2011 Oregon State Mars Rover Design Report

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***Abstract*—This report serves as an overview to, and provides insight into the technological aspects of the, 2011 Oregon State University (OSU) Mars Rover. The Mars Rover is a robot built to compete in the 5th annual University Rover Challenge, hosted by the Mars Society. This robot is OSU's 4th entry to the competition, taking 3rd place. from 2008 to 2010, OSU has placed 1st, 4th, and 1st again. At a glance, the design may appear unaltered from 2010 to 2011. However, the 2011 Mars Rover is the result of a much more ambitious effort in engineering as most of the components are designed from the ground up by team members. The wireless video system has been updated to allow for improved non-line-of-sight transmission. The robotic arm is significantly more capable in comparison to the 2010 design. It is still a challenge to enhance previous designs while maintaining the 50 kg (110 lb) weight limit and keeping the project within the $15,000 budget. Due to the large effort towards designing application specific modules, the 2011 OSU Mars Rover is a significantly improved design over its older siblings.**

***Index Terms*—University Rover Challenge; The Mars Society; Mars rover; robot; robotics club; robot design; Oregon State University, competition,**

CONTENTS

I. INTRODUCTION

This report is an overview and insight into the technical details of the 2011 Oregon State University (OSU) Mars Rover, a robot built to compete in the 5th annual University Rover Challenge hosted by the Mars Society. This robot is OSU's 4th entry to the competition. To date the team has

Figure 1. The 2011 OSU Mars Rover (setup with scoop end effector)

placed 1st, 4th, and 1st from 2008-2010. The 2011 Mars Rover took 3rd place.

There are four scenarios in which the robots will be required to perform varying tasks, they are as follows.

- *Site Survey:* Perform a remote survey to determine the precise coordinates (including altitude) of field markers that are unreachable by the rover.
- *Sample Return:* Collect and return samples from sites determined to have the greatest likelihood of containing photosynthetic bacteria, other bacterial colonies, and non-bacterial extremophiles such as lichen.
- *Equipment Servicing:* Perform several dexterous operations, such as pushing buttons, flipping switches, and connecting plugs into electrical outlets, on a equipment panel at a remote location according to the instructions printed on the panel.
- *Astronaut Assistance:* The rover must locate and distribute packages weighing up to 6 kg (13.2 lbs) from the rover to up to five astronauts working in the environment of Mars.
- *Presentation:* Give a 15 minute presentation describing the overall design of the rover, team structure and project budget, followed by a short question and answer session with the judges.

The competition takes place each year at the Mars Desert Research Station managed by the Mars Society, located near Hanksville, Utah, USA. This year the competition dates were June 2nd-4th, Thursday-Saturday, during week 10 of OSU's spring term, *Dead Week*. All tasks must be completed in a certain time limit, usually ranging between 30-45 minutes. All operators of the rover must not be able to view the rover directly. All control must be performed using onboard cameras and/or sensors. The weight and value of the robot is limited to 50 kg (110 lbs) and $15,000.

II. Review of 2010 Rover

The 2010 Rover was a successful and novel entry to the URC and the most functional and reliable robot built by the OSU rover team to date. It is key to the development of the 2011 rover. The prominent design features of the 2010 Mars Rover as stated in the 2010 OSU Mars Rover Design Report [2] are the following.

1) Six wheels with balloon tires: Placing the rover on six balloon tires distributes the weight over a large area, making it easy to drive in sand and improving skid-steer performance.

In addition, the wheel spacing reduces the risk of jamming objects between the wheels.

2) Direct drive: Each wheel is mounted to its own dedicated drive motor, eliminating the need for additional shafts, sprockets, chains, and bearings, reducing overall weight and complexity. Additionally, placing the motors inside the wheels locates some of the heaviest components very close to the ground. This lowers its center of gravity, thereby improving the rover's ability to navigate steep terrain without the risk of toppling over.

3) Flexible chassis with high ground clearance: The chassis reduces the chance of becoming high-centered on obstacles and insures all six wheels stay on the ground, greatly improving all-terrain performance. This type of chassis does not require any springs, bearings, or shock absorbers, reducing complexity and improving reliability.

4) Non-skid-steer and zero radius turning ability: By being able turn in place without skidding greatly increases the Rovers all-terrain capability as it no longer requires smooth or loose surfaces to turn on; it is capable of turning over large, complex obstacles.

5) Ergonomic electronics bay: If the electronics require troubleshooting or repair, the entire electronics bay can be removed from the chassis with a few wing nuts. This allows the electrical and mechanical teams to simultaneously work on different sub-systems in separate locations. For example, machining work can be performed on the chassis while the electronics bay is in the lab for testing of electrical systems. The electronics bay could be accessed by popping two latches and removing the cover. This saved a lot of time during testing, this allowed for testing of Rover subsystems without their removal. Additionally, each of the custom designed electronic modules interfaced with the rover via a back plane. If a module required testing or fixing, it could simply be pulled out of its slot without the need of tools. Modules could also be re-installed without the possibility of incorrect installation as they can be installed in any back plane slot.

6) Adjustable camera mast: The use of a tripod allows the camera to be quickly located anywhere over the rover, providing any point of view desirable.

7) Protecting the electronics from the elements: Since much of our testing takes place in Oregon, it is necessary that that rover can withstand occasional precipitation. This was done by employing high quality weather-resistant connectors, a sealed electronics bay, and sealing exposed connections with heat shrink. It must be kept in mind that the rover is to drive in unpredictable environments. Dangling wires are highly susceptible to being pulled out when driving in the outdoors. Eliminating dangling wires greatly improves the reliability of the rover by preventing cables and wires from becoming caught in external objects. Dangling wires were avoided by combining wires into a wiring harness, wrapped in nylon sheathing. Wherever possible the wiring harness was placed inside of the hollow frame of the chassis.

As successful as the 2010 rover was, there were several aspects that were not ideal. These are described below.

8) Weight: The rover was marginally under the weight limit of 50 kg (110 lbs) during competition weigh-in. the team could have incurred a penalty if they had been unable to make sacrifices to make weight. It is recommended that the rover be obviously under-weight as to reduce any potential for penalty.

9) Freewave radios: The Freewave radios used for data communication were expensive units, consuming much of the limited budget. As effective and reliable as these are it would be favorable to find a cheaper alternative.

10) Non-line-of-sight wireless video transmission: A clear limitation of the Rovers operation was its inability to operate in non-line-of-site (NLOS) with the base station antenna. This caused the video to cut, out severely limiting the operator's ability to control the rover. Developing a system that does not have this limitation would allow the rover to drive behind hills and dramatically increase the rovers versatility in competition.

11) OSWALD, Rover onboard mini computer: The 2010 Rover's onboard processing is performed by the Oregon State Wireless Active Learning Device (OSWALD) a hand held linux computer developed by undergraduates at Oregon State [3]. This lightweight computer was effective in relaying commands to the Rovers sub-systems but proved to be unreliable. It failed to boot correctly 50% of the time and had a complicated start up procedure. The OSWALD is not recommended for robotics applications.

12) Turning the rover on: The rover took 10-15 minutes to turn on. This is unacceptably slow. A single switch to turn on the rover is recommended.

13) Wheelie problem: Inherent to the design of the rocker hinges was an issue which caused the rockers to wheelie. This proved to be problematic when the rover was climbing hills as the center of mass rose with the front wheels, increasing the potential of flipping over backwards. This is a worst case scenario that could be controlled by a careful operator.

14) Robotic Arm structure: The structure of the arm was tall and bulky. When the Rover drove, the arm rocked on its supports in an uncontrolled fashion. This motion was not intentionally designed into the structure and is a source for fatigue failure. It is recommended that there be no loose, wobbling structures on the rover.

15) 3D vision system: Some time was spent developing a 3D vision system which was not fully developed. This is an interesting and potentially advantageous system to have on the rover and it should not be discouraged from being developed, but, it was not essential to the robots minimal functionality. It could have potential use in future designs.

16) Printer Circuit Board design: A significant portion of work time was expended on developing Printed Circuit Boards (PCBs). While a great learning opportunity for the team's electrical engineers, development time could have been saved by using off the shelf products.

III. Introduction to the 2011 OSU Mars Rover

The 2010 OSU Mars Rover was a champion robot and a novel entry to the URC. It received much attention and notoriety through public events such as the OSU Engineering

Expo, OMSI Space Gala, and numerous publications. The most notable of these was an event with the OSU football team [?]. The 2011 Rover team approached the project with the goal of revising the 2010 design to make it more elegant and application specific. Before going into detail about the rover's systems, a brief overview will demonstrate how these lessons helped define the design of the 2011 Mars Rover. The prominent design features of the 2011 Mars Rover are the highlighted in the following.

17) Manufacturing: The overall manufacturing concept of the 2010 Rover was excellent. The 2011 team sought to improve improve the manufacturing process to reduce weight.

18) PCB Design: The time spent learning how to design and implement PCBs in 2010 was applied this year, allowing team members to be more productive in PCB design. the team developed more complex designs in less time than in 2010.

19) User Interface: As stated in Section II-16, the Rover's software user interface contained more features necessary to operate the rover. This resulted in wasted development time. In the future ideas for the user interfaced were discussed during team meetings.

20) Four-Bar Bogie Hinge Design: This is the team's solution to the 'wheelie problem' described in Section II-16. It uses a four-bar linkage to change the mechanics of the joint so that the wheelie problem is eliminated (Section IV-C).

21) Robotic Arm Design and Control: The robotic arm was completely redesigned from 2010 and exhibits dramatically increased functionality and strength.

22) Radio Communication: The radio communication system is designed to address the NLOS transmission issue from the 2010 rover. This allows the rover to operate in more adverse contidions, an impossible task for the 2010 rover.

23) Embedded Firmware: The 2011 Mars Rover is required to be controlled only by ATMEL microcontrollers running low level, embedded firmware. The advantage to this approach is that the rover can be operated almost instantly after power-up as there is no operating system to be started before functionality can be realized. Embedded firmware is much better suited for tasks such as quickly routing data packets via different serial interfaces than a computer running an operating system. Embedded firmware interfaces almost directly with the hardware it is intended to control.

24) Simple Rover On-Off: The rover can be turned on or off with the Rover's power switch and is ready to receive commands within seconds.

25) Light Weight Design: The chassis, though similar to the 2010 design, is 6.8 kg (15 lbs) lighter. This is achieved with use of lightweight composite materials and a more efficient design. This has allowed more weight to be allocated to other systems. The overall weight of the robot is just below the 50 kg (110 lb) limit and the function is greater than the 2010 rover.

A. Differences/Additions in the 2011 URC Rules

While the rules and theme for the URC in 2011 are similar to those of previous years there are differences that are important when understanding the design of this robot. [1]

1) Site Survey Task: The rover is to investigate potential sites of interest near the base station, recording their GPS coordinates, elevation, and a unique identifying mark. The identifying mark of each point of interest is a new addition for this years rules.

2) Sample Return Task: This task is unchanged from the 2010 URC rules.

3) Equipment Servicing Task: This task is unchanged from the 2010 URC rules.

4) Astronaut Assistance Task: Formerly called *Emergency Navigation*. In 2010 the Emergency Navigation Task required the Rover to locate a distressed astronaut and deliver a package to him or her. The last known GPS coordinates of the astronaut are provided. The rover was expected to navigate adverse terrain and NLOS condition. The new Astronaut Assistance Task places up to five astronauts in the competition area with known GPS coordinates, each of which needing supplies from the base station. The supplies are in containers of varying shapes and can weight up to 6 kg (13.2 lbs). The rover is loaded with these supply packages and must deliver them within 1 meter of the correct astronaut. The astronauts are located in areas of varying difficulty ranging from flat terrain, close to the base station and within line-of-sight to relatively rough terrain, far away and NLOS conditions.

5) Presentation Task: Each team is to prepare and present a 15 minute presentation pertaining to their team structure, rover design and how it is intended to complete the competition tasks, and the project budget. This task is new to the URC.

IV. Rover Mechanics

A. Overview

The 2011 Mars Rover chassis is the second iteration of the 2010 Rover. The 2010 Mars Rover design had many successful aspects that are worth keeping. The goal this year is to optimize the weight of the chassis by using a wider variety of materials and manufacturing processes. A performance goal for this Rover is to prevent the front rockers from 'popping a wheelie.'

Similar to 2010, the overall Rover configuration is a six-wheeled triple rocker system with two front rockers and a rear rocker. The purpose of the chassis seves as a mounting point for the rockers, electrical box, and the robotic arm. The zero radius turning capability is a returning feature which operates upon the same principles as the 2010 version. It uses linear actuators to turn the four corner wheels, allowing the rover to rotate around a central point. One new design aspect for the chassis is to use a round tube frame in place of the square tubing frame from last year. This reduces the amount of material in the main chassis while keeping maintaining. Also, the hinge points for the rockers are incorporated into the frame itself, reducing the number of parts. The dimensions of the rover were similar to last year with a 76.2 cm (30") wheel base and 88.9 cm (35") track length. The center of gravity

[1] For a full description of the 2011 URC rules see Section I.

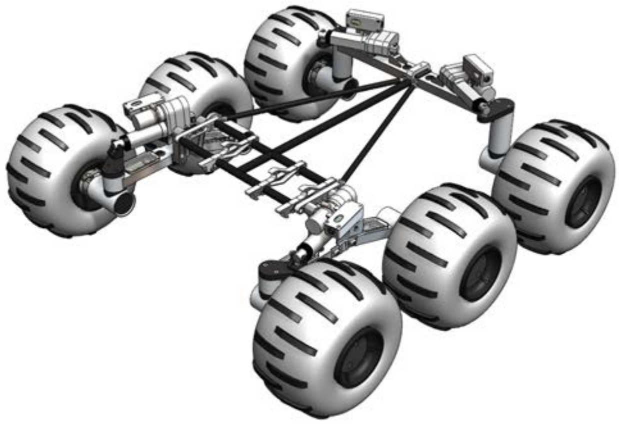

Figure 2. 2011 Mars Rover Chassis

resided approximately in the center of the Rover above the middle wheels at a height of 25.4 cm (10") from the ground.

Another feature of the chassis is the four bar linkage attachment point for the two front rockers. This idea was introduced to help eliminate the wheelie problem that occurred with the 2010 Rover. Using a four bar linkage, it is possible to move the axis of rotation of the rocker low to the ground. This change makes it difficult for the rocker to reach an angle where the wheel torque is greater than the opposed torque caused by the weight of the Rover. The four bar linkage prevents the middle motors from lifting the front rocker in a wheelie.

B. Frame Design

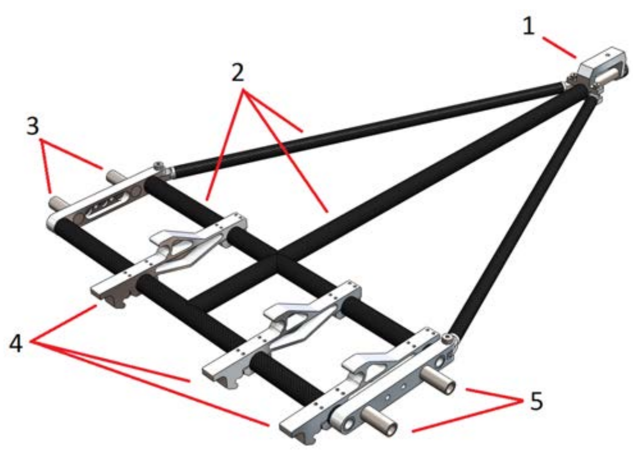

Figure 3. Main support frame constructed of carbon fiber tube and aluminum mounting inserts providing attachment points to the tripod and rockers (1) Rear rocker hinge (2) Carbon fiber tubes (3) Front right rocker four bar linkage hinges (4) Arm attachment structure (5) Front left rocker four bar linkage hinges

The design requirements for the 2011 OSU Mars Rover frame were focused on reducing overall weight and maintaining strength through the use of composite materials.

This chassis consists of a carbon fiber, aluminum composite truss configuration. The tubes of carbon fiber are connected by epoxy and wrapped with carbon fiber. The aluminum hinge joint inserts are epoxied to the carbon fiber tubes. The rear hinge is supported by two cross truss sections to absorb any side loading. The front parallel tubes are reinforced with aluminum spanners which also serve as the mounting point for the robotic arm.

The strength of the uni-directional carbon fiber tube and glue joints were called into question after construction. The back bogie joint (Figure 4) was of particular interest as it was a location for stress concentration. If one of the back wheels were to collide with a rigid object, then a large moment would be applied to this joint. Finite Element Analysis (FEA) (Figure 5) was performed. A fracture test verified the results of the FEA. Similar analysis were performed at each hinge which led to the use of high strength titanium pins and stainless steel fasteners

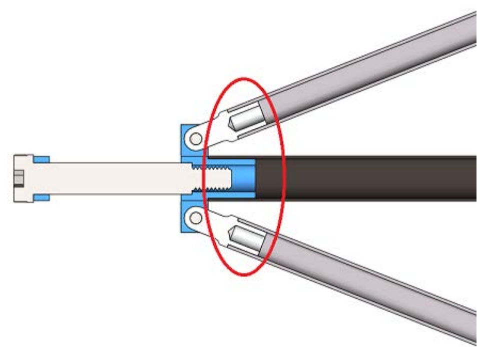

Figure 4. Top down cross-section of the back bogie hinge. The carbon fiber tubes glue to the aluminum parts in three places indicated by the red circle. The larger middle joint is of interest for FEA analysis described in this section. The blue component is the complex back hinge, machined from aluminum

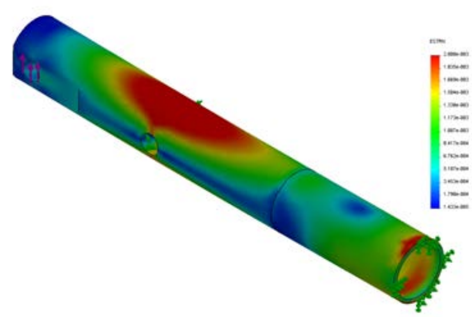

Figure 5. FEA deformation plot of the analysis validation specimen

C. Rocker/Suspension Redesign

Figure 6 shows the 2010 Rover rocker and hinge configuration, specifically the relationship between the middle motor and the rocker hinge point.

