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MIT ROBOTICS TEAM

2014 Robo-Ops Rover Technical Report

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Executive Summary

The following report describes the design and implementation of the MIT Robotics Team's rover for entry in the 2014 RASC-AL/NASA Exploration Robo-Ops competition. The Robo-Ops competition challenges competitors to construct a planetary rover prototype designed to collect rock samples at the Johnson Space Center while being tele-operated from the team's home campus. Through the course of the competition, the rover will be tasked to navigate difficult terrain and identify small rock samples in a large, open environment. Restrictions and requirements for the competition include:

- A maximum size and weight of 1.0m*1.0m*0.5m and 45.0kg respectively
- The ability to traverse obstacles up to 10cm in height, grades up to 33%, and loose sand.
- The ability to identify and collect colored rock samples ranging in size from 2 to 8 cm and weight from 20 to 150 grams.
- The ability to operate in harsh outdoor conditions, including rain.

The MIT Robotics Team, as a new entrant to the RoboOps competition, has carefully studied the successes and failures of previous teams and created a robust, effective rover prototype that combines proven concepts with innovative new ideas. Key highlights include a flexible multi-pivot averaging suspension system, a robust five degree of freedom arm, a powerful onboard image processing system, and an intuitive piloting interface that takes advantage of the latest real-time video streaming and mobile connection technologies.

1. Rover Systems

1.1 Chassis

The final iteration of the rover chassis is designed to provide a robust, rigid structure while keeping weight minimal. The final chassis is constructed of tig-welded water-jetted aluminum sheet. This construction method allows for rapid fabrication, as the sheets are cut directly from the prepared CAD files. Additionally, mounting holes for all onboard components can be included in the design, significantly decreasing assembly time. Compared to the
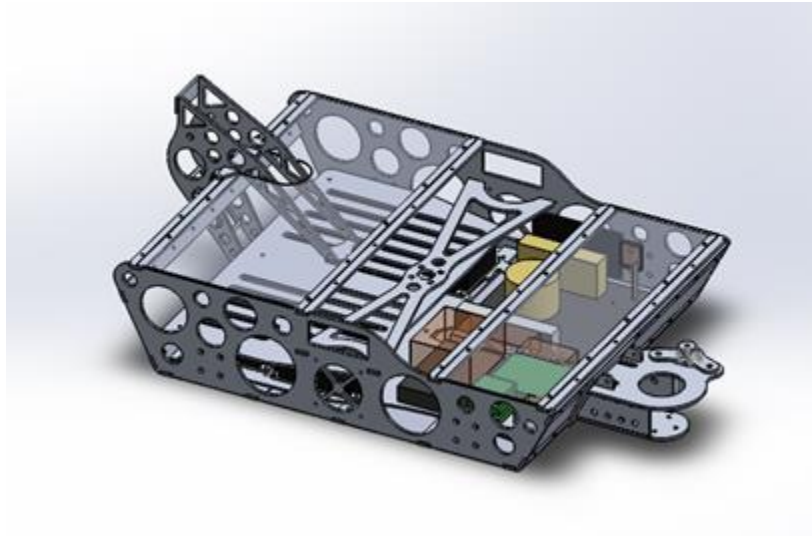

FIGURE 1: ROVER CHASSIS

first-generation chassis, which was constructed of 80/20 extruded aluminum barstock, the final design achieves a chassis weight reduction of ~100% while retaining similar rigidity and decreasing assembly time.

1.2 Drive System

The rover incorporates an innovative multi-pivot passive averaging suspension system. The system allows for the traversal of large obstacles and superior traction on uneven surfaces. Compared with designs that rely on a single pivot point, the mult-pivot system significantly increases chassis durability, payload capacity and rigidity. Additionally, the geometry of the system can be quickly reconfigured. These benefits translate to increased operation speed by allowing for field optimization as well as reducing camera jitter during roving and chassis movement during arm operations.

FIGURE 2: DRIVETRAIN IN ARTICULATED STATE
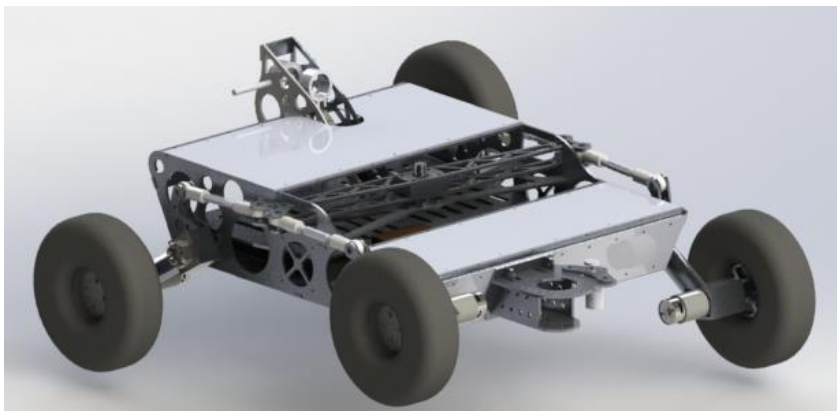
The suspension system consists of several components. Averaging is provided by a center linkage, fabricated from aluminum sheet metal, which rotates on a pivot secured to the chassis. This bar is connected on both ends to the drive legs via heim-joint rod ends and turnbuckle style male threaded rods. The linkages allow for simple adjustment of overall drivetrain geometry. The

drive leg assemblies are attached to the chassis via dual-taper-roller bearing assemblies. These rugged bearing assemblies can withstand both axial and thrust loads while allowing for free movement of the wheel's position relative to the chassis. This entire system provides an extremely robust single degree of freedom drivetrain design that conforms to the geometry of the landscape the rover is driving on.

Finally, the wheels used on the rover are 10" diameter foam-filled turf tires, selected for their excellent traction, and durability along with their low cost. They attach to specially manufactured wheel hubs that connect to the gearbox-motor assembly as well as the optical rotation encoders.

