marsokhod rover designed by the Soviet Union in the early 1990s [Kemurdjian et al., 1992]. The Marsokhod was designed to traverse Martian terrain, which makes it especially well-suited for replication for this competition. Like the original Marsokhod, this rover has three axles, each holding a wheel at each end for a total of six individual wheels. Each axle has independent roll and pitch articulation from each of its neighbors so that all six wheels are always in contact with the ground. The large conic and cylindrical section that compose each wheel ensures that the rover will have sufficient traction to drive and skid turn on almost any terrain.

Chassis and Drive System

Wheels and Chassis

Capabilities

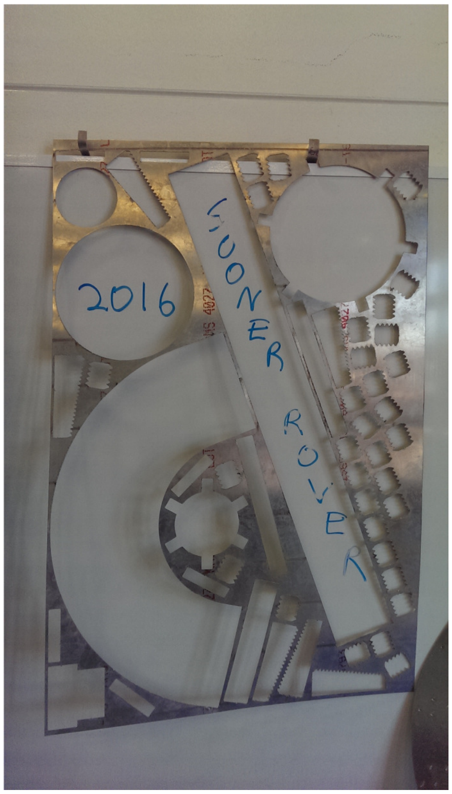
Mobility was at the forefront of the design philosophy for this rover, with an emphasis on traversing the Mars rock yard. An analysis of the reports from previous years and of the rock distributions from video feeds revealed that the rock yard was by far the most point-dense area of the field. As such, the rover was designed to have very large diameter wheels, as this aspect alone offers incredible off-road performance. The large conical sections of the wheels also provide great mobility on sand. As the wheel starts to sink, the effective surface area in contact with the ground increases dramatically. In addition, the motors were chosen such that (assuming sufficient traction) any two wheels could pull the rover up a completely vertical surface, so that insufficient torque should never be a problem.

Wheels

The current rover drive system resembles the preliminary design, that of three axle-pairs that will navigate through skid turning. Each of the six wheels are driven by an internal motor that is mounted to a stationary 1020 DOM ½" outer diameter tube axle. The 1020 DOM is a cold worked low carbon steel that offers exceptional strength and hardness characteristics. The outer shell of the wheel is driven by a gear connection (in a 3:2 ratio) in the center of the outer face and is connected to the axle via ball roller bearings. The shell and tread of the wheel is constructed from T6 aluminum coated in truck bed liner [Flippo 2009].

Wheel Interior

Upon starting fabrication, the team came across several manufacturing challenges. The aluminum parts were difficult to position correctly before welding and warped due to the heat of the welding process. The process of using the CNC plasma cutter to cut the sheet metal required extensive code tweaking to obtain consistent and precise cuts. In addition, welding the thin aluminum proved difficult and required many hours of practice.



Wheel Cutout

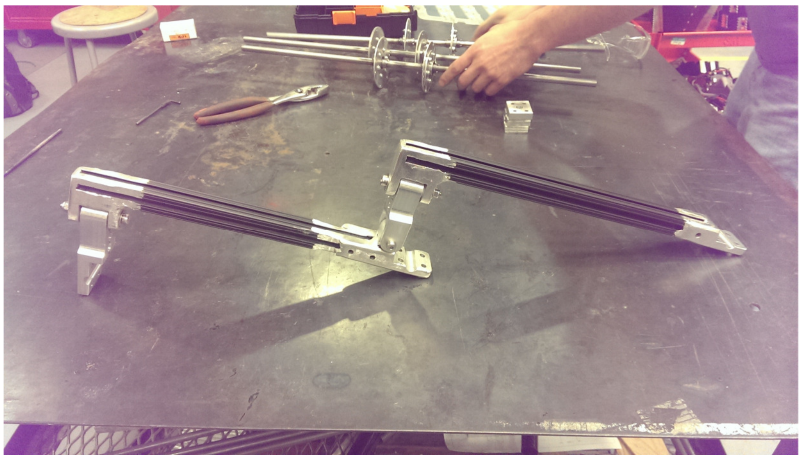
After several prototypes the team had a repeatable process that could be used to produce nearly identical wheels. The final design of each wheel consists of 41 individual aluminum pieces cut from six square feet of sheet aluminum. Two of these pieces were rolled in a metal slip roller to form the conical and cylindrical sections of the wheel. These pieces along with bolt rings for connection to the inner and outer face were riveted together with connecting tabs. This structure formed a rigid wheel that would hold its shape. The seams of the pieces were then welded together and ground smooth, forming a continuous shell. Riveted supports were then removed and holes filled in with welds. Next, the shells were coated with bedliner mixed with rubber crumb, giving the smooth aluminum a rough, tacky surface that enhances traction in sand and gravel [Flippo 2009].