According to the formula in Figure 6, a wheelie will occur when the motor torque is greater than the moment created by the perpendicular component of the Rover weight on the

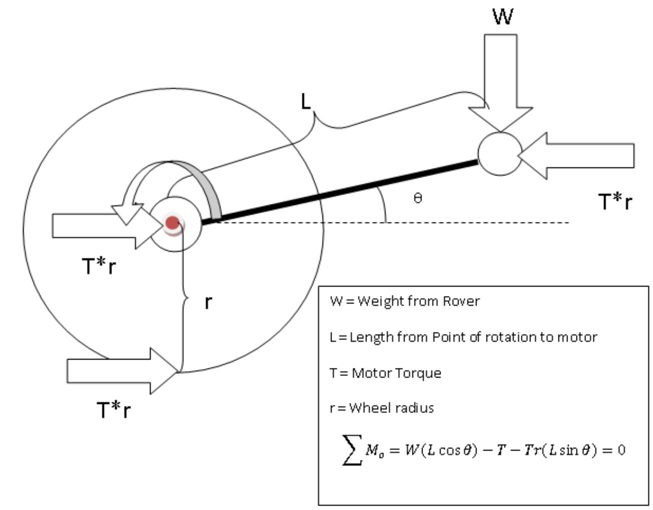

Figure 6. Free body diagram of the middle wheel and front rocker hinge during driving

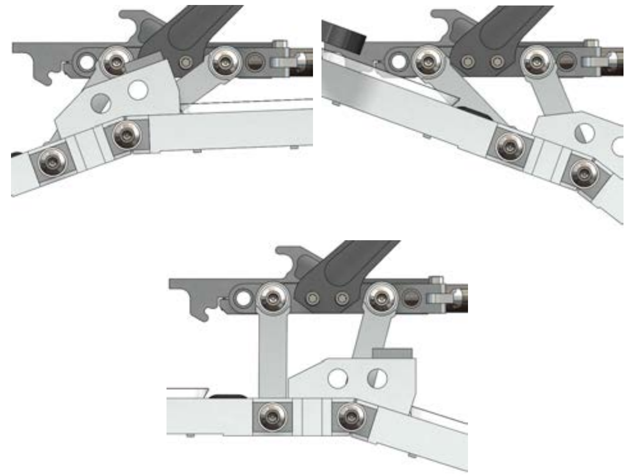

Figure 7. The four bar linkage pivot of the front rockers. (top left) front wheel lower than middle wheel (top right) front wheel higher than middle wheel (bottom) level rocker, wheels at same elevation

hinge. One of the main problems that occurred was when the rocker articulates; the angle with respect to the rest of the Rover changed. When the angle of the rocker (with respect to the ground) changes, the amount of the perpendicular component of the Rover weight counter acting the torque of the motor is altered. A greater angle results in less of a moment from the weight of the Rover to counter act a wheelie. Last years Rover rocker orientation normally had an inclined angle, making it possible for the rocker to reach a critical angle and wheelie. The 2011 Rover suspension system the rockers point of rotation is placed in a more favorable spot to eliminate this problem. A four bar linkage is used to place this virtual point of rotation at ground elevation.

Two different designs were considered for the four bar linkage; an equal arm length system and an unequal arm length system. Both of these allow the rocker center of rotation to be positioned below the axle of the middle motor, reducing the tendency to wheelie, but the difference between the two is how this center of rotation migrates as the rocker moves through its range of motion.

Several iterations of kinematic design analysis were performed to help choose an appropriate design. The rocker system was modeled for flat driving conditions and for driving on a 30°slope. The model was compared to the performance of the 2010 rocker system. [1]

With the correct swing limiting for the rockers, this data shows the elimination of the conditions for a wheelie. These results prove that this design has similar articulation characteristics while eliminating the possibility of the front rocker wheeling.

Figure 9 shows the torque values calculated using our new four bar linkage design. The first plot shows the torque profile of the 2010 rover driving on 30°of incline. The next plot shows the improvement with this years design over the same incline set. The last plot demonstrates the improvement of this year's design over last year's by comparing the two torque profiles.

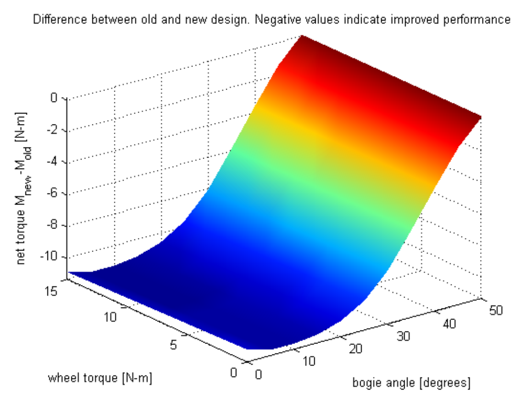

Figure 9. Plots showing calculations for net torque on the front bogie due to applied wheel torque compared to the angle of the bogie with respect to level. This plot shows the difference between the 2010 and 2011 designs showing a dramatic improvement over all ranges of bogie angle. Negative values of net torque are better here.

The design for the rockers themselves was reconsidered as well. The orientation of the linear actuators was a major redesign. The front actuator swing arms were rotated approximately 135° to reduce their interference with the front of the Rover. This also allowed the whole construction of the rocker to be more compact and lightweight. The actuators on the rear rocker were oriented on their sides. This reduced the number of components used for attaching the actuators.

The wheel swivel that attached to the actuators were made from Delrin plastic because of its strength, low density and low friction coefficient against metal. This permitted the swivel to act as a bushing and load bearing compoinent. This reduced the number of components in all the rockers, further reducing weight. The main structural part of the rockers was welded

[1]The results of this analysis are shown in Figure 8

Figure 8. Range of motion of the front rockers (left) neutral position (center) counter-clockwise rotation limit (right) clockwise rotation limit

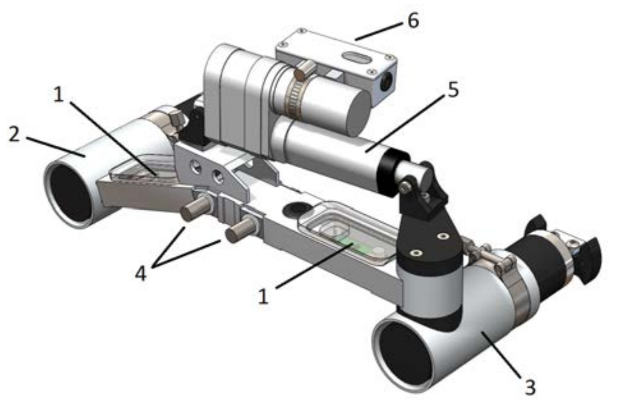

Figure 10. Overview of front rockers sub-assembly (left rocker shown, right rocker is and exact mirror) (1) Drive motor controller PCBs, mounted *inside* the rocker (2) Middle wheel drive motor assembly (3) Front wheel drive motor assembly (4) 4-bar linkage pivot points (5) Steering mode linear actuator (6) Linear actuator motor controller PCB within protective housing

aluminum square tube. These served as attachment points for the wheel mounts, actuators, hinges, and as heat sinks for the motor driver boards.

D. Pan/tilt system

Similar to last year our camera attachment system consist of a tripod with a pan/tilt extension. The tripod used this year is a Manfrotto carbon fiber tripod. This allowed the same capability to adjust the height and position of our pan/tilt system as last year. The attachment points for the Rover were two front mounts extending from the sides of the chassis and the back hinge. Each attachment point had a swivel clevis to allow for rotation of the mounting points. A new feature for this year is the quick disconnect capability of the tripod feet. This feature consists of a threaded retaining collar to quickly unscrew and remove the tripod feet.

The pan/tilt system was a hybrid version of the design used last year. This year, the pan/tilt construction was custom designed to incorporate Dynamixel AX-12 digital servos. This allows the pan/tilt system more precise movement. The main

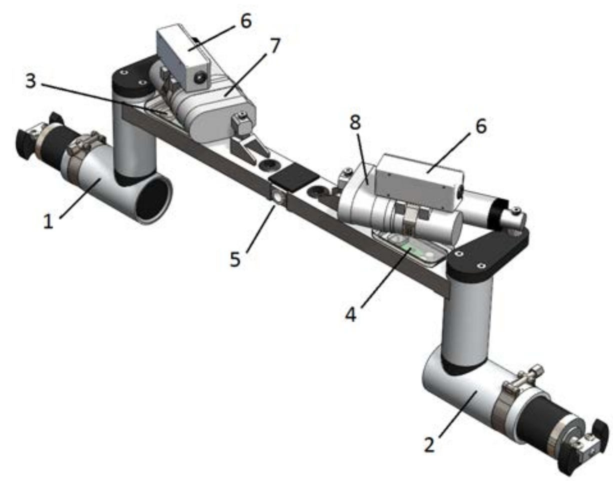

Figure 11. Overview of rear rocker sub-assembly (1) Left rear drive motor assembly (2) Right rear drive motor assembly (3) Left rear drive motor controller PCB, mounted *inside* the rocker (4) Right rear drive motor controller PCB, mounted *inside* the rocker (5) Rocker Hinge, connection point to chassis (6) Steering mode linear actuator motor controller PCBs within protective housing (7) Left rear steering mode linear actuator (8) Right rear steering mode linear actuator

Figure 12. Tripod attachment feet, designed to allow quick removal of the the tripod for transporting the rover through doorways, in motor vehicles and to allow installation of the Astronaut Assistance Supply Rack. (1) A simple threaded connection is used to connect/disconnect the tripod feet from the rover mounts.

structure was constructed of laser cut, 1/4 inch ABS sheet. Another design feature was a lockable base to allow the pan/tilt system to be leveled and secured in place. This was a feature that was not available for the the off-the-shelf 2010 Rover pan/tilt system.

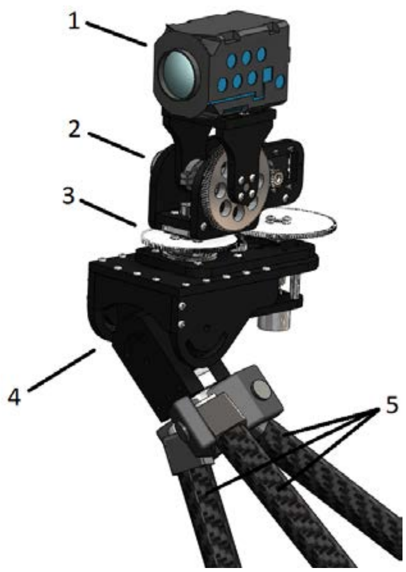

Figure 13. The custom designed and manufactured pan-tilt system, which mounts atop the tripod. The black, bolt-together parts are ABS plastic, laser cut (1) Rover main camera (2) Tilt joint, powered by an AX-12 servo geared 4.45:1 (3) Pan joint, powered by an AX-12 servo geared 4.45:1 (4) Tripod head, 2 degrees of freedom, used to level the pan/tilt assembly in a given tripod position. (5) Manfrotto tripod legs

1) Tripod & Pan/Tilt Recommendations for Future Designs: The tripod was not used to its full potential because of the narrow placement of the two front attachment points. The quick disconnect feet would have been more user friendly if the retaining collars had better grip for hand threading.

Thumb screw were used to lock the pan tilt system in position, these were difficult to turn by hand.

E. Drive system

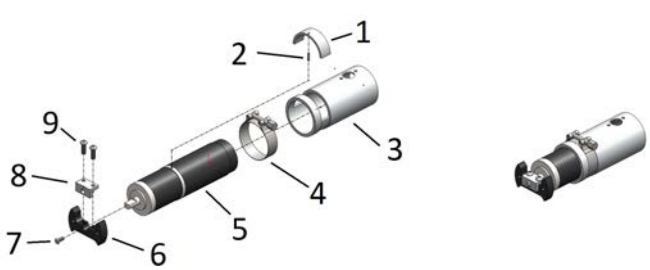

Figure 14. Drive motor, located in each of the six wheels. (right) Assembled (left) Exploded view (1) Motor armor clamp half (2) Motor armor torsion lock pin (3) Motor armor (4) Motor armor clamp (5) IG-52 planetary gear motor, 136:1 gear ratio, 24 volt (6) Wheel hub (interfaces with wheel rim) (7) Axial restraint bolt (8) Hub clamp (9) Hub clamp bolts

The 2011 drive system is an optimized version of the 2010 drive system (Figure 14. The motor armors attach the brushed DC gear motors to the rockers and protect them. Tread was added to the tires in the same manner as last year (Figure 15).

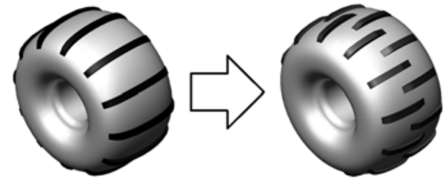

Figure 15. (right) 2010 tread pattern (left) 2011 tread pattern. The 2010 tread pattern caused the rover to "bounce" when driving on flat and smooth surfaces, like concrete. This is minimized with the 2011 pattern by doubling the frequency of tread contact along the centerline of the wheel.

F. Electrical Box

The electrical box has been simplified this year. An aluminum sheet metal box was manufactured using 20 gauge sheet metal fabricated by AJK Precision Sheet Metal. The dimensions are 38.1 cm (15") squared and a height of 0.95-1.58 cm (3/8"-5/8"). The lid is flanged to help locate it and is attached with two draw latches. Four Delrin clamps attach the box to the chassis truss. The 2010 Rover had a quick disconnect capability that was unused and deemed unnecessary for the current design. The electrical box is semi-permanently mounted to the Rover. The antenna mounts are located on the sides at the rear of the box. The mounts are designed to fold allowing the antennas to lay across the top of the box (Figure 16). This feature decreases the difficulty of moving the rover through doorways. Draw latches are also used to secure the antenna in operational position. A harmonic analysis was performed in order to guide the design of a bracket that is resistant to harmonic resonance caused by the long antenna structures' tendency to oscillate when the rover drives.

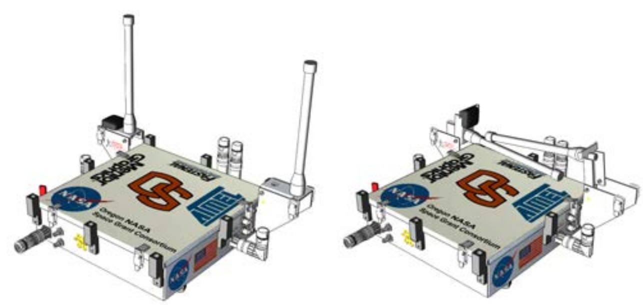

Figure 16. Electrical Box with antenna mounts shown locked into operating position (left). The antennas could be easily folded down to minimize the height of the rover for carrying it sideways through doors as well as for van transport to competition.

G. Astronaut Assistance rack

The astronaut assistance rack (Figure 17) is the package carrying system for the astronaut service task. The rack is comprised of pultruded carbon fiber tubes configured in a truss with rapid prototype plastic joints. The rack is designed to hold up to five of the largest and heaviest packages specified by the 2011 competition rules. Six mounting points, attach the rack to the electrical box secured with retaining pins. The rack is separated into three main sections; the area over the electrical

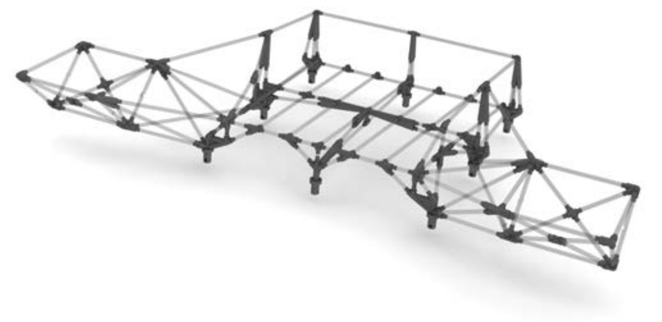

Figure 17. Astronaut Assistance rack, also known as the 'Luggage Rack.' Designed to carry packages to astronauts working in the landscape of Mars it holds them securely as the rover drives over steep and rough terrain.It is easily accessible for the robotic arm to load and unload packages.

box and two extensions over the front rockers. During the competition, the left hand extension was excluded because the arm can only rotate far enough to use 2 of any 3 rack areas.