FIGURE 3: EXPLODED VIEW, LEG ASSEMBLY

1.3 Sample Retrieval System

The design of the sample retrieval system is based on the arm design of a commercial excavator. It has five degrees of freedom and is comprised of a rotating boom, stick, claw, and thumb. The design is extremely robust and rigid, allowing for precise maneuvering. The boom is actuated by a two-inch stroke, 150lb force linear actuator. After considering mechanical advantage, the boom is capable of exerting 62 lbf at its tip. The boom to stick joint is controlled by two 100mm F16-P Firgelli linear actuators, each with a 22.5lb load capacity. The claw is actuated by a 50mm F16-P Firgelli actuator, also with a 22.5lb load capacity, via a two-bar linkage. Finally, the thumb itself is opened and closed by a Hitec HS-5645mg high torque servo, with an output torque of 26lb/in at 6.0V. The thumb is mounted such that it is actuated relative to the claw's position. In this manner, once a sample is grasped, the claw may be curled without risk of dropping the sample.

All structural components of the sample retrieval system, save for the gears and the actuators, are manufactured in-house out of aluminum stock and sheet metal. The boom and stick are made from water jetted 3/16" and 1/8" aluminum sheet metal welded and pinned in place with a truss inspired cutout design that minimizes weight while maintaining robustness and optimizing speed of manufacturing. The claw was made from thicker ½" and ⅜" aluminum sheet and designed to ensure a proper grip on the rocks that the rover will retrieve. The outer fingers of the claw taper inwards to help grasp around the sample.

FIGURE 4: 5-DOF SAMPLE RETRIEVAL SYSTEM

The entire arm assembly is mounted on a rotating hub geared at a 1:7. The hub is rotated by a Pololu 131:1 metal gearmotor which operates at 80 rpm. Taking the gear reduction into account, the arm rotates at approximately 11.5 rpm which corresponds to a 5.25 second 360° rotation period. To improve operational range, the arm is mounted to the front corner of the chassis. This location places the arm closer to the ground, and also allows for an
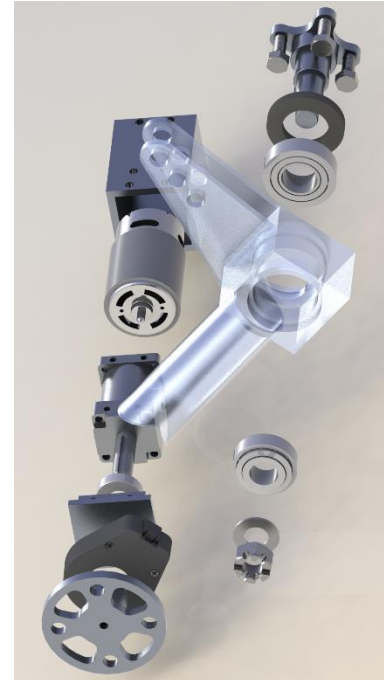
effective service area of about 260°. This system rotates on a set of dual taper roller bearings that are of the same specification as the drivetrain leg assemblies. The entire system is mounted to the chassis via a welded aluminum mount. This allows for easy removal and modular options that allow the system to be bolted at different locations along the chassis

1.4 Camera Array

The Rover incorporates a folding camera mast which can be stowed and deployed remotely using a Firgelli 100mm L16 linear actuator. The mast carries a payload of three Teledyne Dalsa BOA PRO color image processing cameras, which perform continuous sample detection in a 180 degree arc. It is also capable of optionally carrying an additional pilot cam to provide additional perspective to the pilot.

When deployed, the mast sits approximately one meter above the ground plane, providing an elevated perspective of the course. Slop in the mast system is minimized through the use of the worm drive system of the linear actuator to hold positive force against a backstop when deployed.

FIGURE 5: CAMERA BOOM

1.5 Onboard Computing

To provide the considerable computing power required for compressing multiple video streams and providing low-latency control, a micro-ATX form-factor PC is used. The onboard PC utilizes an Intel I5 4570 processor, 4GB of DDR3 ram and a 64GB solid state drive. The computer connects the various onboard electromechanical systems through PWM, serial, USB and Ethernet interfaces. A visualization of the control signal flow can be viewed in Appendix II: Control Flow.

1.6 Communications

The rover achieves high-bandwidth, low-latency communication with mission control through use of Peplink's SpeedFusion technology. SpeedFusion is a connection bonding technology which performs seamless packet-level load balancing, hot failover, and bandwidth aggregation. This technology enables the onboard rover software to treat its multiple broadband wireless connections as a single, faster connection. The rover is able to seamlessly transition between wifi, single 4G, dual 4G or all three without dropping control or video.

The equipment to achieve this functionality consists of a Peplink SURF OTG for wifi connectivity, as well as a Peplink MAX HD2 Mini onboard the rover. At mission control, a Peplink Balance 580 router re-bonds the disassembled packets from the rover into a cohesive stream.

During competition, two 4G connections from two competing providers: Verizon, and AT&T will be used to provide maximum redundancy and reliability. A complete schematic view of the rover's networking topology is available in Appendix III: Rover Networking Schematic.

2. Software

The rover's software systems can be viewed as several distinct components. The Rover's on-board software is written primarily in C++, using the ROS (Robot Operating System) architecture and Ubuntu 12.04. The low-latency video streaming and control interface for piloting uses a C++ server in linux and a C++ client in Windows which communicate using lossy, low latency UDP packets. The navigator and spotter clients connect to C++ TCP/IP servers and are written in C# .NET.

Each server running onboard the rover acts as a ROS node, providing an interpretation layer between ROS's local communication architecture and the proprietary bandwidth-optimized format used to transmit messages to mission control. Additionally, there are three Teledyne Dalsa Boa Pro cameras which run "Sherlock Embedded" image processing software for on-board rock detection. An overview of this software layout can be accessed in Appendix IV: Software Flow Diagram.

2.1 Pilot GUI

The pilot GUI, modelled after the design paradigm of a first-person-shooter type video game, enables fast, efficient, and intuitive control of the rover. The client sends and receives control and video data via lossy UDP packets for the lowest possible latency. The video stream is decoded locally using the ffmpeg library and drawn to screen using the SDL library. End-to-end latency is typically under 600ms. The application is designed to be run on two monitors, with one stream viewed on each monitor at a 16:9 aspect ratio. Gui elements are minimal and non-intrusive; the minimum possible set of information required for navigation is overlayed on top of the video feeds.