Two aluminum hubcaps seal the ends of the wheels and serve as a mount for the bearings and the large gear. Finally, 30 aluminum grousers were bent and riveted to the outer wheel surface for additional grip. The grouser teeth angles were designed with the ratios Phi (1.618) and Pi (3.14) to enhance the aesthetic appearance and increase turning efficiency [Flippo and Miller, 2014]. The conic section, which is only utilized when the rover is sinking in sand or gravel, has large fins that act as paddles.

The internal mechanisms of the wheel have evolved throughout the project into a refined and surprising success. Early on in the project, the team opted to go with bigger than originally anticipated motors to reduce the chance of getting stuck. With an increase of available torque, the motors operate in the lower end of their power capability during typical testing. The new design also includes a battery mounted inside each wheel that is only connected to a local speed controller mounted above the motor. In this configuration, each wheel is electrically isolated which reduces the risk of catastrophic failure and requires only data lines be passed through each axle. The motor, battery, and speed controller are mounted firmly to the axle with two aluminum clamps machined with a CNC mill. A high carbon steel bolt was welded to the DOM shaft and was slid into a corresponding hole in the aluminum clamps to ensure that the battery and motor mounts would not rotate. The batteries are cradled in an aluminum box lined with Velcro.

Chassis

The chassis of the rover is of very simple construction. It is a spine of metal that stretches a total of 65 cm from the front to rear axle and has pivot joints located at the middle and rear axle to allow for the individual pitch and roll articulation of each wheel. The team opted to use 8020 Inc. hardware to construct the entirety of the chassis and articulation points instead of manufacturing from stock. The 8020 parts are welded to the axle clamping brackets. The clamping brackets that mount the axles to the frame were machined from aluminum stock in the CNC mill. The 1020 DOM axles have a central nipple that is constrained by the bracket to ensure that the axle does not slip and the signal wires are protected. During drive testing several minor problems were identified. The continuous flexing of the frame loosened the passive 8020 joints allowing for flexing in an undesirable axis. In addition, the joints were too weak in their intended axes, which caused the hardware to yield. In order to fix these problems, the team switched from the 8020 passive pivots to custom-built pivots and welded them to the chassis so that they could not rotate in any unintended axis. In addition, mechanical stops were welded to each pivot such that the angle of articulation is restricted. This restricts the mobility of the rover, but allows additional room to mount equipment such as the arm and electronics along the spine and does not cause an appreciable detriment to the rover's capability to traverse the terrain. The final mass of the chassis is approximately two kilograms.



Bare Chassis

Cameras

Five cameras are attached to the rover. The primary camera is the “drive” camera, which is mounted firmly to the camera mast. This camera, a Point Grey BlackFly, offers manually adjustable zoom and focus and computer adjustable resolution and exposure. The second

Camera Feed from Downview Camera

camera, also a BlackFly, is the "spotter" camera, mounted just above the drive camera on the mast on a pan-tilt servo mount. Mission control can adjust the resolution as needed to get the maximum possible practical resolution during the competition. The third camera is mounted below the drive camera, and offers a fish-eye view over all of the wheels of the rover so that the driver can easily tell if the rover has become stuck and how. The team has also mounted a fish-eye camera looking through the clear plastic that serves as the backstop to the rover claw. This will allow for precise positioning of the rover's manipulator during competition. The final camera is the "backup" camera and will be placed facing towards the rear of the rover on the camera mast so that the driver can know of the surrounding terrain in case the rover must be driven in reverse. Other than the "spotter" camera, all cameras are in fixed positions with respect to the rover. Because of the limited bandwidth, only three cameras will be streamed at a time. The "drive" and "spotter" cameras will always be streamed, with the option to switch between the arm, downward view, and backup cameras as needed. The mast itself will deploy upwards from a horizontal position using passive springs that will release when the rover starts to move to a maximum height of 115 cm.