V. ROVER ROBOTIC ARM

The Rovers robotic arm is a very different machine from the 2010 concept, dissimilar in nearly every aspect. It is a jointed three or six degree of freedom design with three different configurations each designed for different competition tasks. The arm is designed for use in three of the five competition tasks, these include: Equipment Servicing, Soil Sample Return and Astronaut Assistance. The arm includes a video camera mounted on a actuated structure for the operator to get different perspectives of the arm and its workspace. The arm is designed to stow itself on the rover to lower the center of gravity of the robot for improved agility over rough and complex terrain navigation. As well as to reduce the rovers capacity to damage the arm, for example, by driving it into obstacles. A problem noted from the 2010 Rover was that the tall monolithic structure of its robotic arm had a tendency to rock and bounce when the rover was driving. This was very undesirable as it stressed the structure of the arm and it connection to the rover.

A. Robotic arm as a Senior Project

As in with the 2010 Rover, the 2011 robotic arm was delegated as a senior project which gave three mechanical engineering seniors the opportunity to spend class time working on this otherwise extracurricular project. A difference this year is that it was a multidisciplinary project including three seniors from the Electrical Engineering Department. This collaboration was a great benefit to the project as the mechanical and electrical design and construction were under similar deadlines as per the class structure.

Weekly meetings between these two senior project teams were essential to keep both teams and the design coordinated. Meetings were also held on a weekly basis with the entire rover team where progress reports would be given as well as expected accomplishments for the upcoming week. Interfaces between different rover sub-components were discussed during these meetings as well as major design decisions.

More information pertaining specifically to the technical details of the design process taught in the capstone class and used on this project can be found in the project report available online, see References [1].

B. Arm Mechanical Design

For design purposes the arm was divided into 6 sub assemblies, so that each of the 3 mechanical engineers could work on an assembly while allowing one of the others to work on a different assembly. These assemblies include: the base, limb, camera arm, scoop end effector, equipment servicing end effector and the astronaut assistance end effector. The following sections will show the design and manufacture of each of these sub-assemblies including recommendations for future design.

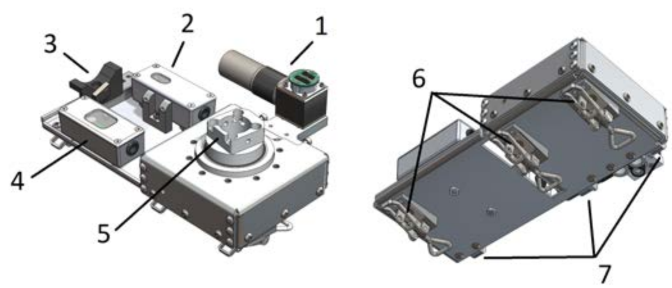

Figure 19. Overview of components for the base sub-assembly of the robotic arm (1) The motor that drives the base. IG-32, 721:1, 10 RPM right angle gear motor with RMB30SI 13-bit absolute magnetic rotary encoder mounted to output (2) Base motor controller PCB in its protective housing. (3) Stowing rest. Holds the limb in stow position. Includes a trigger switch used to indicate when the arm has reached stowed position. (4) Arm controller PCB in its protective housing. (5) Mount for limb. It is hollow to allow all wires for the limb and end effectors to rout through the pivot point to protect the wires and reduce strain. (6) Toggle latches, used to secure the arm to the rover chassis. (7) These three rounded edges mate into features on the rover chassis when the toggle latches are engaged.

1) Base: The base provides the side to side rotation of the arms "shoulder" as well as the arms attachment to the rover. The base is the anchor for the power of the arm, as the arm is capable of lifting over 40 pounds. The base distributes this force to the rover chassis. A requirement of the arm was to attach and detach from the rover in less than 5 minutes and requiring no tools. This is accomplished with the use of 3 toggle latches and custom Computer Numerically Controlled (CNC) machined parts, see item (6) in Figure 19.

The base motor is a IG-32, 721:1, 10 RPM right angle gear motor that drives the base via a timing belt. The timing belt provides a further 8:1 gear reduction amplifying the torque and reducing the speed to a more user friendly 1.25 RPM. The low speed prevents the user from sudden, uncontrolled movements that could damage the arm. Thus the speed is kept low for safety and for precision movements. Sensing of the base actuators position is accomplished with a pair of sensors. The first is an absolute, 13-bit (8,192 counts per revolution) magnetic encoder with serial communication from Renishaw

Figure 18. The robotic arm. Designed, built and included on the 2011 OSU Mars Rover. (left) setup for the Astronaut Assistance task and reaching towards the rear of the rover (center) Setup for the Soil Sample Return task reaching towards the ground to aquire a sample. The arms camera is positioned to view the sample as it is captured by the scoop. (right)setup for the Equipment Servicing task

Inc. specifically the RMB30SI. This provides very accurate position feedback for the base of the arm. But because the motor is geared to the output via a timing belt the motor encoder will rotate 8 times for every one revolution of the base actuator. This is undesirable because you want a one to one ratio here, for each position of the base actuator there should be one sensor value. If the sensor is not coupled to the output with a ratio of 1:1 then for each returned value of the sensor there can be multiple possible locations of the base actuator. To eliminate this the base actuator output is fitted with a simple 3-bit (8 counts per revolution) sensor, one count for each revolution of the motor. Notice that this matches the timing belt gearing ration from earlier. This sensor indicates which of the 8 revolutions the motor sensor is within. This sensor pair is capable of 65,536 counts per revolution equivalent to a 16-bit sensor, a very high resolution sensor, good for very accurate position and velocity control.

The base houses the motor driver for the base motor as well as the microcontroller that controls the entire arm. Electrical connectors that connect the arm to the rover are contained on the arm and rout through the base of the arm directly up the center of the timing belt drive to reduce cable movement and strain.

2) Base Recommendations for Future Designs: The belt is the limiting factor in the maximum torque for this actuator. The teeth skip over the drive pulley which not only limits the torque but ruins the calibration of the joint sensors. The problem is inherent to the tensioning system used for the belt. Figure 21 shows the pulley system and identifies the key components of this assembly; refer to it for the following description. The drive pulley (4) is mounted on a separate structure from the output pulley (1). Two machine screws (2) are used to push these two pulley structures appart, applying tension into the drive belt (5). Four idler pulleys (3) are used to maximize the belt wrap around both the drive and output pulleys. A clamp (7) is used to fix the belt to the output pulley and allow it to be driven by the drive pulley. When the system is loaded one side of the belt from the drive pulley has high tension while the other side is at zero tension. As the load on the system is increased toward the maximum output of the motor the belt is stretched slightly allowing slack to accumulate on the zero tension belt. This slack allows the belt teeth to skip on the drive pulley.

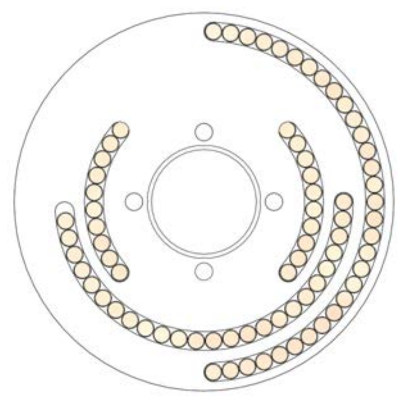

Figure 20. Custom 3-bit (8 counts per revolution) sensor developed for the base actuator. A custom hall effect sensor board senses 3 rows of magnets arranged in a gray scale pattern to determine the correct orientation of the arm for the high resolution encoder sensing the motor output position.

A solution to this problem is to add compliance to the system specifically in the idler pulleys. Spring loading the idler pulleys to 'pinch' the belt between them will eliminate this problem. with this addition the high tension side will pull the idler pulley contacting the slack side and transfer tension.

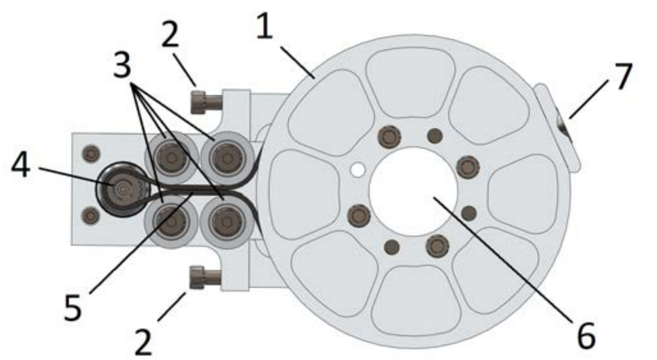

Figure 21. Overview of components for the pulley and belt tensioning system used in the base actuator (1) Output pulley, directly mounted to this is the 3-bit encoder shown in Figure 20 (2) Machine screw, used to increase or decrease tension in the drive belt (3) Idler pulleys, used to maximize belt wrap around the output and drive pulleys (4) Drive Pulley, directly driven from the IG-32, right angle gear motor shown in Figure 19 (5) Drive belt, a 3/8" wide MXL (0.080" pitch) timing belt with kevlar tension members (6) hole in base actuator to allow wire (7) Belt clamp, this fixes the belt to the output pulley and impart torque from the drive pulley

Ideally the tension is balanced between what was the high tension and zero tension belt. Further more the belt will be unable to slip around the drive pulley.

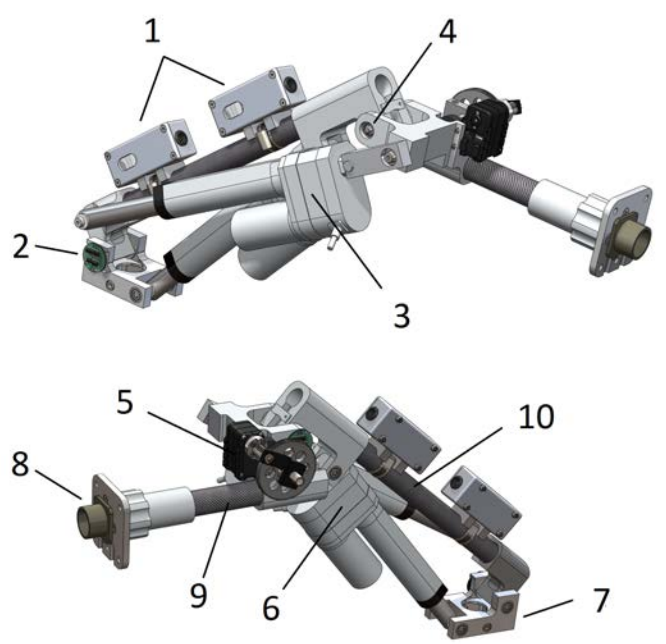

Figure 22. Overview of components for the limb sub-assembly of the robotic arm (1) Motor controller PCB's for shoulder and elbow joint actuators in protective housing (2) Shoulder Joint, rotational position is sensed by an RMB30SI, 13-bit absolute encoder (3) Elbow joint actuator, a 4" stroke 24v electric linear actuator, 270 lbs output force distributed by Midwest Motion Products (4) Elbow joint, rotational position is sensed by an RMB30SI, 13-bit absolute encoder (5) Camera arm mount point (6) Shoulder joint actuator, a 4" stroke 24v electric linear actuator, 270 lbs output force distributed by Midwest Motion Products (7) Attachment point to base assembly (8) Universal attachment point to each of the three end effectors (9) Forearm, constructed from filament wound carbon fiber tube (10) Upper arm, constructed from filament wound carbon fiber tube

3) Limb: The limb is 'the arm' sub-assembly. It includes the shoulder and elbow actuators, attachment point for the end effectors at the wrist, and camera arm mount at the elbow. See Figure 22 for a visual breakdown of limb components.

The limb's shoulder and elbow joints are each actuated by a Midwest Motion LA-3, 24 volt, 100 mm stroke, 270 lbs output force linear actuator. The shoulder actuator was given a $110°$ range of motion while the elbow was given $170°$. The limb is designed to fold in half, becoming very compact for stowing. The output torque of each joint was calculated using Matlab and optimized by changing the pin geometry of the joint and the actuator to place the peak torque output in the most useful orientations for the use of the arm. For this we assumed that the maximum load the arm will lift is 13.2 lbs at 15 inches from the shoulder axis requiring a shoulder torque of 200 in-lbs. Through this iterative process we ended up with peak output torques of 650 in-lbs at $45°$ from level for the shoulder and 530 in-lbs at $60°$ from a straight joint at the elbow.

Position sensing for the limbs joints is accomplished with the same RMB30SI 13-bit absolute encoders as mentioned in the base design. The magnet for these sensors is glued into the shaft at the joint itself measuring it's rotation relative to the other half of the joint. A technical requirement to use these magnetic sensors is that the shaft material be non-magnetic. Because of this we used a titanium shaft that meets this requirement as well as the strength requirement of the joint.

The 'bones' of the limb are hollow, cross-weave carbon fiber tubes, 24 mm outside diameter with 2 mm wall thickness. These tubes are very stiff and around 25% lighter than an equivalently strong aluminum tube. The joints of the limb are aluminum parts featuring threaded holes and bearings for attachment and joints respectively. To connect to the carbon fiber we used Hysol Epoxy 9460 which is recommended as the best carbon fiber to aluminum bonding agent and provides a very strong connection.

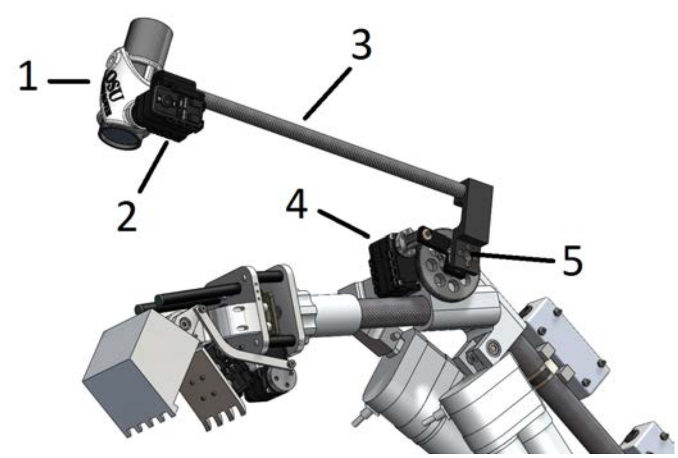

Figure 23. Overview of components for the camera arm sub-assembly of the robotic arm (1) Arm camera, color, 3X zoom (2) Camera tilt servo (3) Support tube, unidirectional carbon fiber tube (4) Camera arm positioning servo, geared down 4.45:1 (5) 300° turn potentiometer (behind large metal gear) used for sensing the absolute position of the joint

Attached to the limb at the 'elbow' is a jointed mount for a camera. This mount is actuated at the elbow and at the camera to provide rotational movement about the elbow joint as well as camera tilt. This allows the operator to select a camera position that is best for the task at hand. For example, for use in the equipment servicing task the operator may choose the have the camera above the end effector for a more downward point of view. As opposed to operating in the soil sample return task where the operator would want to see what is actually getting scooped into the bucket and choose to place the camera below the elbow.

The 'wrist' of the limb is the point of connection for each of the three, interchangeable end effectors. A customer requirement of the senior design team was to make the end effector attach and detach process as simple and quick as possible, requiring no tools. Designed to be strong yet quick to interchange end effectors it features a 14 pin, MIL spec threaded electrical connector. These connectors are lightweight aluminum yet are a very rugged connector, good for transmitting large forces at the end effector to the limb. One need only to unthread the connector to release the end effector, or vise versa, which takes approximately 30 seconds. Structural pins were added to relieve bending moments and torsion loads applied to the connector from the end effector, thus increasing the strength capacity of the wrist.

4) Limb Recommendations for Future Designs: Soon after the completion of the arm it was discovered that the arm had potential to damage itself when unstowing. The cause is inherent in the design of the linear actuator pin locations during unstow which were within $5°$ of the toggle point (as per the theoretical design), see Figure 24. This meant the arm had great (non-zero) potential to rotate the forearm backwards, into itself instead of forwards correctly. When this occurs the linear actuators are imparting their significant force directly into the joint pins, permanently bending them. It is also impractically difficult for an operator to overcome this problem if it were to occur in a competition scenario, rendering the arm inoperable.

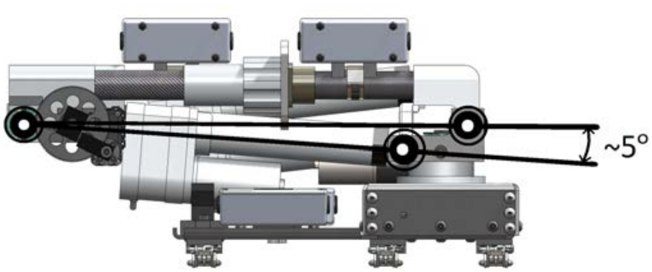

Figure 24. Front view of the arm in stow configuration (camera arm and end effector not shown for clarity of the unstowing problem). The joints are highlighted with white filled black circles and are connected with black lines to show the imaginary lines of the linkage. These links are about $5°$ out of alignment. Because these links are this close together the arm has trouble unstowing.

After considering options to fix the problem it was decided that stowing was not viable. The origin of this problem is traced back to the design range of motion for the elbow joint. The design maximizes range of motion of $170°$. $5°$ remained at each extreme from the toggle point, the point at which the linkage can *toggle*, from rotating the correct direction to the incorrect direction. With the forearm extended this did not surface as gravity assisted correct motion. However, with the forearm retracted into the stow configuration gravity does not assist, allowing the chance for correct unstowing to be random. To fix this problem for future designs simply reduce the range of motion of the elbow joint to no more than $160°$, and even this is cutting it close. With this maximum allow for the range of motion to be no closer than $10°$ from the toggle position.