Control input is from two Logitech 3-axis Joysticks. Buttons on the Joystick can be used to switch between control modes and the two throttle sliders can be used to change the level of control scaling and exponential curving on the fly. Control processing is done client-side. Current control modes include:

- Arcade-style drivetrain control on right joystick, pantilt control on left joystick
- Tank-style drivetrain control across two joysticks.
- John-Deere style arm controls across two joysticks
- Arm + Drivetrain across two joysticks
- Arm + Camera across two joysticks.

As the rover progresses through its operational testing stage, control modes may be tweaked or added as deemed optimal.

2.2 Navigation GUI

The Navigation GUI is modeled after a Google Maps type interface in C#. GPS coordinates are streamed using a TCP socket connection. As position data is received, the rover path is plotted visually. Outlier data points are detected by comparing the previous five to ten positions against the current speeds and directions at those points. The map also shades in regions along the path to approximate the area that was seen by both pilot and rock detection cameras.

2.2 Spotter GUI

The spotter is responsible for monitoring and tuning the image processing system in real time, and providing an additional manual set of eyes to ensure the highest rock detection rate possible. The spotter GUI consists of a single screen in which the spotter can tab through stills sent from the automated rock detecting cameras. Each still comes with a timestamp, GPS location, and an ID indicating the camera from which it was sent. When the spotter thinks an area requires further inspection, the position data can be sent to the navigation GUI, which will automatically place a pin at the location of interest.

2.3 On-Board Software

For control, the rover uses ROS's internal message passing framework and publisher/listener event style programming. Each of the four driveline motors and the arm rotational axis motor use high-precision optical encoders enabling the use of a PID feedback loop to maintain correct velocities. Arm movements are calculated and performed using combination of inverse kinematics, pre-programmed patterns, and manual commands. Camera feeds can be dynamically toggled on and off at the discretion of mission control.

The navigation server will provide the Navigation GUI with GPS coordinates from the rover, detailed state and diagnostic information, and position of interest coordinates detailing likely rock positions from the spotter seat and vision systems. All information is exchanged over a TCP/IP socket connection.

The spotter server handles the task of coordinating the transmission of images between the rover and the Spotter GUI. Image retrieval rates and other parameters may be modified in real time to accommodate available bandwidth. The Server uses TCP and FTP protocols to pass messages and images. The spotter server also accepts commands from the spotter GUI, such as place point of interest pin, etc. In this manner, if the Spotter thinks there is a rock at a particular location, this information may be logged.

The pilot server performs video compression and streaming using the ffmpeg library and the x264 codec. The server also provides basic rover health information to the pilot and accepts control commands. Both video and control commands are sent over a lossy, low-latency UDP connection. To achieve video latencies under 600ms (nominal <450ms over wifi), the server uses techniques described in the article, "x264 The best low-latency video streaming platform in the world"[1] and code snippets from opensource project, RoboCortex[2]. To allow for instant hot-swapping between video feeds, and for maximal efficiency, only a single 32:9 video stream is used. The content of this stream is determined server-side. Typically, the server encodes two 16:9 camera feeds onto the canvas. However, the pilot may request other configurations and any combination of presets can be created in advance, including simultaneous streaming of all cameras.

2.4 Image Processing

The Rover's three Teledyne DALSA BOA PRO Cameras, which run Teledyne's Sherlock Embedded software, enable on-camera image processing. This functionality offloads expensive processing from the main onboard computer, allowing the computer to devote more computing power and resources to other intensive tasks such as video encoding. The Teledyne software also allows for rapid implementation of machine vision algorithms using a graphical interface. The cameras are able to accept TCP connections to facilitate communication and reconfiguration during operation. During competition, pre-programmed modes specific to different terrain can be activated simply by sending a message via the TCP/IP connection. The main purpose of the onboard processing is to automate the task of detecting colored rocks. This functionality significantly reduces operator workload and bandwidth requirements.
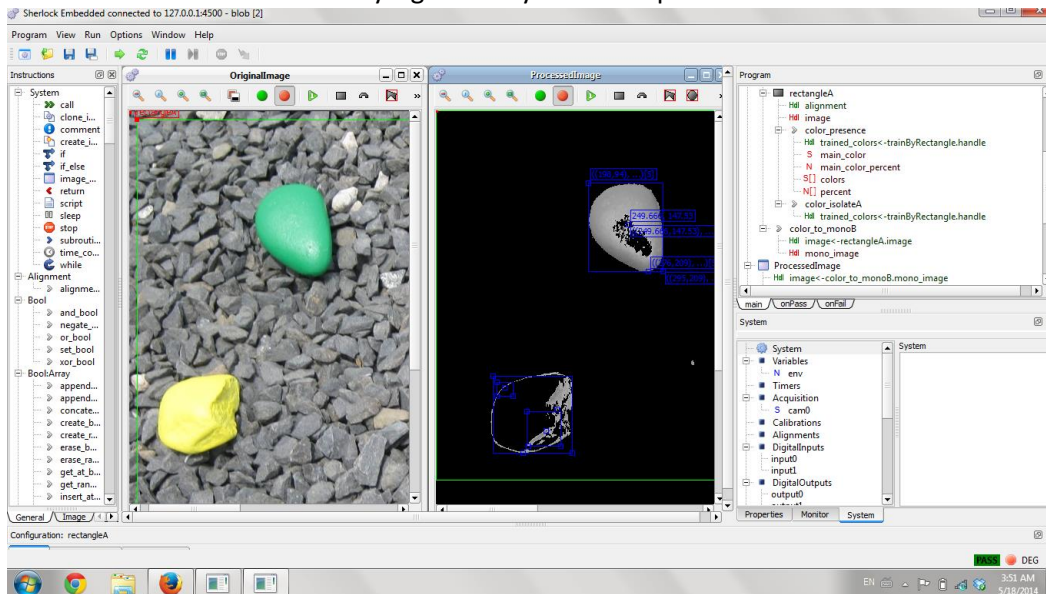

FIGURE 6: IMAGE PROCESSING USING SHERLOCK EMBEDDED

The Rover's image processing code involves two parts: identification of relevant objects, and color recognition. First, all colored images must first have thresholding applied to eliminate noise and irrelevant information such as background colors and possible glare and/or shadows. After this preliminary round of processing, the colored image must be converted to a monochromatic image to allow for binary large object (blob) detection analysis. If a relevant blob is detected, the camera will send a TCP/IP message to mission control, which will be reflected in the Spotter's GUI.

