UTA Rover Team Final Report

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1 Introduction

The UTA Rover team has worked over the past few months on the design and production of a planetary rover for the Revolutionary Aerospace Systems Concepts Academic Linkage (RASC-AL) Exploration Robo-Ops (ERO) competition. The rover's tracked base, chasis, and manipulator arm have undergone multiple design iterations to ensure that the rover can achieve the competition objectives. Each of these major components should be tested to evaluate its performance. The strength and durability of the end-effector for effective manipulation of rocks, the control algorithm for communication with the rover over a wireless broadband network, and the ability for the tracked rover to traverse terrain with soft dirt and rocks to simulate the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) Rock Yard are only some of the testing environments used. The team has also made efforts to inspire and educate the public, in particular kindergarten to twelfth grade (K-12) and university students about current and future space exploration.

The remainder of the report is organized as follows. A description of the rover with design specifications and drawings will be presented, followed by the details of the materials and processes used for producing all the components. Details involved in testing some of the key features of the rover design will be given. The report ends with a description of the education and public outreach activities performed.

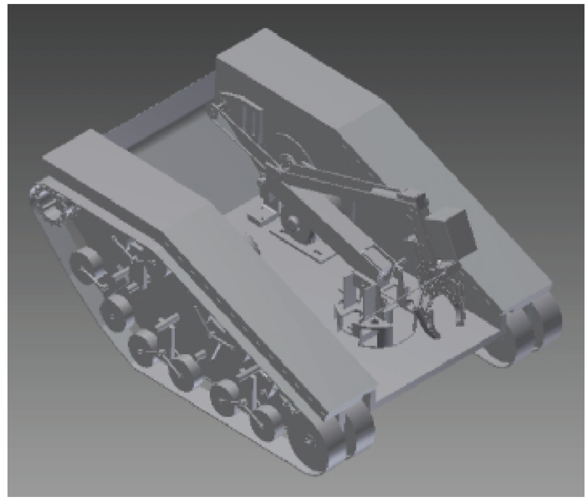

Figure 1: Isometric view of the complete rover.

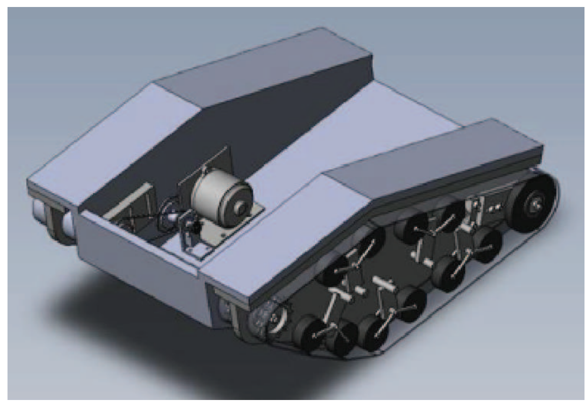

Figure 2: Isometric view of the tracked base.

2 Rover Design

The planetary rover designed for this competition is a tracked vehicle, as in Figs. 1 and 2, that can provide improved route flexibility, cross country mobility, traction on slopes, volume and payload weight distribution, maneuverability on sand [req6], and gap and obstacle crossing. A manipulator arm, shown in Figs. 1 and 3, will be mounted toward the back of the rover but still near its center of mass. Other components such as the drive motors, electronics, and batteries will be secured inside of the chassis and packaged to prevent contamination. A rock collection bin will be positioned at the rear of the rover.

The rover measures about 0.80 m in length, 0.45 m in height, and 0.50 m in width in its stowed position, which satisfies the design requirements [req1]. The clearance below the body is 0.12 m [req3]. It was designed to have a low center of gravity to prevent instability while traversing 33% grades [req4]. The next sections describe the key components of the base and the manipulator arm.

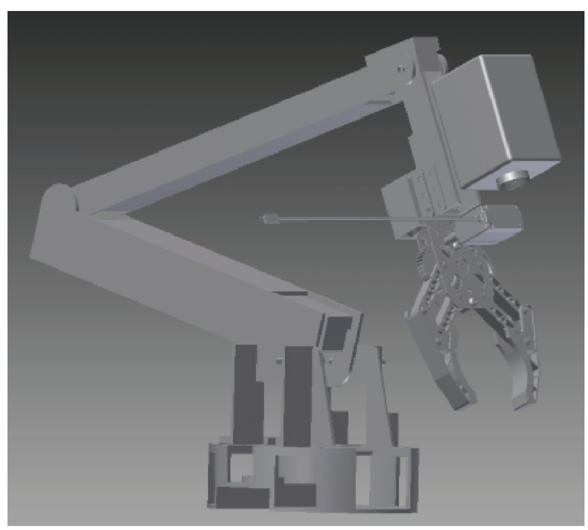

Figure 3: Isometric view of manipulator arm.