The camera mounted to the mobile, jointed arm of the camera proved to be inadequate. One, the camera was of poor video quality, making it difficult for the operator to see the operational space. Two, the range of motion of the camera was not enough to get really useful points of view for the operator. Two things can fix this, the first being a longer structural member allowing the camera to reach further above and below the point of interest, usually the end effector. Second, the range of motion can be expanded into 3D. This would allow the operator to look not just above, below and behind the end effector along a circle, it would be possible to look from the right and left. This would be a very heavy, expensive, and complex system but its usefulness would be unprecedented. This could replace the main camera tripod of the robot.

The wrist connector, while strong and effective in its function was, perhaps, redundant. The structural pins added to resist moments and torsion were indeed strong enough for all forces ever applied to the arm. Also, the threads of the connector did jam after continued use through testing. A connector material more durable than aluminum would have prevented this. A solution for both is to use a bayonet style connector. It is not as structurally strong as the threaded connector but as stated, previously the strength is redundant. The bayonet connector would take less effort on behalf of the user to connect each end effector and would not mis-thread or jam.

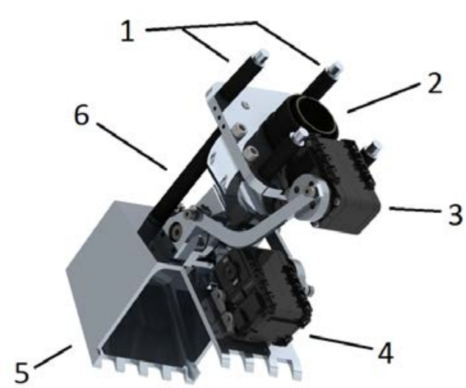

Figure 25. Bucket end effector shown with thumb open, ready to collect sample. (1) Structural pins for wrist connection (2) Threaded Mil. Spec. electrical connector (3) Servo drive for bucket movement (4) Servo drive for thumb movement mounted directly to thumb (5) Bucket (6) Structural pins for bucket support during sample collection

5) Scoop End Effector: The scoop end effector is designed for use in the Soil Sample Return Task. It's primary purpose is to collect and store a sample of soil or rock to be returned via the rover to be analyzed at the base station. Just before collecting the sample photographs would be taken of the sample site and would intentionally include the scoop in the photo. This is used as a scale reference for the picture as the dimensions of the scoop are known.

The basic design for the scoop is from a typical backhoe featuring a bucket and thumb. The bucket is hinged to allow it to *scoop* the material before lifting it. The thumb is also hinged allowing it to close over the collected material and keep it from spilling out. Sticky backed foam was adhered inside the scoop to seal in all material once the thumb was closed.

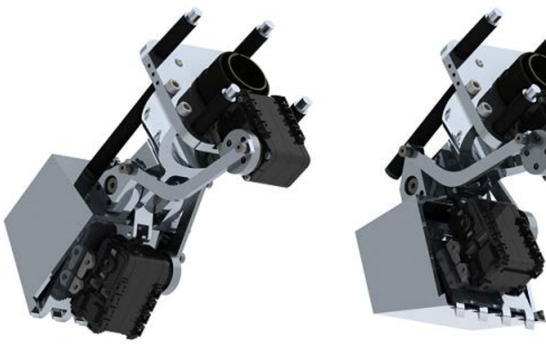

Figure 26. (left) Bucket with closed thumb (right) Bucket closed with sample acquired, ready to return sample.

Backhoes are traditionally actuated by hydraulic systems but because the rover is an electrically powered vehicle AX-12 servos are used in many places on this rover. The original design of the scoop called for PQ-12s, small electric linear actuators from Firgelli Automation, but because of supply problems and low reliability these were scrapped in favor of the more reliable AX-12s. This change called for a redesign of the scoop to fit the new actuators but as the scoop was fully assembled as per the original PQ-12 plan the AX-12s had to be bolted on in a less than aesthetically pleasing fashion. Benefits from this change, however, included increased torque output of each joint, position feedback from the AX-12s and serial communications with the AX-12s as an established standard for the whole rover.

The bucket was machined from 7075-T7351 Aluminum, an aircraft grade metal much harder than the 6061 used everywhere else on the rover and robotic arm. This was chosen because the teeth of the bucket will be digging through tough soil with rocks embedded in it. A soft metal will dent and eventually wear out or break off. The 7075-T7351 Aluminum will not loose it's sharpened edge with continued use.

6) Scoop End Effector Recommendations for Future Designs: Much time was wasted waiting for the PQ-12 linear actuators to arrive and when they did arrive the turned out to be unreliable. In hindsight, it would have been quicker and more reliable to go with the AX-12 servos from the beginning, but also for simplicity of the overall system. AX-12's were the small electric actuator of choice for the entire rover. They were used in the Pan-Tilt system, the wrist of the equipment servicing end effector, the camera arm on the robotic arm, using them on this end effector would have simplified the control system from the beginning to have one connection type and protocol for actuation.

Originally the scoop end effector design called for a mount for sensors to be fitted for taking temperature or conductivity measurements of the soil prior to collecting the sample. This ultimately was pushed off and never completed. If it had been designed and implemented correctly the probes to be mounted to the scoop end effector would have been picked early in the design phase. This would allow the mechanical design team to analyze and ensure that the range of motion of the arm would satisfy inserting the probes into the ground and collecting soil as two mutually exclusive and non-interfering outcomes. Along with this, the mechanical design team must verify that the arm is still capable of stowing while meeting the above criteria.

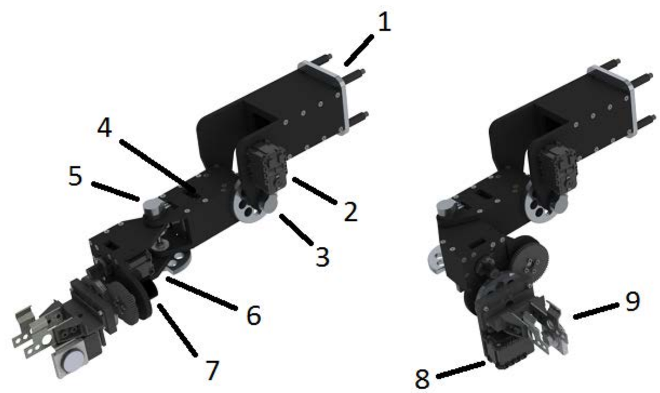

Figure 27. (left) Equipment servicing end effector fully extended (right) showing yaw range of motion to one side. (1) Connection point to limb (2) Pitch servo, geared 4.45:1 (3) Pitch joint, rotational position is sensed by 300° turn potentiometer (4) Yaw servo, inside ABS plastic structure, geared 4.45:1 (5) Yaw joint, rotational position is sensed by 300° turn potentiometer (6) Roll Servo, partially enclosed within ABS plastic structure, geared 4.45:1 (7) Roll sensor, a 3-turn potentiometer, geared 1:1 with roll joint (8) Gripper servo (9) Gripper

7) Equipment Servicing End Effector: The equipment servicing end effector is designed for use in the Equipment Servicing task. It is to interact with and manipulate a control panel featuring push buttons, typical household light switches and standard American 3-prong power plugs. The design includes a 3 degree-of-freedom wrist (pitch, yaw and roll) with a gripper at the end. The 3 degrees-of-freedom of the wrist allow the operator to orient the gripper parallel to the plug and just behind the strain relief. Once gripped the previously dangling plug can be raised up to the outlet for insertion. The tricky part here is keeping the cord from tangling with the end effector. This is up to the user as the wrist and arm have a great enough range of motion to keep from tangling. Next the plug must be aligned with the outlet, this is where camera placement is key. The operator has the choice of the arm camera or the main camera. With these two points of view the operator can then align the plug and push it into the receptacle.

As can be read in the electrical section pertaining to the arm controls, the sophisticated jointed, 6 degree-of-freedom spherical system that is the arm with the equipment servicing end effector is controlled in a user friendly linear cartesian format.

The electric actuators for each joint of this end effector were AX-12s. Each of these AX-12s were wired to potentiometers at each joint to measure the real position of the joint as each joint was geared 4.45:1. This gear ratio was the largest possible from ready made servo gears available from servocity.com. At the pitch and yaw joints 300° turn potentiometers are used, while at the roll joint a 3 turn potentiometer is used. This allowed the gripper to make 3 full turns, very handy when untangling a gripped plug.

The structural components of this end effector were laser-cut plates of ABS plastic. Because of the parts were laser cut the parts could have complex and very rounded shapes. Few drilling and tapping operations had to be made once the cut parts were received but very simple work that was handed off to younger, less experienced members of the mechanical team. The parts were then quickly bolted together.

Figure 28. (left) Equipment servicing end effector shown in stowing configuration (right) showing pitch upward range of motion

The gripper is similar in design to that used on the 2010 OSU Rover. Differences include the use of AX-12 servos instead of the ones that proved unreliable in 2010. The construction is brass and solder braising, a favorite technique of one member of the team. This unique construction had greater gripper forces than other designs built and tested this year.

8) Equipment Servicing End Effector Recommendations for Future Designs: During the Equipment Servicing task in competition the cameras were unable to help the operator align the plug for insertion. To fix this problem a small pin hole camera could be mounted just behind and next to the gripper. This would give the user sight along the plug directly to what it is pointed at.

While the equipment servicing end effector was a bolt together assembly, special care had to be given to the gears for proper meshing. Because the design called for gears to be bolted to the servo output horn this left them with single support, cantilevered from each servo. This meant that as torque was applied to the servo the force between the gear teeth tended to push the gears apart, a typical interaction of gears. The single support of the servo gear allowed it to be pushed away from the driven gear allowing the gear to skip both failing to apply torque to the desired output and, over time, damaging the gear teeth. The solution to this problem was to preloaded the servo gear into the driven gear before tightening the mounting bolts. This solution is less than ideal as it intentionally stresses the bearing support in the servo, increasing its potential for failure, and made assembly of the end effector more complex. It could no longer be bolted together simply with hex drivers and the SolidWorks file as reference for what part goes where. It needed an assembly process which is much harder to document on a project like this and often only one person on the team knows the best assembly process.

The 2010 astronaut assistance gripper featured a vibrator to reduce the force needed to push a power plug into a receptacle. Because the 2011 arm design is much more powerful it was omitted as unnecessary. But it would have been helpful in competition. The thing to remember here is that if it is undeniably helpful, it is worth including in the design, especially when the device in question, a small eccentrically loaded motor (vibrator), is simple, small, simple to control and cheap to include.

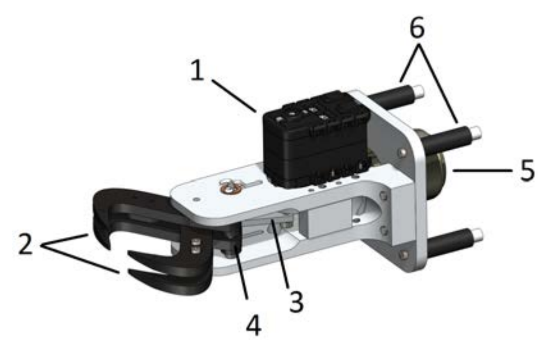

Figure 29. Overview of components for the astronaut assistance end effector (1) Servo actuator (2) Pincher/ gripper, designed to interface with the loops velcroed to the packages. This pincher requires zero force from the servo to maintain a positive grip on the package. (3) Linkage delivering force from the servo to the pinchers scissor mechanism (4) Scissor mechanism. (5) Threaded electrical connector, the user threads/unthreads this to attach/detach the end effector respectively (6) Wrist support pegs, designed to mate with the limb and transfer loads around the electrical connector

9) Astronaut Assistance End Effector: The package deploy end effector is a new design not present in the 2010 robotic arm design due to the rule changes, see Section III-A5. It's purpose is to grip the packages to be loaded onto or unloaded from the rover. The packages are stored on the rover in the Supply Rack, see Subsection IV-G.

The as per the competition rules, the packages to be deployed are fitted with velcro, loop side, and are available for teams to attach to for loading and deployment purposes. OSU's solution to this was to utilize the velcro by attaching a strip of velcro to the package with a small loop. The loop can then be gripped by the astronaut assistance end effector for loading and deployment.

Gripping this loop is accomplished by an aggressive looking pincher shown in Figure 29. The shape of these pinchers is designed such that that while closed they support the full weight of the heaviest package, 6 kg (13.2 lbs), without requiring any force input from the actuator. This design allows the actuator to be much smaller than it otherwise would have been. The rover standard AX-12 servo is used for this purpose.

10) Astronaut Assistance End Effector Recommendations for Future Designs: Early in the design process consideration was given to the idea of incorporating a roll degree of freedom for this end effector. The idea was that if the end effector could rotate about the axis of the forearm the pinchers would be capable of gripping package loops that were not correctly oriented towards the end effector. This would be useful if the packages jumbled around in the luggage rack while the rover navigated rough terrain in rout to the astronauts. This idea was scrapped because the introduction of an actuator to roll the end effector would reduce the lifting capacity of the robotic arm, increase the size and complexity of the end effector. Length is critical for this end effector as it must not be too long or it will interfere with the Rover's tripod legs. For a more capable system the roll degree of freedom would be most helpful when the design challenges mentioned above can be mitigated.

The rovers camera tripod was in a very unfortunate position, limiting the space in which the robotic arm could rotate to reach the back luggage rack area. This makes the operator's job harder than necessary. One potential solution is to place the Rover's main camera atop a single pole instead of a tripod. The range of positions that the main camera can be placed in is more limited with a pole but can be made up with an increased number of cameras mounted on the rover. The pole can have many positions it mounts to on the rover chassis depending on what task is at hand. In truth, the pole solution to the camera mount can be just as effective as the tripod solution, in fact it can be lighter.

As with the scoop end effector the astronaut end effector suffered from the distribution problem encountered with Firgelli Automation's PQ-12 small, electric linear actuator. The AX-12 servo was a later addition to the design after it was built. As with the the scoop end effector it can be concluded that standardizing the actuators of similar scale during design phase can save much time, money, and stress.

C. Arm Electrical Design & Control

The six degree of freedom robotic arm used on the 2011 OSURC Mars Rover presented some technical challenges from a control perspective. The arm used on the 2010 rover was easily controllable due to the inherent Cartesian system, in which the arm operated, and maintaining this simplicity was a goal in the design of the 2011 arm. Towards that goal, an inverse kinematics model and control system is developed such that the user could instruct the arm to move in a Cartesian system and the actuators on the arm would work in synchronization with each other to provide the desired Cartesian movement. The inverse kinematics allowed the freedom to translate the inherent spherical nature of the arm into any coordinate system desired, including a cylindrical system which is used for the shovel and astronaut assistance end effectors.

1) Architectural Overview: The electrical control system of the arm was designed with modularity in mind. One master device arbitrates data to the various subcomponents on the arm, including motor controllers, servos, and sensors. A high level block diagram of this system is shown in Figure 30.

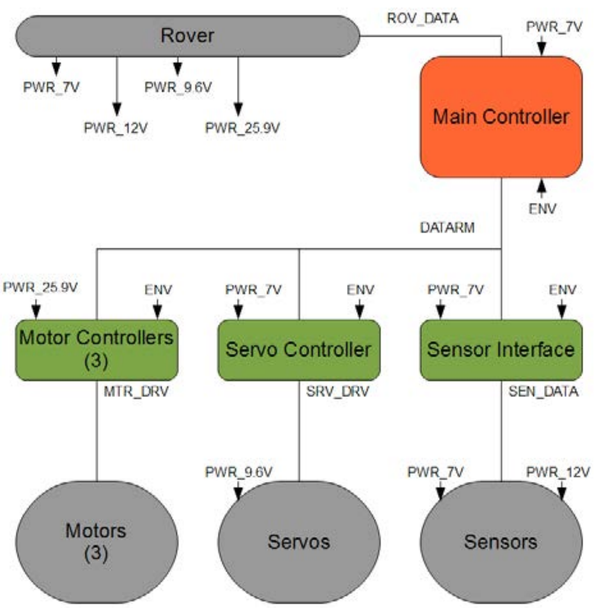

Figure 30. High level block diagram of the robotic arm

The distributed modular approach simplified troubleshooting and allows for simpler overall interface between the rover and the arm. When information is sent to the arm, an abstracted collection of data is sent from the Rover to the Main Controller. The Main Controller then interprets the data and passes necessary commands on to the sub components. Additionally, the Main Controller monitors the state of the arm, offloading the task from the Rover mainboard.

2) Inverse Kinematics: To solve the inverse kinematics and develop the control algorithm for the arm, a software simulation of the arm was created. A screenshot of the simulation is shown in Figure 31.

This simulation allowed the control algorithm to be tested without the risk of damaging the physical arm by requesting an illegal and potentially self damaging position. Furthermore, the simulation is integrated into the user interface of the Rover, and was used in competition to provide feedback on arm position without use of a camera. The inverse kinematics function itself is a complex sequence of trigonometric and vector math, with an input of an x, y, and z location and output of all six angles of the arm. A variation of the function

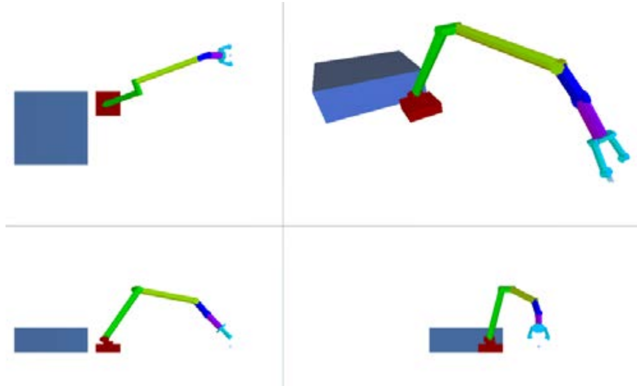

Figure 31. Screenshot of the robotic arm simulation. Used to verify the inverse kinematic equations used to control the arm.

inputs r, θ, and z for cylindrical control.