In terms of color recognition, the program will contain a pre-defined color palette containing a range of saturation for each color of interest: red, purple, blue, green, yellow, and orange. To provide redundancy, the cameras will transmit a subset of the images acquired, at a rate determined by available bandwidth, to mission control for manual verification. If the Spotter is aware of many false positives, or there are missed positives, the Spotter will be able to fine-tune several parameters of the vision system on the fly to increase accuracy.

3. Operational Stratagy

In order to perform strategic optimization, highly simplified statistical models of the rover, JSC Rockyard and rock point distribution are used. These models will mature as additional data from previous competitions and rover behavior are gathered. Two optimization problems are discussed:

1. **Tactics**: The goal of tactics optimization is to determine the maximum time to spend trying to pick up a rock of a particular point value in a particular region such that the team maximizes its expected score: Mars Hill (time vector), Sand Dunes (time vector), Lunar Craters (time vector), Rock Field (time vector). Note that in some cases the recommended time may be zero, indicating that it would be better to ignore a rock and search for a different rock. The initial model discussed here addresses whether a rock of a certain value is worth picking up given what is known about the point distribution.

2. **Strategy**: The goal of the strategy optimization is to determine how best to distribute time among the four regions such that the expected score is maximized: Mars Hill (time vector, ordering vector), Sand Dunes (time vector, ordering vector), Lunar Craters (time vector, ordering vector), Rock Field (time vector, ordering vector).

The strategy/tactics optimization above assumes that there is no separate phase of "surveying" territory. This initial simplification was chosen for the following reasons:

- Based on previous years' live stream data and competition rules the rock distribution will be quite sparse among the 4 different regions.
- Based on previous years' live stream data and rover specifications the rover will likely only be able to identify a rock at a distance of a few meters. The characteristic length scale of the rock yard is 100 meters.

The above two points mean that surveying territory may take a significant amount of time and will only give information on $O(10)$ rocks within each field.

The RASC-AL competition is somewhat similar to the travelling salesman problem with the following differences:

1. Not all locations need be visited.
2. No locations are known a-priori
3. Locations have different value (rocks range from 1-6 points and the alien gives 20). The value of visited locations needs to be maximized over a 1 hour time period.

Though not addressed here, the team may consider different routing strategies given rock distribution data from previous years.

3.1 Tactics Optimization

3.1.1 Inputs (parameters)
- Time spent in each area (strategy model output)
- Rock score distribution (testing and previous years' data)
- Rock location distribution (testing and previous years' data)
- Likelihood of getting stuck in each region (testing and previous years' data)
- Mean time to pick up a rock (testing and previous years' data)
- Mean time between finding rocks (testing and previous years' data)

3.1.2 Outputs (optimum)
- Minimum point value of rocks that should be picked up

3.1.3 Basic Equations

The decision to be made is whether it is beneficial to spend the time to pick up a rock of a certain point value or ignore it. This will depend on the remaining rock scores that for now it is assumed are uniformly distributed (may incorporate Bayesian inference). We therefore optimize to find the optimal minimum point value p at or above which a rock is worth picking up.

Design Variables:

p : Minimum score of rocks worth picking up

Parameters:

$T_{remaining}$: Remaining time

t_{pickup} : Mean time to pick up a rock (assumed constant here)

t_{find} : Mean time to find next rock

p_r : Observed rock point value

Internal Variables:

K_p : Expected number of rocks rover can visit in remaining time

Objective:

$$max \sum_{p_r > p} \left(p_r \cdot P(score_i \geq p) \cdot K_p \right)$$

Optimal strategy is to pick up rock if $score_i \geq p^*$

Constraints:

$$\sum t_{pickup} + \sum t_{find} = t_{pickup} \cdot P(score_i \geq p) \cdot K_p + t_{find} \cdot K_p = T_{remaining}$$

Re-arranging:

$$K_p = \frac{T_{remaining}}{t_{pickup} \cdot P(score_i \geq p) + t_{find}}$$

3.1.4 Analysis Examples

If the remaining rock score and pick up time have a uniform distribution:

i. Pick up rocks with score 6 only ($p^* = 6$)

$$score = 6 \cdot \frac{1}{6} \cdot K_p = \frac{T_{remaining}}{\frac{t_{pickup}}{6} + t_{find}}$$

ii. Pick up all rocks ($p^* = 1$)

$$score = \left(6 \cdot \frac{1}{6} + 5 \cdot \frac{1}{6} + 4 \cdot \frac{1}{6} + 3 \cdot \frac{1}{6} + 2 \cdot \frac{1}{6} + 1 \cdot \frac{1}{6}\right) \cdot K_p = \frac{7}{2} \cdot \frac{T_{remaining}}{t_{pickup} + t_{find}}$$

This highly simplified model does not take into account the alien life form, points for visiting each part of the rock yard and points for returning to Mars Hill. The model will be expanded to take these into account by competition date. Additionally, instead of assuming a uniform distribution, the remaining rock score distribution (and possibly also the remaining rock pick-up distribution) may be constantly updated as more information becomes available (Bayesian inference).

3.2 Strategy Optimization

The model for strategic optimization at this time is still undergoing fine-tuning and testing. When complete, the model will determine the order and distribution of time for each competition area. To perform this optimization, data from previous years will be used, as well as data from any live-streams viewed directly prior to the Team's competitive run. Examples of the type of data considered for this optimization are included in Appendix V: Optimization.