Microphone

Microphone placement was not a high priority throughout the development of this project. Although auditory feedback is important, the main function that the microphone on the rover serves is to alert the driver and arm operator if they hear noises indicating that the rover is having trouble or is stuck. In addition, the battery cell monitors installed in each of the wheels emit a loud noise if the battery voltage drops below a pre-programmed level. This way, the driver will know through the microphone if a battery has been drained and that they need to make a dash for Mars Hill. Only one microphone is needed to monitor both of these considerations. The Logitech C920E webcam that is serves as the backup camera on the camera mast has a built in microphone that will be connected and streamed continuously, even when the camera feed is not. The positioning is also ideal because if the microphone were mounted to the chassis, it is very likely that noise from the rigid metal wheels would drown out all of the important audio feedback.

Manipulator

The rover's sample collection system (arm) is modelled after a backhoe-style digger with five degrees of freedom. The first three degrees of freedom provide yaw-pitch-pitch movement, while the last two manipulate the angle of the bucket with respect to the rover arm and open and close the bucket so that samples can be collected at a wide variety of distances and heights. Samples will be collected by closing a toothed bucket over a clear Lexan sheet. A wide angle camera was mounted on the rear of the Lexan sheet such that the claw can be opened and the sheet aligned exactly with the sample using the streamed video from the arm camera. Each of the servos in the primary yaw-pitch-pitch configuration of servomotors has been geared down past the stock gear reduction ratio for increased torque. The arm has 2.5 times as much torque as it would need to hold a one kg rock straight out at full extension (approximately 70 cm), which gives a large safety factor for the 150 gram samples. It takes approximately three seconds for the arm to traverse from complete storage to full extension.

Arm and Claw Setup

The master-slave method of controlling the arm that was proposed in the team's original project plan has been met with great success. The rover's arm, the "slave", is controlled by an identical arm, the "master", at mission control. The master is constructed from the same hardware as the slave but the servos have been removed from their gearboxes. The signals from potentiometers mounted to each joint of the master are passed out to an Mbed microcontroller, which are in turn mapped to signals that are be sent to the rover. The slave arm reproduces the exact configuration of the master arm at mission control. The arm operator simply pushes the master arm into the desired position of the slave to collect a sample. In practice, the use of this arm combined with video feedback from the camera on the manipulator claw is very intuitive and it allows for the rapid collection of samples and the precise positioning of all arm joints simultaneously rather than the individual tuning that would be necessary with a standard controller.

Control and Communication System

The rover contains two Odroid XU4 octacore ARMv7 computers. Both computers stream video, however only one (the 'main' computer) connects to mission control. The main computer relays mission control's movement commands for the arm, drivetrain, and camera gimbal to the rover's microcontrollers. The main computer also executes commands for changing the current video and audio stream configuration, and relays these commands to the second computer as well. The second computer is used only to process video.

The mission control center for the rover is designed to consist of at least three computers, as each instance of the mission control program is only designed to control one of the rover's subsystems. Specifically, a mission control process can be configured as *Arm*

Control, Drive Control, Camera Control, or *Spectator*. All mission control processes must be able to communicate and broadcast over the same subnet, and one mission control is configured to act as ‘master’, and brokers the actual communication with the rover.

Mission control requires a dual monitor computer to display correctly, as one entire monitor is dedicated to a single video stream. In total, mission control presents three video streams to the user, along with connection/system status information and a map showing the rover’s position overlaid on an embedded Google Maps webpage.

The rover’s arm is designed to be controlled by a replica ‘master’ arm containing potentiometers in each joint. This master arm connects through ethernet to its corresponding mission control process. The drivetrain and camera gimbal are controlled by ordinary gaming controllers.

Video/Audio Compression

Video streams can use either MJPEG, MPEG2, or H264 video compression, and the codec, framerate, bitrate, and other encoding options are all configurable from mission control. The team believes these three codecs are the most efficient for its purposes as they provide low-latency and relatively non-CPU intensive encoding [Iqbal et al., 2013]. However, MJPEG is still more efficient to encode compared to any other option, at the expense of a much higher bitrate for comparable quality.