3) Technical Challenges: In the preliminary design, the inverse kinematics function was intended to be implemented in the Main Controller microcontroller. However, after investigation, it was discovered that the math would be too slow when executed on a processor without a hardware floating point unit, and the desired microcontroller with a floating point unit was not in production at the time. The adopted solution is to perform the inverse kinematics function on the base station computer, which uses an x86 based processor with a floating point unit, and transmit the resulting data to the arm via the rover wireless link. The arm would then receive discreet positions and interpolate linearly between the two. New position data is sent rapidly enough that the linear interpolation results in a location accuracy better than 2 millimeters of the desired location, which was entirely within the specified engineering requirement for accuracy and adequate for tele-operation of the robotic arm.

4) Actuator Control: Two types of actuators are used on the arm: DC motors and digital servos (AX-12). The highest force joints (shoulder and elbow) are powered with DC motors driven with the same custom motor controller in use on the other rover DC motors, see Section VI-B and Figure 36. The lighter duty joints are controlled with digital servos. These design choices ultimately result in the effectiveness of the arm. By using a custom designed motor controller, it is possible to directly interface the motor controller to the RMB30SI absolute rotary magnetic sensor and to the rest of the arm control system. The specific control loops required are also implemented directly into the motor control module, which increases the simplicity of the system.

For the digital servos, an interface device (the Servo Controller, shown in Figure 32) was created which interprets commands sent from the Main Controller and passed them on to the attached chain of AX-12 servos. Similar to how the Main Controller acts as a central hub for information flow between the rover and the components of the arm, the Servo Controller is the hub for communication between the Main Controller and AX-12 servos.

Figure 32. Servo controller PCB shown in water proof housing

VI. Rover Electronics

A. Electrical Systems Overview

This section covers the electronics designs of the main rover components, not including the arm. The list of subsystems covered includes power, camera control, video encoding, drive, radio frequency communications, and the main control/navigation systems.

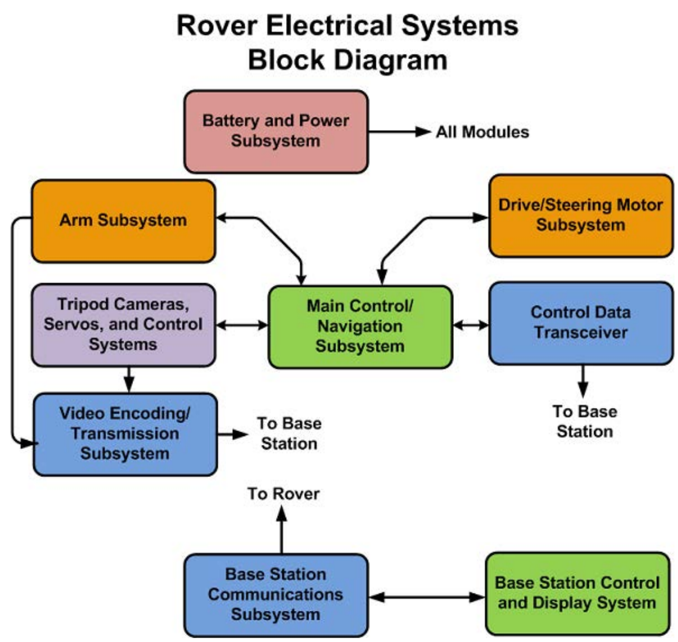

Figure 33. Rover Electrical Subsystem Structure diagram

While no drastic functional differences were made over the 2010 design, the 2011 design process did focus on making incremental improvements. Most of the major changes came in the main control system, video transmission system, and the overall design philosophy of the electrical team. The three following goals highlight the electrical design process on the 2011 OSU Mars Rover:

- Reduction of control complexity by exclusively using microcontroller architectures, on a single board communicating with satellite modules.

- Increase the focus on designing and fabricating electronics modules in-house.
- Reduce the cost of each module, while increasing all around performance.

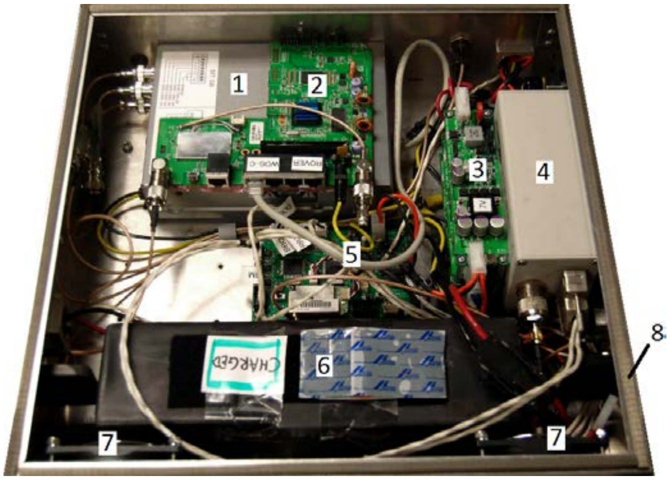

Figure 34. 2011 Rover Electronics Bay: (1) Video server (2) Router (3) 3x DC-DC converters, 12V, 9.6V, 7V (4) Freewave radio transmitter (5) Rover mainboard (6) Batter (7) 2x fans

B. Power Systems

Similar to previous OSU designs, all onboard electronics and propulsion systems were powered by a single battery and a host of power electronics used for regulation. Most of the hardware selected for the 2010 Rover was either reused or reimplemented in this year's power system.

1) Battery Pack: The 2011 rover reused a replaceable 21Ah 25.9V lithium-cobalt oxide polymer battery pack from the 2010 Rover. This particular battery was chosen, despite its $6-700 value, as it provides a number of advantageous characteristics for our power system. Over other lithium-ion technologies like cylindrical/prismatic lithium-cobalt oxide or lithium iron phosphate batteries, lithium polymer provides a superior light weight, high reliability, reasonable current capacity, and form factor that is optimal for small spaces like a rover.

The battery also includes an integrated power control module (PCM) that controls the charging, discharging, and balancing of the 7-cells in the pack. The PCM prevents overcharging, overdischarging, and overcurrenting the cells, ultimately allowing for a safe to operate rover.

2) DC-DC Conversion / Preregulation: Aside from high power devices such as motors and actuators, the remaining electronics on board the rover were not compatible with the battery voltage, requiring the use of step-down voltage regulators. This year, three primary DC-DC converter units designed for reconfiguration via USB, down from four in the previous year, were used as standalone modules to provide power to the remaining electronics at voltages of +12V, +9.6V, and +7V. The +12V rail was used to power a video server, cameras, and radio hardware. The +9.6V rail was dedicated solely to the large number of AX-12 digital servos used on the rover. The +7V supply was used as supply for all other low voltage electronics. All devices using +7V further regulated this voltage down to the required voltages of +/-5V and +3.3V on the dissipating module itself. This allowed for headroom for smaller switching regulators or low-dropout linear regulators to effectively produce the desired output voltage.

Figure 35. DC-DC USB module used for 2011 regulation/preregulation

3) Grounding and ESD Protection: Similar to the 2010 design, a hanging ground wire was attached to the electrical housing to provide an Earth grounding point. In 2010 it was determined that the electrically isolated rover readily built up charge over time. Upon conductive contact of the frame with an Earth potential object, the resultant rapid electrostatic discharge was often severe enough to disrupt or damage the delicate electronics systems. Thus a dragging ground wire design from 2010 was redeveloped and improved with a catch-resistant dragging mass. Additional ESD protection was also implemented in many of the modules through the use of ESD protected components or the use of ESD protection diodes where critical external wire-to-board connections were made. None of the major ESD problems found during testing in 2010 were experienced during testing and deployment this year.

4) Recommendations for Future Designs: Lithium-polymer batteries have served the Rover well as a safe, reliable, and lightweight power sources for the previous three years of rover design. Continued use of similar batteries is highly recommended.

Despite measuring large voltage transients (>100mV) on the outputs from the reconfigurable DC-DC converter modules, using them as regulators and pre-regulators is strongly recommended for future designs. The easy setup and reconfiguration over USB, small size, and high reliability of the modules makes the excellent candidates in future power systems.

C. Drive Subsystem

This year's drive system was quite similar to the 2010 drive system, featuring six-wheel direct drive with a four actuator steering mode. Prototyped in 2010, the drive system once again used distributed motor control, with an individual intelligent motor driver controlling each motor. The major change this year came with the internal design of a new motor driver module.

1) Motors: Similar to the 2010 design, the 2011 Rover featured a compliment of six 24V 52mm brushed DC motors with a 1:26 ratio planetary geartrain. These motors gave the rover both reasonable torque and speed, with each motor being rated with a stall torque of 300kgf-cm and a top speed of 136rpm. This compliment, in conjunction to the rocker bogie system, allowed the Rover to climb steep slopes and traverse rough terrain with ease.

Each motor shipped with a 38 pulse per revolution magnetic encoder, however, these were removed as they proved to be electrically and mechanically unreliable. Current-feedback was instead used on the motor drivers to implement a more complex control loop that required no shaft encoders.

2) Steering Actuators: Similar to the 2010 Rover design, four linear actuators were implemented to turn the four corner wheels into a low friction, zero radius turn mode. Electrically, the steering actuators system is upgraded from 2010, with faster and more reliable actuators. Each steering actuator is a Midwest Motion MMP LA-3 series actuator with a 50mm stroke length.

3) Universal Motor Driver: One goal of this year's electrical design was to implement a low cost, high reliability, and high design reusability 24V DC motor driver. One of the numerous PCBs designed this year satisfied those requirements, the universal motor driver.

The small size and highly application-adapted, yet flexible design of the universal motor driver saw extensive use throughout the rover. Thirteen universal motor drivers were used throughout the rover: six for the drive wheels, four for the linear steering actuators, two for the arm linear actuators, and one for the rotating arm base.

Each motor driver had a separate bus address, and communicated to either the mainboard or main arm controller via RS-485. Over the communications bus, speed commands could be sent, while the motor drivers handled much of the low level control of the motors, such as speed ramping. Board temperature and current data could also be requested by the main controller over the bus.

The motor driver board featured a full H-bridge constructed from four discrete N-Channel MOSFETs driven by an Intersil HIP4081AIB 4-channel NMOS driver. Each H-bridge driver was controlled by pulse width modulation signals generated and controlled by an onboard Atmel ATMega168 microcontroller.

To address power dissipation and heatsinking in confined spaces, the motor drivers were heatsinked directly to the bogie using very high thermal conductivity interface foam. On the board itself, large copper planes were used to handle both high currents and provide heatsinking for high power dissipation components. Temperature feedback was also available through the use of a thermistor.

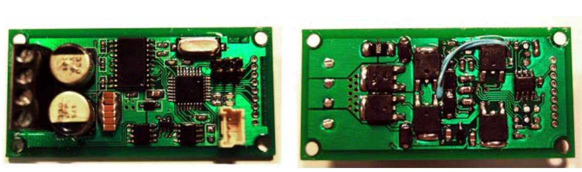

Figure 36. Universal Motor Driver. 13 of these modules were used on the Rover

4) Recommendations for Future Design: Continuing the use of in-house design motor drivers is highly encouraged. This process allows for a reduction of cost compared to most commercial solutions and allows for the implementation of custom features.

While functional mounting and thermal interface system was devised for this year's motor drivers, each board was tensioned down on the ends with mounting screws and was only supported underneath by the thermal interface material. This caused occasional mounting issues with board flex and component leads unadhering from the boards. A more solid mounting system that retains thermal contact should be devised for future motor driver designs. This design should not only incorporate an easy mounting mechanism that prevents board flex, but should also allow for easy removal of the driver in the event of failure.

D. Video Subsystem

Of the systems redesigned on the 2011 OSU Rover, the video system saw the most changes. Last year's system relied entirely on analog NTSC video cameras, analog multiplexing, and an analog FM transmitter/receiver pair for transmission. This year's iteration implemented a digital video system that utilizes similar analog cameras to the 2010 Rover, but encodes the video signals into an MPEG4 Part 10 based video stream transmitted across an 802.11g network at a significantly lower output power than the analog systems used in past years.

1) Tripod Control Board: To facilitate control over the tripod camera systems, sensors, and pan-tilt servos, a custom tripod systems control board was designed, manufactured, and installed on the side of the primary camera. This board contained three linear voltage regulators as well as an inverting charge pump to power all tripod logic, the camera, tripod sensors, and a differential audio and microphone interface. At the center of this control board is an Atmel ATMega644 microcontroller. This MCU is responsible for processing all control commands from the mainboard and controlling the two AX-12+ pan-tilt servos as well as the main camera via TTL level serial. Bus control buffers were used to interface to the two different devices as the camera and servos relied on disparate protocols and serial electrical layers.

The tripod MCU was also responsible for interfacing via a level translated I2C bus to the tripod accelerometer and pressure sensor on a separate board located on top of the camera. For more information on these sensors, see Section VI-F.

An audio amplifier and transmission circuit was also implemented on the main tripod board. Inputs are taken from a simple electret microphone on the tripod sensor board, amplifying and applying bandpass filtering before transmitting the signal to the mainboard receiver with a Burr-Brown DRV135 differential transmitter.

The tripod board also served as a video pass-through, adapting the flat-flex connector from the main camera to a coaxial 75-ohm BNC connector.

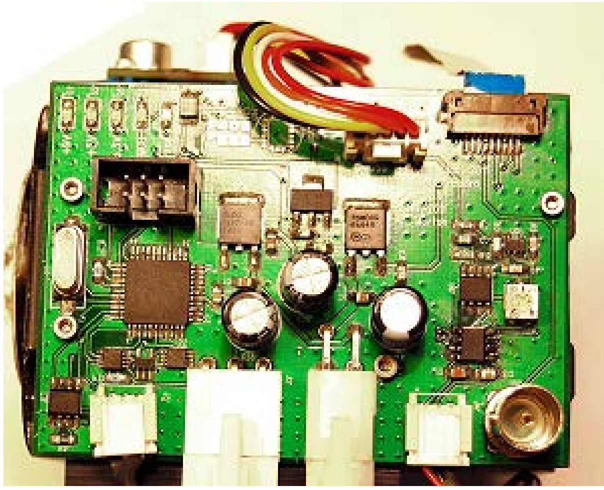

Figure 37. Tripod Control Board, mounted on Main Camera

2) Main Camera: After the astounding results of using a Sony FCB-EX1010 block camera in 2010, the team opted to use the successor model, the FCB-EX1020 in the 2011 design iteration. This camera was mounted atop an adjustable tripod and provided excellent optical zoom capabilities (36x) that proved incredibly useful in discerning distant objects. Control of the camera was implemented via VISCA protocol TTL serial sent from the tripod control board.

3) Arm Boom Camera: A second actuated camera was included on a servo driven boom with a tilt-axis end effector. While this camera provided a decent vantage point of the arm end effectors and the arm objective, it in some cases, such as the equipment servicing task, could not easily view both items simultaneously. Additionally, the low cost and quality of the camera chosen for the arm boom led to issues with white balance and poor image quality in bright sunlight.

4) Arm Fixed Camera: A fixed pinhole camera was placed at the base of the arm, directed and focused at the ground near the front of the rover to view potential science samples quickly during the sample return task. This camera could also be reconfigured to point at other arm objectives prior to the start of a competition task.

5) WJ-GXE500 Network Video Server: In order to encode our analog video signals into digital streams an off the shelf Panasonic WJ-GXE500 network video server was used. This server offered 4 NTSC analog inputs and offered both MPEG-4.10 (H.264) and MJPEG digital video codecs for enhanced performance and quality. The higher quality and lower bitrate H.264 codec was chosen over the motion-JPEG codec. A standard 100Mbps ethernet connection bridged the video server to the RF transmission hardware.

While the specifications of this video satisfied this year's requirements on paper, the actual unit was not able to provide multiple high-quality simultaneous streams in a usable format. Firstly, encoding latency frequently was greater than 250ms, even with reduced frame rates and encoding quality. This added significant delay between control sequence execution and visual feedback to the rover operators. Additionally, the Internet Explorer based HTTP interface and lack of an available interface API restricted the team's ability to integrate video streams into the primary Rover interface.

6) Pan/Tilt and Control: The tripod camera was placed atop a servo based 2-axis pan-tilt mechanism for pointing. Both the pan and tilt mechanisms were based upon AX-12+ digital servos attached to a custom geartrain to provide the necessary precision and holding torque for the cameras. Each of the servos came with a 300 degree position control range, insufficient for our application. In order to rotate the camera gear train more than 360 degrees, the servos required multiple rotations with position control. To achieve this, the internal position feedback potentiometers were replaced with external potentiometers coupled to the geartrains. Control for the servos was provided via TTL serial communications with the tripod control board over a protocol proprietary to the servos.

7) Transmission: Transmission of the encoded video streams was conducted via an 802.11g network using off the shelf router hardware. More details on this implementation can be found in Section VI-F1.