3.2.1 Inputs

- Rock score distribution (previous years' data)
- Rock location distribution (testing and previous years' data)
- Average travel speed in each region (testing and previous years' data)
- Average pick up time in each region (testing and previous years' data)
- Likelihood of getting stuck in each region (testing and previous years' data)
- Time to return to start from each region (testing and previous years' data)

3.2.2 Outputs

- Ordering of regions (3 design variables, 4th is dependent)
- Fraction time spent in each region (3 design variables, 4th is dependent)
- Come back to origin (Boolean)

3.2.3 Strategic Java Simulation

To help evaluate, visualize and test different strategies and tactics, a simplified JAVA simulation has been developed. The simulation distributes rocks of different point values as shown in the rectangular area below. The rover (black) has a field of view (white) within which it can "discover" and pick up rocks.
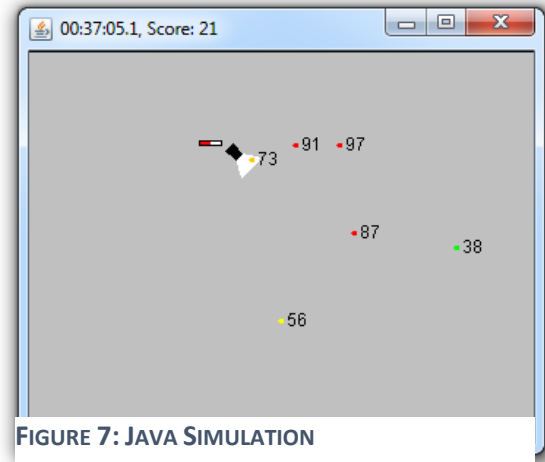

FIGURE 7: JAVA SIMULATION

4. Budget

Through the generous support of corporate and academic sponsors, the team was able to construct the rover to initial design specifications without monetary issues. The two tables below summarize actual team spending and sponsorship contributions. In-kind donations are not included in the cost totals:

Item	Cost
Rover Mechanical	2800
Machining (water jet fees)	1000
Rover Electrical	4500
Competition Registration	1200
Travel Expenses	2400
Outreach and Media	300
Mission Control	1500
Tools & Equipment	800
Total	14500

TABLE 1: TEAM SPENDING

Company	Sponsorship Level	Contribution Type
Peplink	Title	In-kind + Monetary
Teledyne DALSA	Platinum	In-kind
MIT Aero/Astro	Gold	Monetary
Massachusetts Space Grant Consortium	Gold	Monetary
MIT Edgerton Center	Gold	Working Space
MMF Systems	Silver	Monetary
Dassault Systemes	Silver	In-Kind
US Digital	Bronze	Discount
Roboteq	Bronze	Discount

TABLE 2: SPONSOR INVOLVEMENT

5. Public/Stakeholder Engagement

This semester, the team has executed a strong public outreach campaign. Through several events, connections were established with corporate sponsors, the general public, MIT alumni, K-12 students, and peers.

On the MIT campus, the team showcased the rover at events such as the Edgerton Center MIT Alumni Open House and the Campus Preview Weekend Activities Midway. During the activity midway, the team showcased the rover to over 1000 graduating high school seniors with an interest in STEM. Presence at these two events resulted in support from MIT alumni, faculty, and both current and potential students.

Outside of campus, the team also made active efforts to reach the general public and younger students ranging from elementary to secondary school. The team held a booth at the FIRST Robotics New England District Championship at Boston University which reached approximately 1000 robotics enthusiasts in the form of business professionals and aspiring young students. Team members present at the competition shared technical knowledge of the rover, answered questions regarding practical applications of robots, and encouraged high school students to further pursue science, technology, engineering and mathematics in college.

Finally, the team held an interactive session with elementary school children at Einstein's Workshop, a hands-on learning center in Burlington, MA. Team members taught the children about the basic structure and function of the rover and assisted them in driving the rover. Simple CAD diagrams of the rover were also given out and children were invited to label the different parts. Additionally, the MIT Robotics Team shared the importance of fostering a passion of with interested parents, encouraging them to continue to expose their children to opportunities to build, create and innovate. At this event, the team interacted with around 50 parents and kids at grade-school level and below.

The team also made significant effort to generate positive publicity through social media. The "MIT Robotics Team: Robo-ops 2014" Facebook Page is constantly updated and maintained with photos and videos of team members working on various parts of the rover, progress of the rover, and participation in outreach events. The Facebook page has over 820 "likes", and statistics from the page calculate a total reach of about 4,800 users.

The Communications and Outreach sub-team also designed a team logo, publicity materials such as posters, an outreach presentation, and a sponsorship package. The sponsorship package consists of tiered merits, each tier guaranteeing specific incorporation of company logos on team attire, official flyers and on the rover itself. Dedicated members of our Communications and Outreach team focused on contacting local, national and international corporations.

Through a strong sponsorship campaign, the team was able to secure title sponsorship from Peplink, platinum level sponsorship from Teledyne Dalsa, and smaller contributions from a variety of entities such as: MMF Systems, MIT Edgerton Center, MIT Aero/Astro, US Digital, Roboteq, Dassault Systems and Massachusetts Space Grant Consortium.

These efforts enabled the team to construct the rover as initially proposed, without financial constraint. Continuing onwards, the team is making a strong effort to maintain positive, personalized ties with our corporate sponsors. For example, to receive training for the Teledyne Dalsa Vision system used on the rover, several members of the Robotics Team visited the company facility in Billerica, MA. There, the MIT Robotics Team representatives presented a short PowerPoint including general information about the RASC-AL RoboOps Competition, an overview of the rover design and specific benefits sponsoring would entail. In a later visit, the team brought the completed rover to the corporate facility, providing a live demonstration of the various functions of the robot.