The mission control layout is designed to present 3 active cameras, as it would be necessary to have more than one viewpoint for certain operations. Due to this and limits and bandwidth and processing requirements, the bandwidth of each stream must be strictly monitored. The resolution used by each camera can vary between 480x360 and 960x720, and the framerate (especially important in MJPEG) can vary between 10 and 30 frames per second. Each individual stream can be configured to account for approximately 1-10 megabits per second, depending on the desired quality. For example, a 960x720, 15fps MJPEG stream at 70 JPEG quality peaks at 10 megabits per second, making it suitable for a situation where the team would like to view a medium framerate and high quality stream from one camera, while the other two active cameras are configured for extremely low bitrate streams as alternate viewpoints.

Audio streams will use the vorbis codec at 128 kilobits per second. Audio compression is far less taxing in bitrate and processing requirements compared to video.

Latency

Latency can be divided into 3 components

1. Communication latency
2. Processing latency
3. Physical latency

The communication latency between mission control and the rover is expected to be approximately 200 milliseconds, and is outside of the team's control. This is also the most unstable latency, as it can fluctuate depending on the load on the network.

The processing latency, or the time spent processing data, is negligible for movement and control commands. However, video encoding and decoding latency is quite significant - even higher than communication latency. The rover computer takes between 200-500 milliseconds to encode video depending on the codec used, and mission control takes approximately 100 milliseconds to decode and display this video.

The physical latency, or the time spent by physical motors and servos executing commands, is also significant in regards to arm control. Although the arm will begin to move as soon as it receives an instruction to do so, it takes time to accelerate and reach its intended position. This is hard to quantify. However, it adds an extra feeling of latency for an arm controller.

Overall, the time between executing an action and observing its result should be between 500 and 1000 milliseconds.

Technical Specifications

Mass

The final mass of the rover is projected to be approximately 29 kg.

Rated Payload

The only payload is the set of rock samples. There is room for 30 medium rocks in the collection box, giving the rover enough volumetric storage space to clear the course.

Max Speed

The maximum speed of the rover is 1.8 meters per second. The team expects to hit this speed frequently during competition as it dashes between samples.

Max Obstacle Size

The largest vertical bluff that the rover has scaled was approximately 30cm. In practice the driver will not likely charge towards similar scenarios, but the idea that the rear sets of wheels would push the front set up a face was proven to work very well.

Operating Time

The batteries were sized such that the rover can drive under strenuous conditions for 1.5 hours. The team's endurance tests have verified that the rover has a 50% safety factor for operation time.

Drive Power

Each wheel motor draws approximately 2.8 amps at 13.5 volts at full speed over flat terrain giving a power consumption of 38 Watts per wheel and 228 Watts in total.

Battery

Lithium-Iron (LiFe) batteries were chosen over Lithium-Ion (LiPo) for their enhanced stability and safety. This choice sacrificed power density for safety, but the team deemed it acceptable to avoid concern over explosions caused by electrical shorting. Fuses were installed in the leads of each battery to further reduce the risk of failure. 4S (13.2v) Li-Fe 8.4 Amp Hour batteries were selected for high operation times but after initial tests it was concluded that 4.2 Amp Hour batteries would be more than sufficient for 1.5 hours of driving and would reduce overall battery weight by three kg.

On-Board Computer System

The rover uses two Odroid XU4 octacore ARMv7 computers running Ubuntu 15.04. In addition, two mbed microcontrollers are used to movement commands to PWM signals.

Communications Interface

All computing devices connect through ethernet, and are assigned static DHCP reservations on the rover's subnet with the appropriate external ports forwarded. All cameras used are either USB2 or USB3, and connect directly to the Odroids.

Software

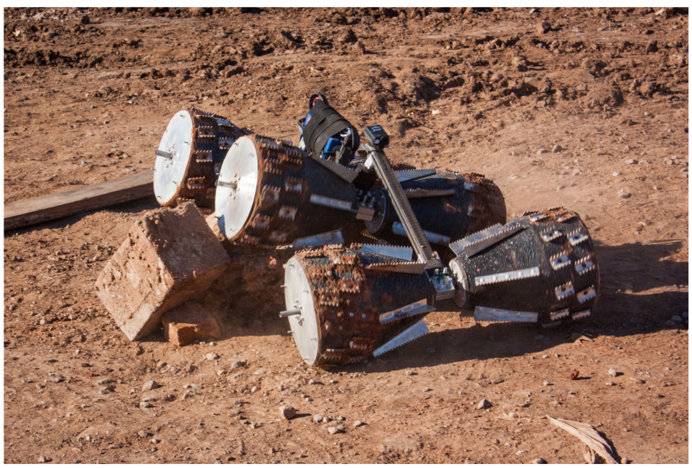
All of the software (excluding the mbed programs) depends on the Qt 5.X framework and gstreamer. Qt is primarily for the GUI construction and networking, while gstreamer is used for video streaming. In addition, mission control depends on SDL for controller input, and the rover programs depend on the FlyCapture2 SDK for interacting with Point Grey cameras.