8) Recommendations for Future Design: In the testing phase, it was determined that the latency of encoding was much greater in most cases than the latency of data transmission. With digital transmission video quality could more or less be conserved at a distance; however a large decrease in frame rate had to be accepted to make this quality possible. Despite the relative consistency of video quality, there were frequent brief periods of encoding distortion. This is inherent in the use of H.264 video encoding which caused the appearance of image artifacts and a blocky image.

If digital encoding systems are used again in future designs, a superior video encoding system should be used. While the network video server used this year was costly, it was still not able to provide high quality video at high frame rates and with low latencies necessary for smooth Rover operation. Additionally, the requirement to use a web browser based interface severely limited the integration of video streams and server control into the main user interface and should be avoided in the future. These factors should be taken into account, and more design and financial emphasis for the video transmission network should be considered for future designs.

While the image quality of the primary camera was superb, the image quality of the two lower quality and lower cost cameras was markedly worse. It was discovered in testing, and verified in Utah that each of our cameras suffered from white balance issues due to improper video signal levels. This issue was compounded on the two arm cameras by poor video quality, often making it difficult to discern low-contrast details.

Additionally, there were many vantage points, such as a camera on the end effectors, that would have been very useful in arm related tasks, but no other cameras were implemented. A recommendation for future designs would be to include a larger number of higher quality cameras if cost and weight margins allow.

E. Main Control Subsystem

One significant change over the 2010 design was in the main control architecture. In 2010, central control was carried out with an ARM based handheld computer running Linux and a modified ISA backplane with multiple boards containing only few components. A major goal of the new design was to remove the need for a high-level computer, and to simplify the function of multiple control boards to a single, well integrated mainboard. With the new architecture came a new bus system, replacing the old USB/TTL serial buses with a universal control system use of RS-485.

1) Mainboard: This year's design aimed to simplify the hardware used for primary control, to remove the need for a high level computer system and the underused modular backplane. Thus a single board was designed, based around the use of two Atmel 8-bit AVRXMega microcontrollers.

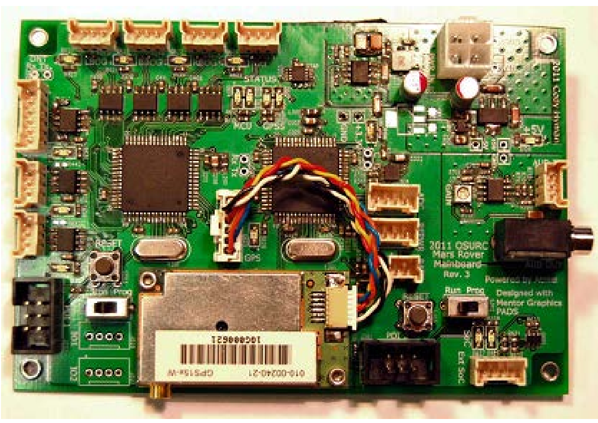

Figure 38. Rover Mainboard

Simplicity was the key goal behind this year's architecture. By implementing the main onboard processing on a microcontroller, the development team was able to circumvent the need for a complex operating system, or the complicated overhead involved with interfacing such a system with low level satellite modules.

The main XMega MCU was used to route all incoming and outgoing packets to both the satellite modules, and the second auxiliary XMega. The second XMega served as a GPS and sensor interface responsible for processing and simplifying the NMEA format GPS data strings in order to maintain a constant watch on the GPS, while not burdening more critical processing taking place on the main MCU. Interfacing the two MCUs was a single 38.4kbps full duplex asynchronous serial line.

External communication was carried out over RS-485 serial lines, through several Texas Instruments RS-485 interface ICs. Communication to the Freewave radio was a full duplex 115.2 kbps line, while the rest of the mainboard connections were simple half-duplex 38.4 kbps RS-485 lines.

The mainboard also featured an onboard GPS receiver. For more information on this receiver, reference the Section VI-F1.

The mainboard design also included hardware support for two additional sensors, a digital temperature sensor and 3-axis accelerometer; however these sensors were not implemented. A differential audio receiver was also designed on the board to interface the tripod audio signal to the video server. This system was also not used in the end as the differential audio transmission system suffered from electrical noise issues and tests determined that more useful audible feedback could be obtained with a chassis mounted microphone. Thus a simple desktop microphone was installed and was connected directly to the network video server.

2) Onboard RS-485 Communication Networks: Why RS-485? A majority of onboard communications on this year's Rover were carried out over an RS-485 electrical layer. Using this particular standard had many benefits, but some were more critical for the application than others. First and foremost, RS-485 relies on differentially signaled serial, which greatly improves the robustness of the data signaling. While common-mode noise from EMI may normally cause data errors on a single-ended serial bus, the reliance on the voltage difference between the pair of communications lines in a differential signaling setup avoids this intolerance to common mode noise. RS-485 also specifies a wide range of common mode transmission line voltages, ranging from -7V to +12V, allowing for better protection of devices that may not be sharing the same reference potential. Finally, RS-485 presents a relatively simple implementation of serial, only needing a simple low cost transceiver to connect a TTL serial device, such as a microcontroller, to the RS-485 bus. In contrast to the USB/TTL/RS-232 communications scheme used in the 2010 OSU Rover, a simple RS-485/TTL scheme was much simpler to implement and debug.

3) Communications Architecture: The mainboard acted as a master node for each individual bus, and communicates via half-duplex RS-485 on a simple proprietary protocol with other satellite devices as nodes on a multipoint bus. Both the mainboard end and all receivers use similar RS-485 transceivers. Bus contention is avoided by having the master node issue addressing and commands, while slave nodes were designed to only respond to the master after receiving an address and command. Each bogie, the tripod, and the arm had its own half-duplex RS-485 bus operating at 38.4kbaud. A 115.2 kbps full-duplex RS-485 link was used to carry data between the Freewave radio and the main XMega.

4) Recommendations for Future Design: The design of a main controller should be a top priority from the start. The first hardware prototypes of the mainboard were not available until after nearly halfway through the development cycle. Many additional board features added significant complexity to the board, requiring more development and testing time. Despite the late arrival of the mainboard, the simple microcontroller architecture with an RS-485 communications standard worked well and would be a useful strategy to implement in future designs.

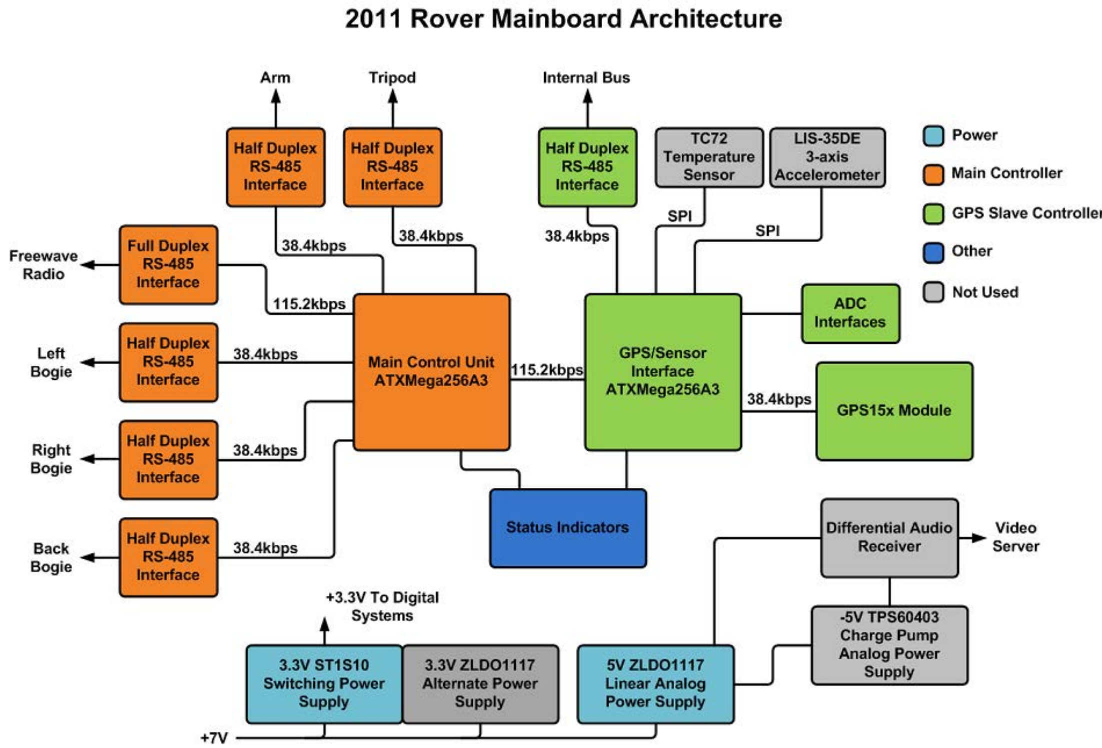

Figure 39. Rover Mainboard Architecture

F. Navigation and Sensing

To adequately complete the navigational and surveying tasks in this year's competition, a number of sensors were implemented onboard the Rover. A GPS receiver, 3-axis accelerometer, and a highly sensitive barometric altimeter were used to determine Rover position and camera heading. The implementation details are described in this section.

1) GPS: A Garmin GPS-15x receiver was integrated on the Rover mainboard, and connected to an external GA-25MCX L-band patch antenna, also provided by Garmin. This module provided abstracted navigation functionality and connected directly to a microcontroller, with no external interface component overhead, to parse the NMEA navigation strings. The GPS receiver had Wide Angle Augmentation System (WAAS) capabilities, allowing for surface position accuracy of less than 3m.

2) Barometric Pressure: As GPS altitude measurements have proven to be highly inaccurate and imprecise in both specifications and from observation. This year's design features a Bosch BMP-085 MEMS barometric pressure sensor as a navigational aid. Using a starting elevation derived from topographical maps, the Rover was able to use this sensor as an altimeter and obtain a much greater level of altitude precision, down to much less than 1m.

3) Acceleration: In order to determine the main camera's angle of elevation, a Freescale MMA8451 3-axis digital accelerometer under the influence of Earth's gravity was used. This camera angle was used to triangulate the relative elevation of site markers in the site and survey task. This accelerometer was interfaced via an I2C compatible two-wire interface to the satellite microcontroller used on the tripod control board.

A second 3-axis accelerometer was included on the mainboard to measure Rover orientation for providing additional Rover orientation feedback to the operations team. This feature, however, was not a high software priority, and was not implemented in the final design.

4) Recommendations for Future Design: It is highly recommended to continue the use of integrated GPS modules with TTL-level serial communications as these prove to be very lightweight and incredibly easy to integrate with microcontroller hardware.

The use of navigational telemetry sensors, including our accelerometer and barometer, is strongly encouraged to be implemented and improved in future designs. Having just a single sensor proved to be highly useful. Having more orientation sensors on the Rover could be useful in preventing the Rover from going beyond its safety limits in traversing steep slopes.

The addition of new sensors, even if they were few in number, provided the operations team with critical feedback for driving. Onboard science instruments, however, were not implemented on this year's design, costing the team points in competition, as well as compromising the science team's ability to characterize possible samples. Implementing other sensors for specific tasks, particularly the sample return task, would be a strong design addition for future designs.

G. Communications Systems

This year's radio system, similar to last year's, utilized two separate transceivers at the Rover and at the base station, one for control data and one for video data. Control and video data were separated into different systems to prevent latency issues and keep the control system simple from start to finish. In order to transport the high data volume for a digital video system, an 802.11g wireless distribution system was implemented. Both transmission schemes operated in the 2.4GHz ISM band but due to differing but intelligent transmission schemes, avoided any significant interference with each other.

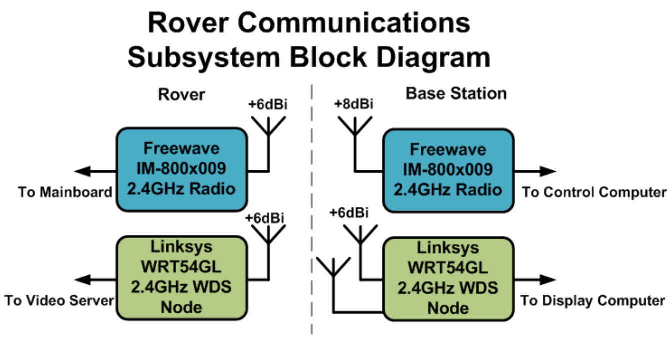

Figure 40. Rover Communications System Structure

1) Control Data Radio Design: An initial design called for designing a 900MHz frequency hopping spread spectrum (FHSS) board based around an RF Monolithics DNT-900P adapter module. The board featured power electronics, bus interface devices, onboard transmission lines, and the DNT-900 module itself. The board was designed to be used as a pair with an identical board to form a 115.2kbps full-duplex RS-485 bridge with the base station. During testing, it was found that at moderate to high output power, the power electronics onboard the DNT-900 modules became unstable causing inoperability of the radios at specification. Thus, due to the module unreliability, the board design was discarded for use in 2011.

After discarding the DNT900 design, a pair of Freewave IM-800x009 2.4GHz FHSS transceivers were implemented. Each Freewave radio fit the bill without any hardware modification or accessories, and both were already in the possession of the OSU Mars Rover team at the time. The main factors against using the Freewaves earlier in development were cost, volume, and weight.

2) Video Transmission System: A wireless 802.11g network was used to transmit the encoded H.264 streams from the network video server back to the base station. Early designs were based around researching OFDM based transmission schemes with strong non-line of sight (NLOS) channel conditions, including multiple 802.11 standards. The final decision to use an 802.11 network came with the use of a standard network video server, and the wide availability of off the shelf network products that could be adapted to suit our needs. Identical low cost Linksys WRT54GL routers running DD-WRT firmware were used, one onboard the Rover and one at the base station to form a wireless distribution system. The custom firmware was used extensively to fine tune many parameters to allow for increased range and lower latency. The maximum output power of the routers was approximately 200mW.

To address this relatively low output power, the initial designs called for the use of a multiple input, multiple output antenna setup, interfaced to the routers by a custom designed transmit/receive module using 1W power RF power amplifiers. Modules were designed, however they were abandoned due to design complications and time cost. As tests showed reasonable NLOS range and video performance in Oregon, no alternate solution was pursued. Due to overestimation of the range capabilities of the unamplified routers, video signal was lost during operation in the astronaut assistance task when range and loss of line of sight caused a loss of connection.

3) Rover Antenna Setup: Of the three antennas on the Rover, two were used for RF communications with the base station, while the third was for receiving GPS signals. The two communications antennas were both identical L-Com HGV-2406U 2.4GHz +6dBi omnidirectional antennas. These antennas were lightweight, and provided a good balance of gain and off-axis tolerant radiation patterns useful on a mobile Rover moving over rough terrain.

4) Base Station: A router and Freewave radio were located on the base station tripod, connected to the control and video computers via a cable bundle. The router used two 2.4GHz +6dBi antennas identical to the antennas on the Rover, while the more robust low data rate and higher power Freewave used a +8dBi omnidirectional antenna with a narrower elevation radiation pattern. All base station radio equipment was mounted to a short aluminum tripod and wood antenna mount that did not require many team members to set up.

5) Recommendations for Future Designs: While the video network functioned well at a low power in line of sight conditions, the loss of transmission in NLOS conditions during the astronaut assistance task highlights the need for a higher power and higher reliability video transmission system. The use of a steered high-gain directional antenna at the base station may help increase the radio range in some scenarios.

Although the Freewave radios used for the previous four years on OSU Rovers have reliably facilitated long range serial communications, they are still costly modules. With the wide availability of low cost commercial wireless serial transceivers available, a suitable communications module with a smaller mission cost than a pair of Freewaves can be readily found. Care should be taken that the modules are evaluated before committing to a design, and that the modules are of a sufficient quality to satisfy Rover requirements.

H. Connectors and Wiring

1) Simplified Wiring Harness: Compared to the previous year's wiring design, the 2011 external wiring was generally simplified. The use of only 24V high power actuators and a simple RS-485 bus architecture, each bogie only required a single pair of power wires and a single shielded twisted-pair data cable. To minimize the number of connectors between the electrical housing and the external modules, combined power/signal M23 circular connectors were used.

For all wire to board data connections, Molex Sherlock connectors were used extensively in standardized configurations. These connectors were chosen for their small size, wide number of pin options, and suitable reliability amongst other choices of plastic connectors.

2) Fuse System: All systems connected to the battery (each DC-DC converter, arm, all drive motors and actuators) were protected by inline fusing using readily available automotive fuses. This not only protected individual circuits from catastrophic damage in the event of a failure, but it prevented battery shutdown and Rover shutdown. The highest circuit failure rates during testing were in the drive systems, and fuses were later added to individual motor drivers to allow for continued Rover operation in the event of motor or actuator loss.

3) Recommendations for Future Design: One of the greatest lessons learned this year involving wiring was the importance of initial design and assembly of the wiring harness. A majority of the external harness had to be rebuilt before Rover deployment to add fuses, consuming large amounts of time that could be better spent on other operations.

It is recommended that any major connector candidates are evaluated and chosen early. Purchasing samples of connectors for quality and reliability testing is highly recommended to avoid any large design commitments to a particular connector set.

While metal circular connectors are a recommended design consideration, the use of Amphenol M23 connectors, while less expensive than more standard connectors, such as MIL-C-5015 connectors, is not recommended. The M23 connectors suffered from heavy construction, a large profile that required panel reinforcement, and proved difficult to change contacts and wires during harness modifications.

Use of Molex Sherlock crimp connectors is strongly recommended due to the low cost, reasonable reliability, and ease of use. Most minor issues encountered early on in Rover assembly were alleviated by the use of proper crimping tools.