In summary, the MIT Robotics Team has established a strong presence on MIT's campus, in the Boston community, and throughout the Northeastern Region of the US. The team actively reaches out not only to MIT students, faculty, and alumni, but also to the general public and K-12 students. With the motivation of increasing awareness and active involvement in STEM, the team provides encouragement, and inspiration for those considering study in a technical field.
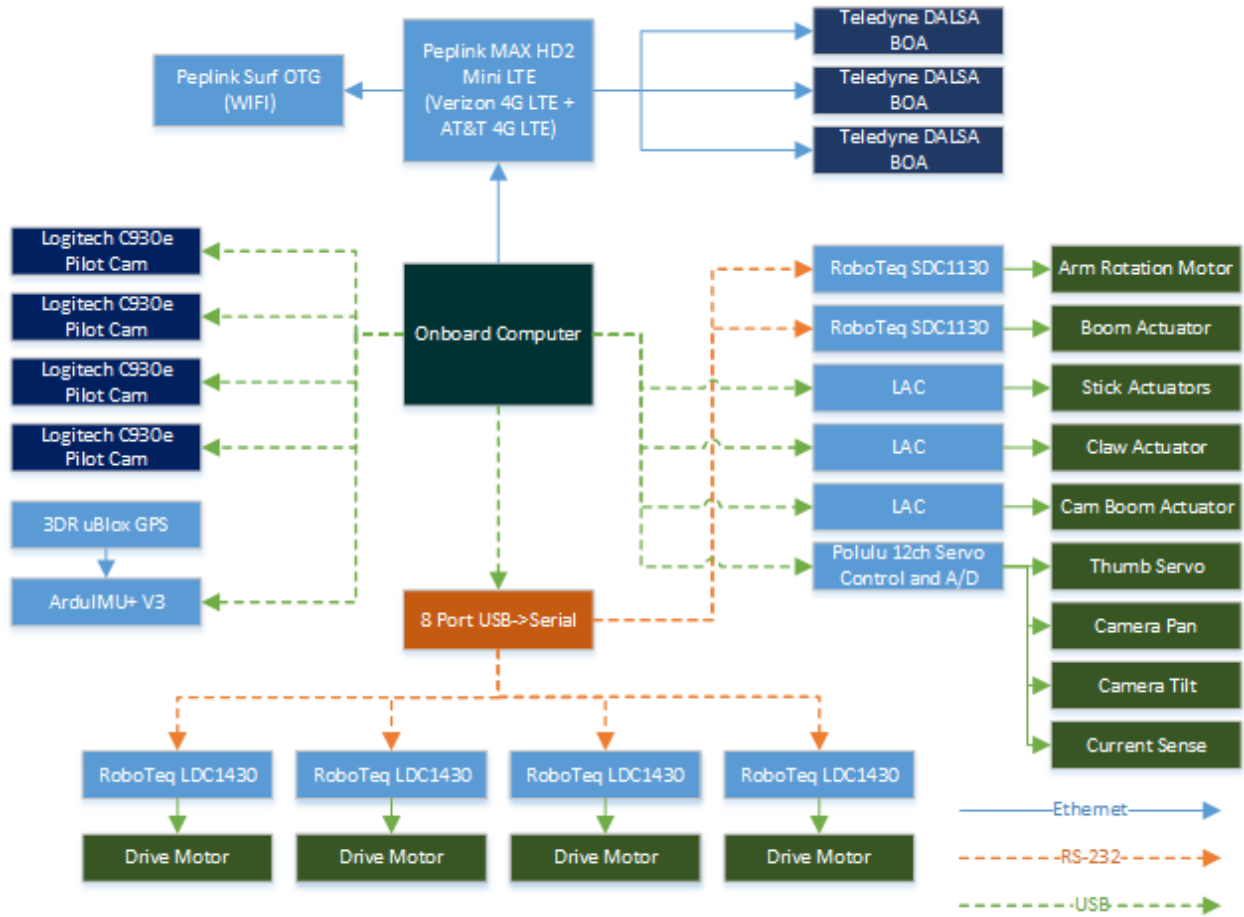
References

[1] Garrett-Glaser. (2010, Jan. 13th). x264: the best low-latency video streaming platform in the world [online]. Available: http://x264dev.multimedia.cx/archives/249

[2] Stg, Phrst, JonasB. (2011). RoboCortex [online]. Available: https://github.com/stg/RoboCortex