The software and required dependencies is all cross platform.

Testing Strategy

The rover was primarily tested at the university's civil engineering laboratory. The property has piles and pits of sand and gravel as well as a dirt mound and hard packed flat areas. These areas cover every type of terrain that the team expects to encounter in Houston. Concrete scraps of various sizes have been used to test the rover's ability to traverse rock fields.

The rover is well suited for all types of terrain but it performs best in sand and gravel. The large wheel footprint allows the rover to stay above loose surfaces and the large paddles in the center of the wheels allow it to maintain traction. It's so well suited for these terrains that it can climb slopes in loose material at the angle of repose.



Testing on Obstacles

On hard dirt the rover's wheels only contact the ground on the outer (cylindrical) surface, which allows the rover to skid steer with ease. The toothed grousers on this part of the wheel give it enough traction to climb hard dirt at steep angles. The flexibility of the chassis allows the rover to traverse large rocks while maintaining all wheel contact with the ground. When the rover is driven over a rock taller than its wheels, the back two wheel pairs push the front wheels up the rock and subsequently the front wheels pull the back wheels up over the rock.

The rover has occasionally been tested outside on the grass in the Engineering Quad for convenience. An unexpected finding from these tests has been that the rover is not well suited for driving on grass. It can drive straight and make long arcs without problem. However, due to the extremely high traction of grousers on grass, skid steering is impossible. If attempted, the middle wheel is pushed up off the ground and the rover curls together until it is driven straight again. Fortunately, the rover will not be competing on grass and it will not have this problem in Houston.

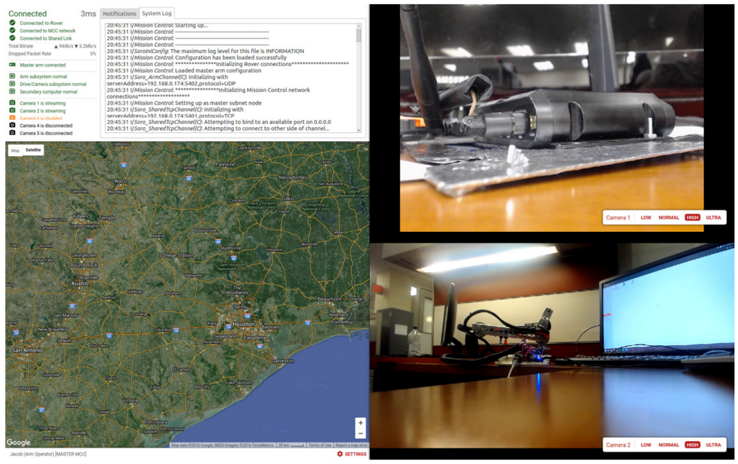
The arm has primarily been tested separately from the rest of the rover. During testing the arm is still mounted to the rover, which is itself mounted on a stand. In order to test the collection capability on the similar surfaces to the competition field, a two compartment box was constructed to be put on the table in front of the rover and to contain sand and gravel test areas. During testing the arm has proven to be best at collecting rocks in sand, where it can scoop far underneath the rock. On gravel the scoop cannot as easily be pushed under the sample rock but can still be wedged under. On a hard surface, if the bucket cannot get under the sample to scoop it completely, the teeth on the bucket's edge pinch the sides of the rock and hold it firmly enough to keep its grip.

Competition Day Strategy

The team plans to be bold on competition day in terms of its operational strategy. After collecting any easy-to-find samples at the top of the deployment hill, giving the camera operator a chance to look around and spot as many high-value samples as possible from afar, the team will plunge directly down the hill towards the Mars rock yard section. This area reportedly has the highest valued samples, so the rover will spend a significant amount of time making sure that it has cleared the area of worthwhile targets. The rover has demonstrated an incredible ability to traverse very rocky and debris-littered terrain, so the rockyard should not be a problem.