Another wiring recommendation is to include fusing for all battery connected devices early on. Not only is it difficult to modify wiring harness designs after they are implemented to add inline fuses, the amount of time that can be spent repairing unfused hardware following failures can be reduced by installing harness fuses early in the build process.

VII. Rover Software

A. Software Introduction

The software of the 2011 Mars Rover is broken into three separate parts: the control interface which runs at the base station, the central rover controller, and the satellite modules. Each system is responsible for a different aspect of controlling the Rover. All the software is written in C or C++ and compiled using the GCC compiler. This allowes for some code to be reused between the major components.

The base station is responsible for interpreting data from the joysticks (for motion and arm control), processing data received from the Rover (GPS, accelerometer, and barometer data), and controlling data sent to and from the Rover. This system's main requirement is to provide reliable, easy-to-use control of the Rover and accurate, up-to-date, clearly presented information on the Rover's status.

The main Rover controller (an AVR XMEGA microcontroller) has a similar task as the base station. It is responsible for processing commands from the base station and sending those commands to the correct satellite module. All the satellite modules are connected to the main controller through half-duplex RS-485 serial links. Some modules (such as the motor controllers) are connected on a bus with other modules. In these situations, the main controller is responsible for coordinating communication on the bus to prevent conflicts. Because of the potential for data loss on these data links, the main controller also handles retransmissions in the event a satellite module does not receive the command.

Each satellite module is a separate microcontroller responsible for controlling an individual piece of hardware. These modules carry out instructions or provide information when commanded or queried by the main controller. Each module receives high level instructions from the main controller about actions to perform and converts them into the instructions necessary to control their hardware.

B. Communication

All communication between devices takes place over serial or USB. USB is used at the base station to interface with devices because of its ease of use in a desktop environment. USB devices have unique identifiers (Vendor and Product IDs), which make identifying devices simple. USB ports are also ubiquitous on laptops now, can power devices, and are fast to connect and disconnect. Using USB for devices at the base station makes the system easy to use and portable between different laptops.

The overhead and features of USB are not necessary for communication on the Rover. All these communications took place over RS-485 asynchronous serial. Due to the bus architecture some of our modules use, as well as the lack of any built-in error detection/correction in asynchronous serial, a universal protocol developed that is used for all serial communications. This protocol is designed to be simple (with low overhead), reliable, packet-oriented, and support multiple devices on a single bus.

To accomplish these goals, each packet is prefixed with a header. This header contains a start byte, the length of the packet, the target address to deliver the packet to, and a checksum. The target address identifies which device on the bus the packet is destined for. The checksum is used to check for data corruption within the packet and is calculated by taking the lower byte of the sum of all the bytes in the packet. In order to make the protocol more reliable, all data (including the header, excluding the start byte) is byte-stuffed. Byte stuffing is a technique of escaping certain characters

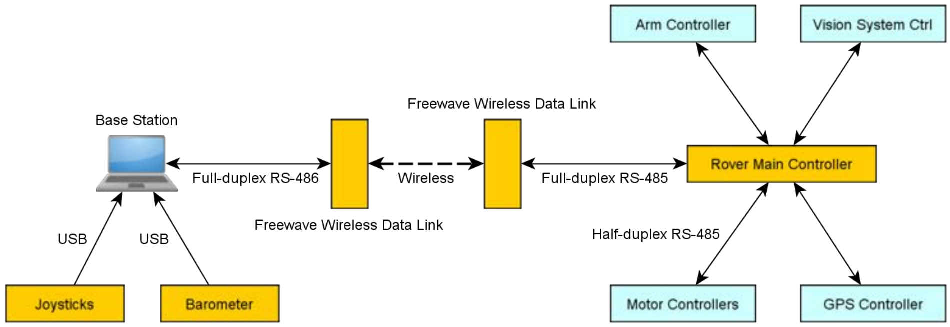

Figure 41. 2011 Rover Software System Overview

which cannot (or one does not want to) appear in the final data stream. In this protocol, the start byte, along with 0x00 and 0xFF (common frame errors) are byte-stuffed.

C. Base Station

The base station software is written in C++ using the Qt library and run on Ubuntu Linux. Qt is an open source cross-platform C++ library, and is primarily used as a toolkit for producing cross-platform GUI applications. The program has three major components: the Tactile Interface, the GUI, and the Virtual Rover. Each of these modules is responsible for a unique task. The system architecture is shown in Figure 42.

1) Virtual Rover: The Virtual Rover module provides an object-oriented interface to the Rover. Each satellite module on the Rover has a corresponding C++ class (a Controller) that is part of the Virtual Rover module. The `VirtualRover` singleton class is responsible for coordinating and providing access to each of these controllers. This class receives all incoming packets from the Rover and routes them to the correct controller for processing. It also provides a public interface which allows other system components (the Tactile Interface and GUI) to access each controller.

2) Controllers: Each controller inherits from the `AbstractController` class, an abstract class which provides an interface which each controller must implement. These functions handle incoming messages (`handleMessage()`) and identify which satellite the controller is responsible for (with the target ID used by packet protocol).

These classes are responsible sending commands to each module and processing replies from them. The functionality of these satellite modules is exposed through public functions in these classes. When a function is called, the class generates the packet necessary to execute the action and sends it to the Wireless Dispatcher to be queued for transmission. The `handleMessage()` function is called automatically when a packet is received, parses out the information, and broadcasts it to the other parts of the GUI that have requested updates from this module (through the Qt signals/slots system).

3) Wireless Dispatcher: The final part of the Virtual Rover module is the Wireless Dispatcher. This class handles all outgoing and incoming packets to and from the Rover. It wraps the packet data in the same protocol described in the Communication section and controls the rate at which packets are transmitted to the Rover. When a packet is received and decoded, it is sent to the VirtualRover class which routes the packet to the correct controller.

4) Tactile Interface: A majority of the Rover's control comes from tactile inputs such as joysticks. The 2011 Rover used 2 joysticks to drive and control the arm. A T.Flight Hotas X made by Thrustmaster is used to drive the Rover and control the main camera while a generic PS2 controller is used to control the arm both shown in Figure 43. The tactile interface reads the joystick signals (axis and button changes), smooths them, and sends updates to the Virtual Rover module. This module's primary responsibility is to map joystick inputs into actions.

Figure 43. (right) controller used to drive the Rover and aim and zoom the main camera (left) controller used to operate the arm

5) Graphical User Interface: This is the most complex part of the base station software. The Graphical User Interface (GUI) is responsible for displaying information from the Rover (such as GPS data, data errors, and information from sensors), assisting with competition tasks (recording points for the astronaut and science task, triangulation for the site and survey task), and displaying a 3D model of the arm.

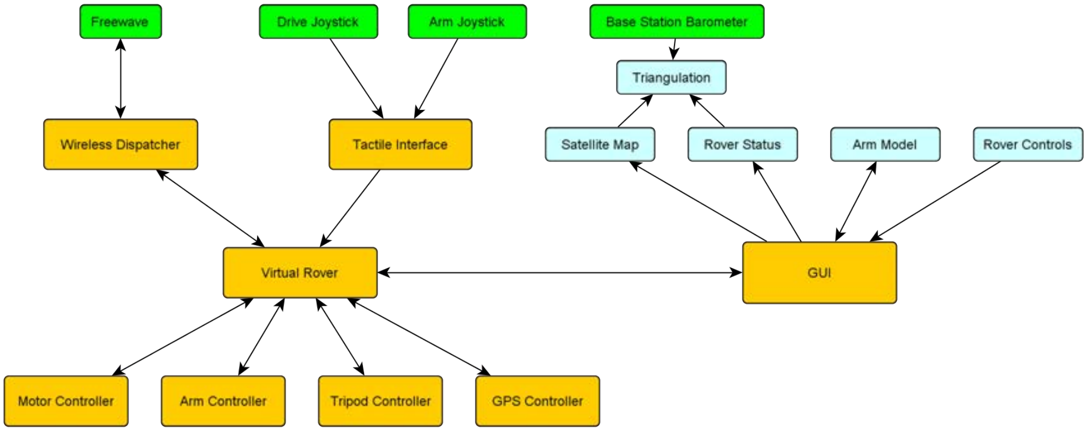

Figure 42. Base Station Software Design

Figure 44. Screen capture of GPS points overlay-ed onto map of competition site.

6) Arm Control: The Robotic Arm is controlled with a generic PS2-inspired controller. Because the Rover has no microcontrollers with FPUs (Floating Point Units), the inverse kinematics calculations are performed at the base station instead of on the Rover. The positions for each joint are calculated at 200 ms intervals and transmitted to the Rover. The GUI displays a 3D model (created in OpenGL) of the arm from four different perspectives. This model is extremely helpful for controlling the arm, since it shows the positions of all components of the arm, not just what is visible in the camera. It also allows the arm operator to control the arm while the driver was using the main camera to drive the Rover. This is useful as it allows the arm operator to begin unstowing the arm as the driver approaches a site or visa versa.

7) Triangulation System: The GUI assists with the Site Survey task in triangulating markers and calculating their elevation. Two different methods of generating the vectors needed for successful triangulation are employed during the task depending on the local topography and presence of distinctively identifiable feature (Figure 45).

Whenever possible, Method #1 is performed as it guarantees greater accuracy. Either way, two vectors are obtained, each from a different direction (preferably perpendicular for maximum accuracy). The intersection of these two lines corresponds to the marker's location. Once the location of the marker was has been determined, the interface calculates the height of the marker using the Rover's current position, barometric pressure, and tilt of the camera.

To calculate the Rover's elevation, the Rover's current elevation is calculated using the on-board barometer. In order to improve accuracy, the Rover's pressure is compared with the pressure at the base station recorded by another barometer. A region's pressure can vary as the weather changes, but the local pressure will remain fairly similar. By comparing these two pressures, the difference in elevation between the base station and the Rover can be calculated. The base station's elevation is determined from USGS topomaps. This allowed the absolute elevation of the Rover to be determined with good accuracy.

To calculate the landmark's elevation, two more pieces of information are required. An accelerometer mounted on the main driving camera is used to determine the angle between the Rover's position and the landmark. The landmark is positioned in the center of the Rover's display and the angle recorded. Because the camera's angle is measured directly from gravitational acceleration, as opposed to the servo's position, it is not necessary to have the Rover positioned on flat ground to get an accurate measurement. Finally, the software calculates the distance between the Rover's current position and the landmark. Using these three numbers, the landmark's absolute elevation is calculated.

D. Rover Software

The two major Rover software components–the main controller and satellite modules–share similar architectures and reuse much of the same code. A common library was developed to abstract away the differences between the microcontrollers in use. This library implements several data structures, a buffered asynchronous serial interface, and a packet delivery system (built around the serial protocol described in the Communication system). Additionally, a build system was

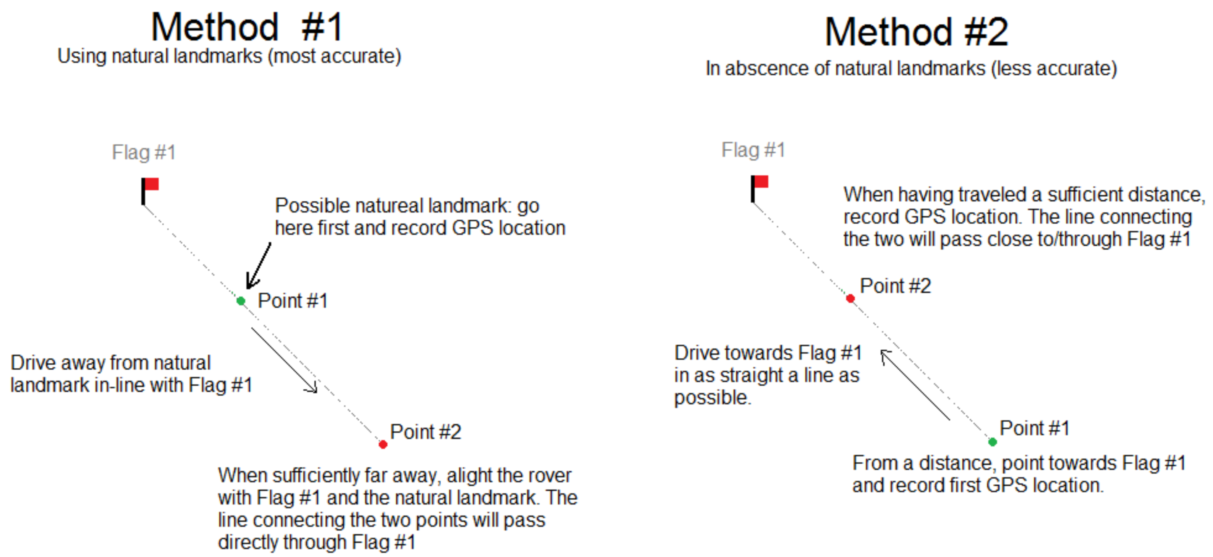

Figure 45. Triangulation methods implemented during the competition. Depending on the availability of natural land marks, one of the two methods is chosen. The user interface uses the data of two line pairs to automatically compute the location of the intersect point.

developed (using Makefiles) to simplify compiling and loading firmware.

1) Main Rover Controller: The heart of the Rover is the AVR XMEGA microcontroller which serves as the main controller. This module's primary responsibility is to route packets from the base station to the appropriate satellite module. Because the wireless link between the Rover and base station may have high latency, the main controller also manages retransmissions to satellite modules in the event that the module does not respond. This improves response time and decreases unnecessary use of the wireless link.

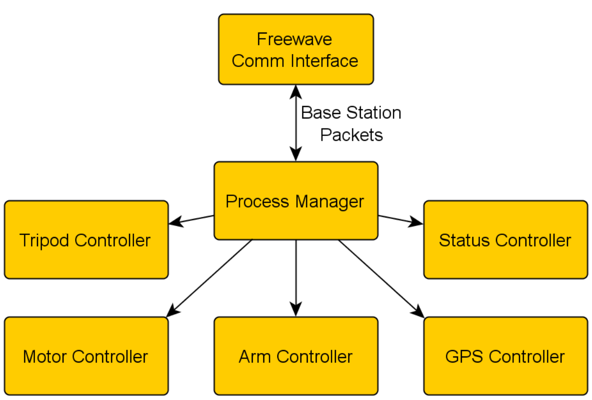

Figure 46. Main Controller Software Architecture

The overall architecture of the system is a simplified version of the Virtual Rover module of the GUI. The Process Manager is the core of the system, processing packets received from the base station (through the packet delivery system described above) and routing them to the correct module. Because the firmware was written is C (instead of C++), function pointers are used to simulate the virtual functions implemented by the Controller classes at the base station. Each module provides two functions, one for handling a base station packet, and one for periodic tasks (which gets called once each time through the Process Manager's main loop). At startup, each module is registered with the process manager, which stores the module's function pointers and target ID (for delivery of packets from the base station).

The complexity of each module depends on what satellite module it interfaces with. Some modules simply act as a pass-through, forwarding messages between the satellite module and base station. Others, such as the motor controller module, are more complex.

2) Motor Control Module: The motor control module is critical to the Rover's operation. It is important that this module was stable, fast, and control the Rover's motion safely. To accomplish these goals, the motor control module implements 3 core features: speed updates, status monitoring, and a watchdog. The module constantly monitors the current used by each motor (by querying the motor controllers), as well as monitoring how many times a motor controller failed to respond to a command. This information was sent to the base station and displayed to the operators. Knowing if a motor is drawing too much current or that a motor has a large number of data failures alerted operators that there was a problem with the drive system. The watchdog system exists to stop the Rover if communication with the base station is lost. If the motor control module does not receive a packet from the base station within a 2 second window, the Rover is stopped.

Because the Rover's 10 motor controllers (6 for drive motors, 4 for linear actuators) are connected on a bus, sending commands to each of these satellite modules is somewhat complex. There are 3 busses (one for each bogie), each with

3 to 4 motor controllers. When a motor controller is sent a command (such as a speed update), it responds, confirming that the packet is received successfully. Because the bus is half-duplex, and in order to monitor the status of each motor controller, the main controller must wait until it receives a reply from the active motor controller before sending the next packet to the next controller on the bus. To accomplish this, the main controller first marks a motor as having a new speed setting. When the motor's bus becomes free (ready for transmission), the speed update is transmitted on the bus. The bus is then marked as in use, and no other motors on the bus may be updated until the motor controller responds or a timeout occurs. Updates may be sent to motors on other busses. If a reply from the motor controller is received indicating that the new speed was successfully set, the motor's last-successfully-set speed is updated and the main controller moves on to updating the next motor on the bus. In the event that the motor controller does not respond and a time-out occurs, the main controller does *not* update the last-successfully-set speed and moves onto the next motor to update. After all other motors on the bus have been updated, the main controller will try again to update the motor that failed previously. This system ensures that all motors will eventually receive the command to update to their requested speed if they are functional, but a disconnected or failed motor controller will not prevent all other motors on the bus from receiving their updates.

E. Suggestions for Future Versions

Several changes could be made to improve the reliability and user friendliness of the system. A majority of these improvements are ones that can be made to the user interface that would either improve the driving experience or with the competition task. A heads-up display for the driver, with information overlayed on top of the video stream, would provide the driver with feedback and guide their driving. Information that would be helpful includes Rover orientation (measured from an accelerometer), heading, current draw of drive motors, and the Rover's driving mode (full speed/half speed, actuated/un-actuated, etc). This display could also be used to display warnings to the driver. For example, a warning could be displayed when the Rover is on dangerously steep terrain and is in danger of tipping. Radio signal strength could be displayed, preventing the driver from unknowingly entering a dead-zone and losing video or data communication with the Rover.