Appendix I: Technical Specifications

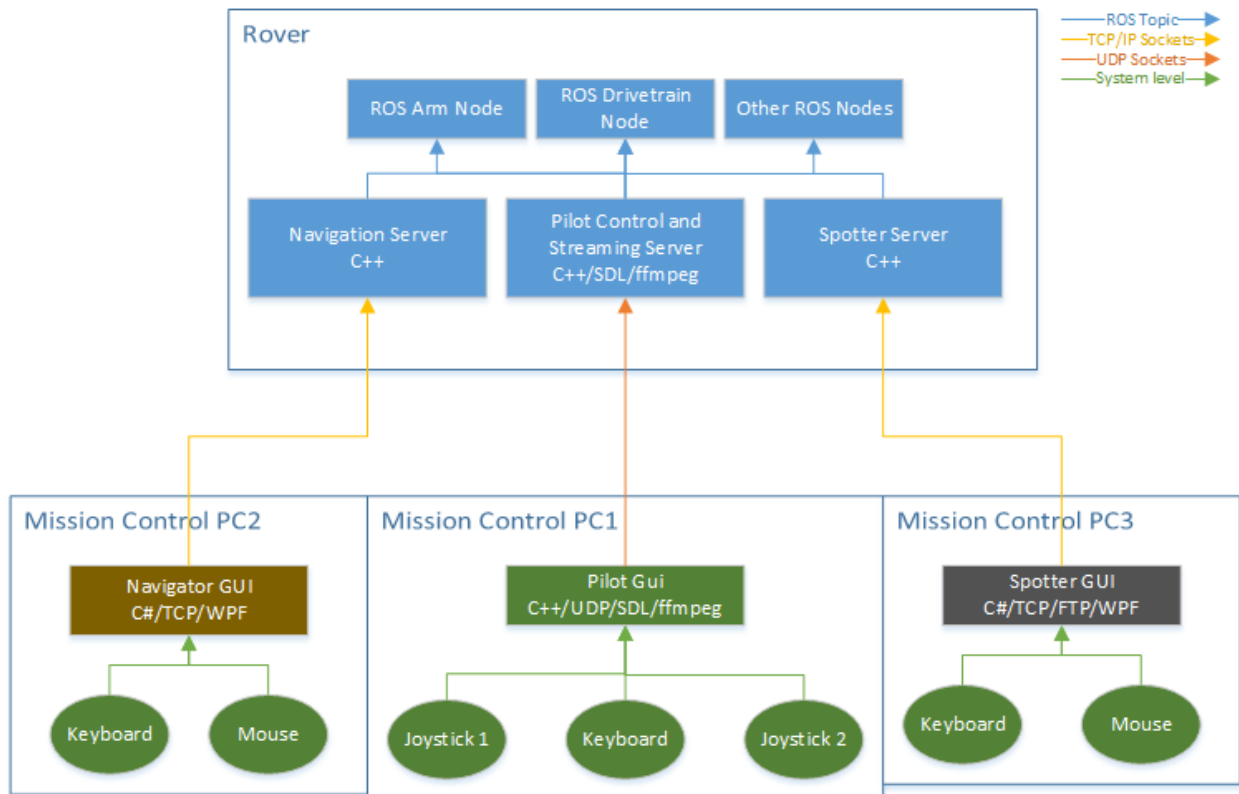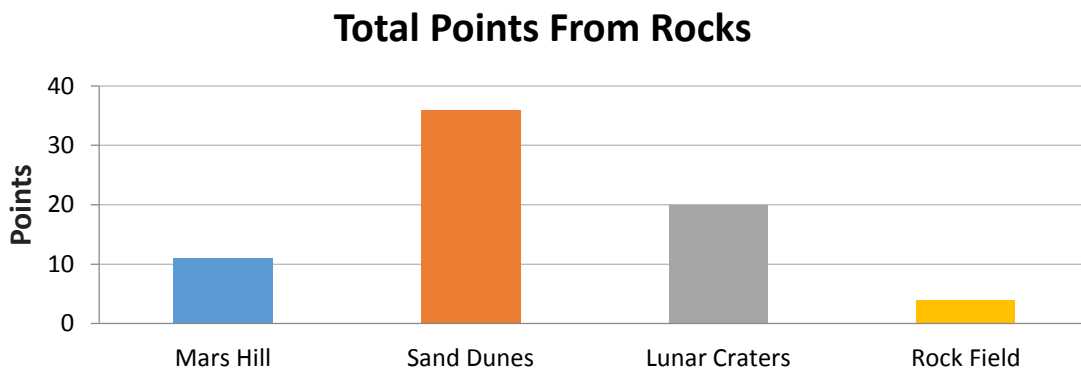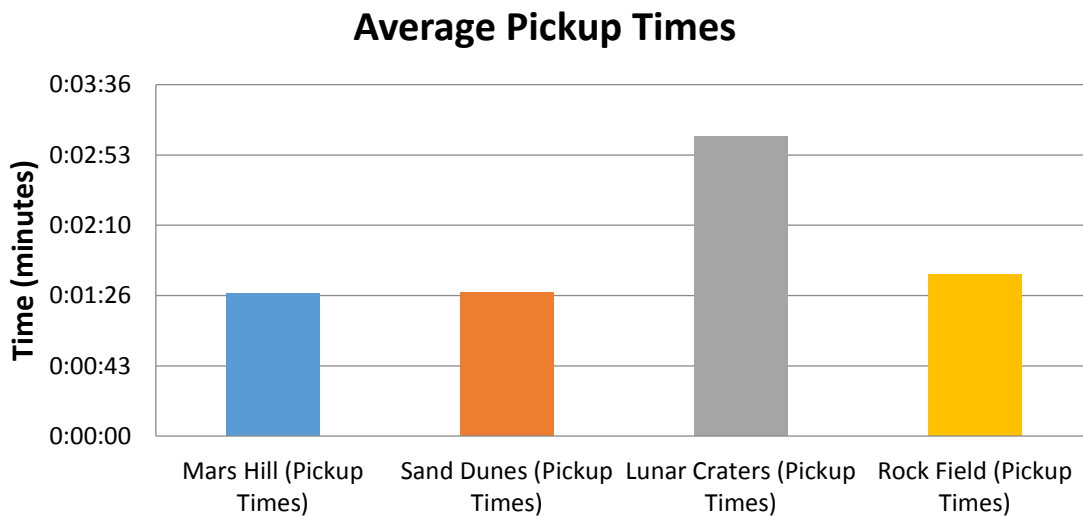|	
Dimensions	1m x .7m x .5m
Mass	40kg 88lb
Rated Payload	45kg 100lb
Maximum Speed	2.2 m/s
Maximum Obstacle Size	20cm
Battery System	Lithium Polymer, 4-cell, 5000mAh packs ~160-480Wh configurable
Nominal Runtime	1.5hr
Power Consumption	48W Idle 200W Typical Operation 1600W Peak
Onboard Computer	Intel I5 4570 based x86-64 Micro-ATX PC
Communications	1x WiFi N 1x Verizon 4G LTE 1x AT&T 4G LTE Peplink SpeedFusion Bonding Technology
Imaging & Cameras	4x Logitech C930e Pilot Camera 3x Teledyne DALSA BOA Pro Smart Camera
Software	Ubuntu 12.02 Robot Operating System: "Groovy" Teledyne Sherlock Embedded