After clearing the rockyard, the bonus missions become the priority, as completion of all missions is worth a whopping 50 points. Ideally the team is later in the lineup than another university that has already found the alien so that that bonus mission is assured. In the last few areas, the team will rapidly dash between high-valued samples to maximize our point return per time while assuring that we are in and out of the area in sufficient time to visit all other areas and return to the top of the deployment hill. Here the initial strategy of running straight into the rock field will help, because the most shallow side of the hill is next to the sand dunes and will make for convenient return when the team has finished exploring the last section.

Mission Control Operational Plan



Mission Control View

Staffing

The rover has three operators; the driver, arm operator, and camera controller. Each of these positions will have a primary and standby team member who has also practiced in that role. There will be a software specialist who will monitor the status of the communications system and manage any issues. Finally, there will be a mission manager who has ultimate decision making authority and monitors the status and operations of every aspect of the rover.

Practicing

After full system completion there are two weeks until competition. During the first week the team will practice regularly with the rover and ground station configured as it will be in competition. During the week before competition, the amount of practicing and testing will be dramatically reduced to avoid the risk of damaging any part of the system with too little time to fix it.

Decision making strategy

The team will use the last week before competition to run through all possible strategic decisions that might come up in competition and lay out a coherent strategic plan. During the competition run the mission manager will be responsible for carrying out that plan and ensuring that the actions of the operators adhere to it.

Plan for Contingencies

The scariest scenario that the team might face during competition is that of partial or complete wheel failure. In order to account for this, the team has manufactured outer hubcaps with bearings but without connection gears so that if the outer cap is replaced for a broken wheel system the wheel rotation will not have to back drive the motor shaft and the other wheels can simply out-power the drag from the broken system.

The team has only one spare of the new, smaller batteries so 2 battery failures before competition will necessitate replacement with one of the larger original batteries and will add 500 grams to the rover.

The claw and wrist servos of the arm are easily accessible and are feasible to replace in 10 minutes. In the event that one of these servos breaks in competition the ground crew can take the mulligan and attempt to replace them.

Should near-catastrophic mechanical failure occur during competition, the team will have a hammer ready in their doctor bag. Almost every problem can be solved with a few blows from a hammer.

Budget

The expenditures for this project total approximately $17,000. The team has received the same amount in grants and donations, leaving no deficit for this year’s project. The expenses and donations are detailed in the following tables.

Expenses

Hardware and Material	$3,627.48
Communications Electronics	$1,966.84
Arm and Mast Components	$2,497.35
Batteries and Motors	$2,761.16
Travel/Registration	$2,852.00
Misc.	$593.66
Total	**$14,298.49**

Donations

Monetary		In-Kind	
NASA/NIA Grant	10,000.00	AT&T	$1,100.00
Donna Shirley Award	1,200.00	Point Grey	$700.00
Gallogly College of Engr.	2,000.00	Solidworks	$300.00
Dean Landers	100.00	Sublime Signs	$150.00
Steve Raybourn	500.00	The Pizza Shop	$60.00
ARRC	1,000.00	ServoCity	$375.00
KIPR	100.00	Online Metals	$225.00
Total	**14,900.00**		**$2,910.00**

Public/Stakeholder Engagement

The team has maintained a presence on Facebook and Twitter and built a significant following. The Facebook page as of this writing has 230 likes, 51 posts with a combined 2,200 likes, and a post reach of 5,500 people in the last month alone. The team has been featured in 8 newspaper articles and television news segments. A “Name our Rover” event was concluded in April in which the team received over 400 name suggestions from the community. Currently, team members are selecting their top five favorite names which will be subjected to a public online vote that will decide the final rover name; the team strongly suspects that the final result will be “Rovie McRoverface,” as there has been a strong public push for this name to be selected. The team organized several events (listed below) featuring technical talks, rover demonstrations, and Q&A.

Library Event

A large part of the team's outreach was directed towards local children. A very successful event was held at the local Botball regionals to draw young students already interested in robotics towards space-related projects. Almost all of the student teams competing there approached the team's stand to watch the robot move around or to receive an autograph signed by a pen held in the rover's claw. In addition, an event was held at the local library during the May Fair which took place in that area to demonstrate to younger children the type of work that can be done through engineering. The children loved "feeding" the rover's claw from their hands with our sample rocks. The focus at this event was the capabilities of engineering in general rather than engineering specific to space.

Date	**Event**	**Visitors**
2/4/16	AME Showcase	20
3/5/16	OK Botball Regionals	150
4/9/16	Big Event Open House	30
4/19/16	Boeing Lunch and Learn	100
4/23/16	Sooner Saturday	50
4/30/16	Rover Day @ Library	50
	Total	400

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