Another improvement to the user interface would be to provide better task assistance. During each competition task, a different user interface screen, specifically tailored for the task, would be active. For example, during the science task, notes could be taken directly into the computer, images could be captured from the video feed, and a LaTeX presentation could be generated automatically, combining the notes, GPS coordinates, and images of each site. This would give the team more time to analyze the returned sample because the presentation would be automatically generated. This interface could also plot data from sensors mounted on the Rover (if any).

Several improvements could be made to simplify and improve the Rover software. Transmission errors (between the base station to Rover and between the Rover and satellite modules) became an issue, and to solve this retransmission systems were implemented for critical systems. Because transmission errors cause performance issues for all modules, this problem could have been dealt with more effectively by making the serial protocol a Reliable Data Transfer (RDT) protocol. A simple acknowledgment system could be built into the communication library which would handle retransmission of lost packets. This would make the Rover's control more reliable, as well as simplify the system's architecture. Individual modules would no longer need to handle acknowledgments and retransmissions themselves, which would result in cleaner code with less duplication.

VIII. Rover Science

A. Overview

The science team conducted research and experiments and directs the Rover operations crew during the sample return task where the primary goal is to find evidence of the presence of life on Mars, past or present. The objective for the team is to investigate several sites using minimally-invasive measurements for evidence of photosynthetic microorganisms, bacterial colonies, or other microbial extremophiles. At each site, at least two pictures are required: one, a close up high-resolution picture and the other, a wide-angle panorama. In post-processing of the pictures, cardinal directions, GPS coordinates, elevation, scale, and accuracy range need to be indicated. The Rover must collect and return a single sample of rock or soil weighing no less than 25 grams and no greater than 250 grams. At the base station, additional tests are allowed for the collection and analysis of data to be put into the field briefing for the judges. The various scored elements of the task are the thoroughness of the site investigation, quality and applicability of the analysis aboard the Rover, sample quality, and quality and applicability of the analysis of the sample performed at the base station.

B. Research

Research conducted prior to competition was concentrated around the local distribution and structure of biological soil crusts and types of soil analysis. Biological soil crusts are colonies of various microbial extremophiles, such as bacteria, lichen, etc., that exist within the top few centimeters of desert soil. The microorganisms found in these crusts are believed to be the link to how early life formed and survived on Earth and possibly to how life exists on Mars.

The science team researched the types of soils located in southeastern Utah. We contacted the Oregon State University's Crop and Soil Science Department and acquired samples of several relevant soil types for testing purposes. One experiment included placing the samples in a terrarium simulating desert conditions. The purpose of this experiment was to track soil microorganism activity. The time frame of this experiment did not allow for any detectable activity, however, we were able to use samples to create a calibration curve for our instruments.

C. Instruments

During the exploration of the competition site with the Rover, the science team utilized the main camera for visual analysis. It was a non-invasive, effective, and time-efficient method for surveying multiple sites for living organisms since there are distinct topographical and coloration differences between soil rich with microbial life and barren soil in the desert in that area. The secondary cameras, although not as high in quality, were useful for investigating potential sites out of the physical range of the main camera.

Figure 47. ALTA II Reflectance Spectrometer

The returned soil sample is analyzed with four different instruments: the ALTA II Reflectance Spectrometer (Figure 47), FieldScout Direct EC Probe (Figure 48), a microscope, and a pH meter. The ALTA II Reflectance Spectrometer was used during the previous competition year and showed to be very useful and applicable. The accuracy of the instrument, however, was unable to be determined, so the collected values are used qualitatively. Reflectance spectrometry is used on NASA probes and satellites as it is noninvasive and the data allows for determination of chemical property. For our purposes, it is used to differentiate soils with photosynthetic biological matter from barren ones. It is a hardy instrument that is simple to calibrate.

Figure 48. FieldScout Direct EC Probe

Another soil property measured is electrical conductivity using the FieldScout Direct EC Probe. To use this instrument, we used the soil samples supplied to us from the Crops and Soils Science Department to make a calibration curve. Since electrical conductivity is affected by free ions, organic material, as well as several other factors, we included these into our calibration curve in order to differentiate between varying conductive conditions.

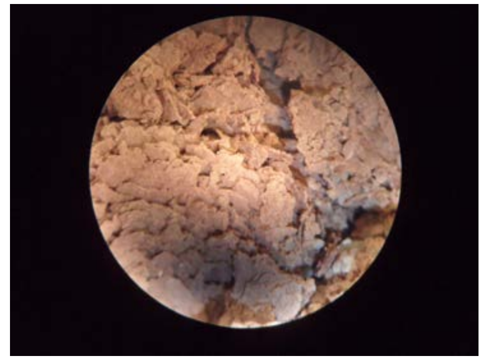

Figure 49. Microscope image of soil sample

When the sample is returned to the base station, we use a microscope to make additional visual observations. Biological crusts have a distinct rough texture compared to barren soil. Visual evidence was also very useful, especially if a potential microbial specimen was on a rigid material, such as a rock, where the EC Probe is rendered unusable within the time frame of the competition.

The last instrument is a pH meter. Although the microorganisms in biological soil crusts are capable of surviving extreme temperatures, they are sensitive to the chemical conditions of the soil. The pH meter is used to provide data supporting the potential for living organisms in the soil.

D. Recommendations for future work

With the success of the team this year there are several improvements that can be made relating to the science team. A large difficulty this year was finding instruments for soil analysis that were sturdy enough to be handled in the field under uncontrolled conditions and still able to give precise and accurate results. The soil electrical conductivity probe was very difficult to decide upon as most are for use under more temperate and stationary conditions. Reviewing detailed data sheets when comparing instruments would have more quickly removed those that were inapplicable for the rugged conditions of this competition. Along these lines, it will be important to research analysis methods that can detect dormant and deceased microorganisms. NASA is a good source for inspiration as the analysis methods on their probes are both rugged and sensitive.

Upon the competition judges suggestion, a more rounded approach for the search of life could be employed. The competition rules suggest many approaches. However, our approach focused on finding samples excluded those that may be in dry river beds and streams. It should also be noted that the competition site this year lacked many natural samples so the judges planted several samples.

IX. Team Management

Because the design of a robotic vehicle requires a team of multiple disciplines (for example, OSU's 2010 and 2011 teams had electrical, mechanical, software, and science disciplines), it is essential that these disciplines work together to achieve the common goal of building a robotic vehicle. For this reason, it was extremely valuable for there to exist some form of team management.

A. Organization

The primary means in which team organization took place during the 2010-2011 academic year was through weekly design reviews, in which all team members came together to review the progress over the previous week and evaluate the progress of designs based on their potential to help meet the design requirements set by both our team as well as the 2011 URC Requirements and Guidelines. The latest version of the CAD model was displayed on a large projector screen to make it visible to everyone; this greatly reduced the number of surprises experienced during assembly and testing. Such transparency in the design process allowed the electrical and mechanical systems to be designed to complement one another wherever possible, reducing weight, cost, and complexity. In addition to the weekly team meetings, each design group (electrical, mechanical, software, and science), held its own meeting in which more complex issues were discussed that were not relevant to the other groups.

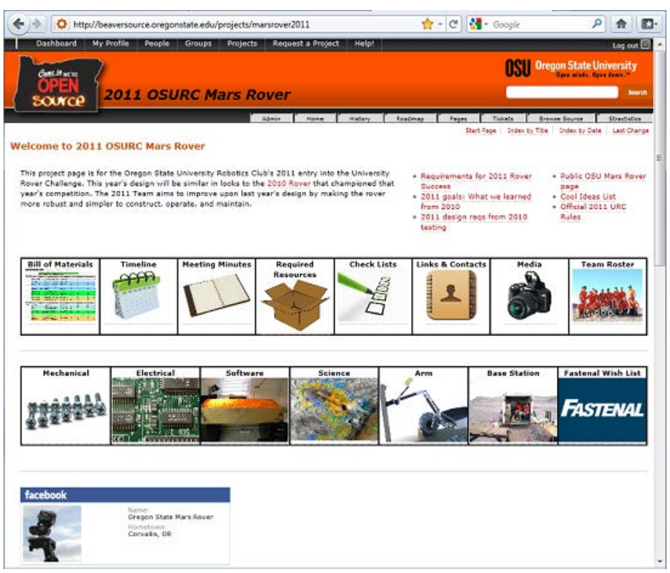

Figure 50. The front page of the Beaver Source wiki page used by the team to organize technical data for the rover design. The wiki can be easily updated by any member of the team.

An additional means in which the team kept track of design progress is through a wiki website, where any of the team members can upload pictures, schematics, descriptions, etc. to continuously document design progress from any location. This website featured a schedule with all major deadlines, documentation for each of the design groups, a bill of materials used to keep track of expenses, order parts, and monitor the value of the rover (which was to remain below $15,000 as set by the 2011 URC Requirements and Guidelines), and numerous other useful functions.

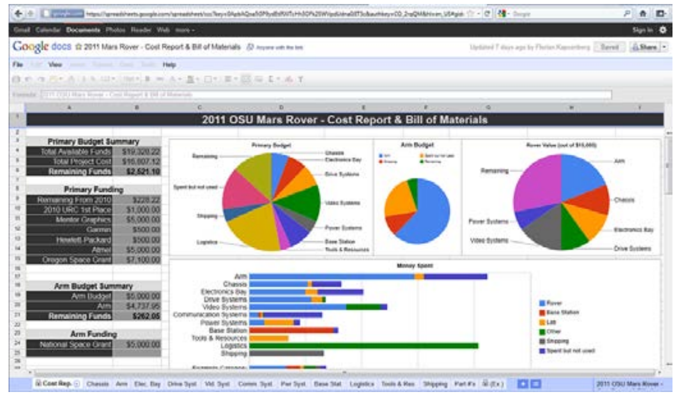

Figure 51. The summary report page of the Bill of Materials (BoM) for the rover project. Summarized here are current spending allocations compared against available funds categorized into subsystem spending and useful versus waste expense. The BoM is a Google document which is easily accesable by any team member and is updated in real time.

One key component of the team structure was the existence of a separate design team for the robotic arm. This team was composed of fourth-year students that volunteered to take on this design challenge as part of their capstone project, an academic requirement set by the university for all engineering students. More regarding the specifics of this project is provided in Section V of this report.

B. Schedule

The schedule followed by the team was driven primarily by the desire to have at least one third of the time devoted to testing and optimizing the design after assembly. This meant that the first three months of the academic year (fall term) were devoted nearly exclusively to design, and the next three months (winter term)were devoted to manufacturing and assembly, leaving spring break to complete the assembly and begin testing the rover's primary systems, leaving spring term solely for testing the systems, improving reliability, and practicing for the competition.

Though one of the goals of the team was to create the opportunity for real design experience, any designs that fell behind schedule or went over budget and had an existing commercial equivalent product were scrapped in favor of the commercial replacement. This strategy allowed the maximum amount of design experience while still ensuring the project stayed on schedule, on budget, and would meet the overall competition requirements.

C. Sponsorship

Because this project required significant material resources, it was vital to find support in the form of donated products as well as financial support. At the beginning of the academic year after some initial design concepts had been explored, a conservative budget estimate was created to estimate the team's expenses. These costs included component costs, manufacturing costs, the cost of additional tools and lab equipment, and logistical expenses such as travel and lodging.

For most of the required components on the 2011 Mars Rover, vendors were contacted and asked if they would be willing to sponsor the team by donating the required components. In some cases, companies were willing to donate the products and provide additional financial support, covering the costs of non-donated components and logistical expenses. In return for the donations, all sponsors received publicity proportional to the combined value of their respective donations. This dictated the size and visibility of logos on the rover and banner, as well as how frequently and to what extent the contribution of these sponsors was highlighted at public events. Sponsors were also provided with monthly updates that allowed them to follow the team's progress leading up to competition. Often sponsors would have questions in which case these were answered as quick and thoroughly as possible. Many of the sponsors have expressed their appreciation for these regular updates, as it allowed them to understand better how their donation were being put to use. The support provided by each of the team's sponsors was vital to the team's existence, and has been sincerely appreciated. The sponsors of the 2011 OSU Mars Rover team are featured in the Acknowledgments Section.

X. Publicity

Another major task in team management was creating public awareness of the team's goals and progress, as well as the URC. Numerous events were organized and attended throughout the academic year including (but not limited to) the following:

Figure 52. Public demonstration of the Rover at Martin Luther King Jr. Park, Corvallis on Saturday 5-14-2011

- Presentation at 2010 Mars Society Conference in Dayton, Ohio
- Showcase at the 2010 Engineering Awareness Week, OSU campus
- Main stage showcase at the 2010 OSU President's Dinner in the Portland Art Museum
- Presentation and showcase for Dr. Steven Sqyres: lead scientific investigator for NASA JPL Mars Rover Program (organized by our team) OSU campus
- Showcase at the 2011 Oregon Stater Dinner in CH2M Hill Alumni Center, OSU campus
- Presentation at the Jet Propulsion Laboratory (organized by our team) Pasadena, Calafornia
- Presentation and showcase at the 2010 NASA Student Symposium
- Showcase at the 2010 Willamette Innovators Night in CH2M Hill Alumni Center, OSU campus
- Showcase at the MECOP Banquet (a dinner for representatives of all companies involved in OSU's MECOP internship program) Portland, Oregon
- Presentation and showcase at the 2010 OryCon science fiction convention in Portland, Oregon
- Showcase at the 2011 First Tech Challenge (a high school robotics event) at OSU
- Showcase at OSU Day at the state capitol where our team met with state representatives. Salem, Oregon
- Showcase at the 2011 Business and Education Showcase at Union Bank, Portland, Oregon
- Showcase at 2011 Celebrating Undergraduate Excellence event, OSU Campus
- Showcase at the 2011 OSU Engineering Expo, Kelly Engineering Center, OSU campus
- Public competition rehearsal and barbeque (organized by our team) at Martin Luther King Jr. Park, Corvallis (Figure 52
- Showcase at the 2011 Roboshock event (organized by the OSU Robotics Club) on OSU campus

These events allowed our team to encourage students to pursue an education in science and engineering, educate the public about what happens behind the scenes at Oregon State University, and make the Mars Society's cause more public.

A. Online Videos

During the year many videos have been placed into the public domain showcasing the Rover. The following is a list of the available videos uploaded by the team.

1) *First Drive Test:* http://youtu.be/X8bE421G5Eo

2) *Weekend 2011 OSU Mars Rover Field Test:* http://youtu.be/0oWxxAtxQUI

3) *OSU Rover Field testing (first arm field test):* http://youtu.be/5ebWqZvKp9c

4) *Arm Linear Movement Test:* http://youtu.be/hf80mZG_UXI

5) *Robotic Arm Lift Test:* http://youtu.be/6kdYeLFP4d0

6) *Rover Push-up:* http://youtu.be/z98TlvkxLuM

7) *Rover + Arm Oscillations:* http://youtu.be/W29U-9nKkiI

8) Robotic Arm Mechanical Engineering Tests: The following video shows the tests performed by the Arm Senior Project Mechanical Team to satisfy in class customer requirements. All tests are developed by the senior project team and are used to evaluate the students project for a class grade. http://youtu.be/HxJb_k-gnqg

9) Robotic Arm Electrical Team Engineering Tests: The following videos show the tests performed by the Arm Senior Project Electrical Team to satisfy in class customer requirements. All tests are developed by the senior project team and are used to evaluate the students project for a class grade.

Final tests http://youtu.be/8Mv69LKBR78

Arm stowing http://youtu.be/_zIt2RM_IlY

Limit indication http://youtu.be/7T9efPqCRPk

Motor current test parts 1 & 2 http://youtu.be/wri7wUUxo1k and http://youtu.be/_ErenB56CmM

Position reading http://youtu.be/sYpUBD3pnAM

Bush test http://youtu.be/ekb_i3En_eg

Current Test http://youtu.be/JSOPmgVjvok

Straight line drawing test http://youtu.be/2c9edoa--mk

XI. Rover Cost Report

As stated at the beginning of this report, the value of the Rover is to be no greater than $15,000. This requirement is met. Figure 53 shows the top level break down of the cost report submitted to competition. It should be noted that this cost report is to include any base station equipment used to communicate with the Rover. The total value of the 2011 OSU Mars Rover is $12,914.

2011 Oregon State Mars Rover Financial Report		
Total Rover Systems Value:	**$12,913.17**	
Date:	May 27th, 2011	
Rover	$11,559.79	Rover Total
Electrical Sub-Total	$6,304.08	
Power Systems/Cooling	$1,560.45	
Connectors and Wiring	$324.97	
Mainboard	$140.97	
Rover Communications Equipment	$1,177.15	
Drive Systems	$1,982.33	
Video and Tripod Systems	$717.00	
Arm Electrical	$401.21	
Mechanical Sub-Total	$5,255.71	
Chassis/Wheels	$1,095.72	
Tripod Mechanical	$717.42	
Housings/Mounts	$768.24	
Arm Mechanical	$2,674.32	
Base Station	$1,353.38	Base Station Total
Base Station Sub-Total		
Base Station Communications Equipment	$1,353.38	

Figure 53. Cost report summary as submitted to the URC before attending competition

Acknowledgments

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