Appendix II: Onboard Control Flow

Appendix III: Rover Networking Schematic

Rover

Onboard Computer

Onboard Router with Peplink SpeedFusion Technology

| Verizon 4G LTE | AT&T 4G LTE | Wifi |

Internet

MIT Network

Mission Control

Peplink Balance 580 Router

Navigation Computer
-TCP control link

Pilot Computer
-UDP video
-UDP Control link

Spotter Computer
-TCP Control Link
-FTP Still Images
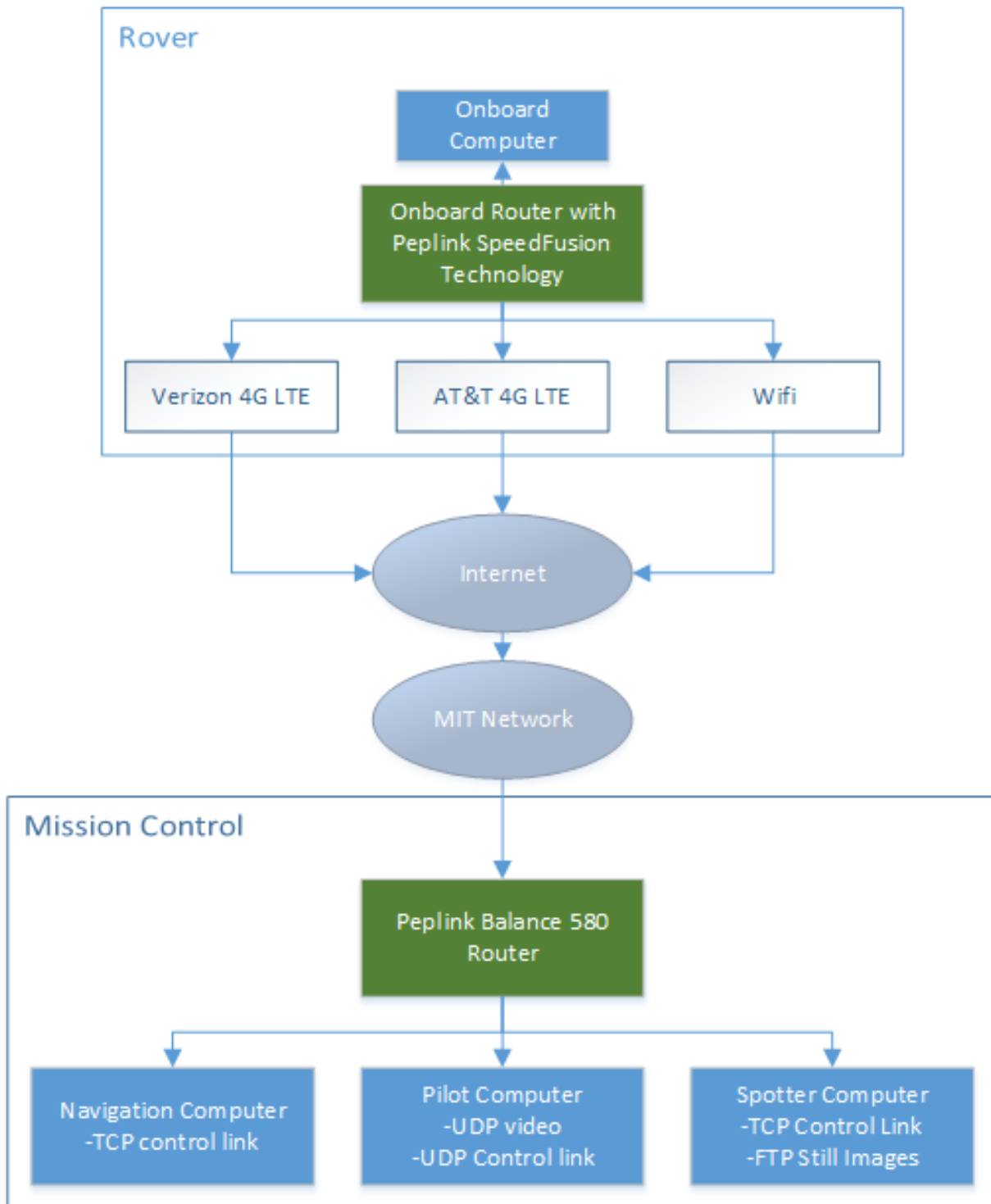
Appendix IV: Software Flow Diagram

Appendix V: Optimization Example Data

Frquency of Rocks

Legend:
- Yellow (1 Point)
- Orange (2 Points)
- Green (3 Points)
- Blue (4 Points)
- Purple (5 Points)
- Red (6 Points)

Average Pickup Times

Total Points From Rocks
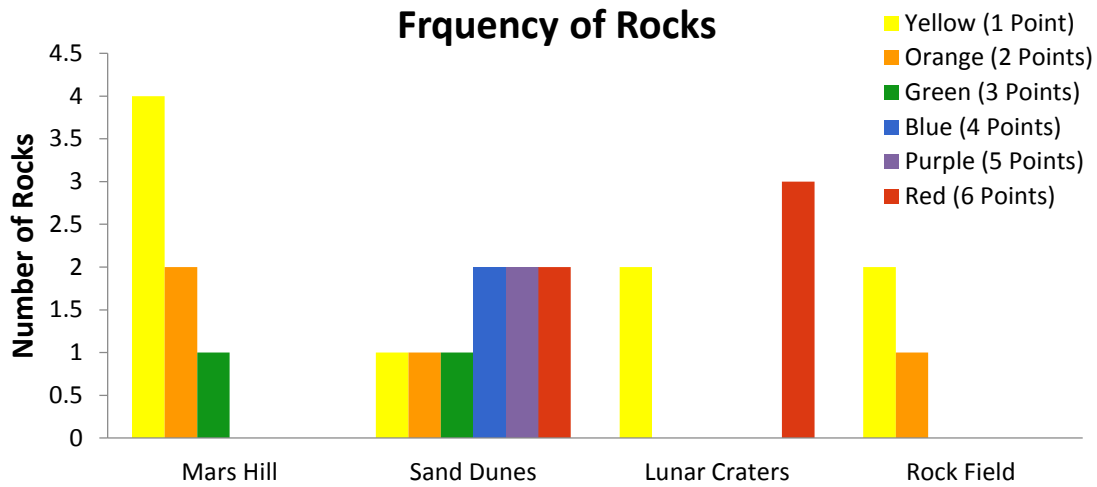
Source: Oryx's 2013 Robo-Ops: http://www.justin.tv/wpiteamoryx/c/2382140
WPI Oryx 2.0: RASC-AL Robo-Ops 2012 https://www.youtube.com/watch?v=93vIxdhwQdA