2.1 Tracked Base

The base rides on two sets of tracks on each side of its body, with 10 mm of separation between them. The tracks are held in place by a "T-joint" plate. Each track will have two large wheels and five bogies with smaller wheels, as in Fig. 4, that will provide tension on the track as well as suspension for the rover. This plate has slots for the bogies, which are fastened to the wheels and other moving components. The large front wheels are driven by two independent direct current electric motors, while the back wheels are passive.

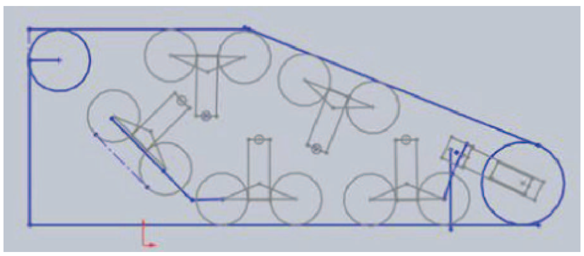

Figure 4: Side view of the tracked base design.

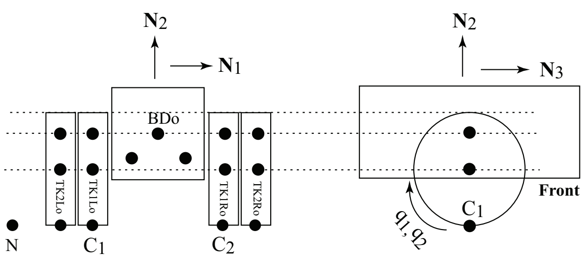

Figure 5: Simplified base model.

A dynamic simulation of a simplified tracked base, shown in Fig. 5 was used to select the drive motors, one of which is shown in Fig. 2, to insure that the platform can climb the required grade. The tracks are modeled as four wheels. However, since each track on both sides will move at the same speed, only two point contacts with the slope, at C_1 and C_2 in Fig. 5, are modeled. The wheels are assumed to experience pure rolling on the slope. Estimates of the mass properties of all four tracks, the chasis, and the drive motors are included in the model. The total mass of the system was approximated at 45 kg, and no friction was modeled. The mass center of the chasis is labeled 'BDo', and the mass center the tracks are 'TK1Lo', 'TK2Lo', 'TK1Ro', and 'TK2Ro'. The unit vectors $\mathbf{N}_2$ and $\mathbf{N}_3$ in Fig. 5 are parallel to the slope.

The dynamic model of the base has the form

$$A(\mathbf{q})\ddot{\mathbf{q}} \; + \; \mathbf{b}(\dot{\mathbf{q}},\mathbf{q}) \; + \; \mathbf{g}(\mathbf{q}) \; = \; G^T \mathbf{\Gamma} \qquad (1)$$

where $\mathbf{q} = [\mathrm{q}_1 \;\; \mathrm{q}_2]^T$ is the vector of generalized coordinates which represent the rotation of the tracks on each side of the vehicle. The vectors $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$ are the generalized velocity and acceleration, while $\mathbf{b}(\dot{\mathbf{q}},\mathbf{q})$ and $\mathbf{g}(\mathbf{q})$ are vectors of nonlinear velocity and gravity terms. The terms A and G^T are the mass and gear transmission matrices. The vector $\mathbf{\Gamma} = [\Gamma_1 \;\; \Gamma_2]^T$ contains the pre-gear motor torques that drive the base.

A controller was also simulated in order to find the actuator torques required to climb the slope:

$$\mathbf{\Gamma} \;=\; G^{-T} \, (\, A(\mathbf{q}) \, \mathbf{\Gamma}^* \; + \; \mathbf{b}(\dot{\mathbf{q}},\mathbf{q}) \; + \; \mathbf{g}(\mathbf{q}) \,) \qquad (2)$$

$$\mathbf{\Gamma}^* \;=\; \ddot{\mathbf{q}}_d \; + \; K_v \, (\dot{\mathbf{q}}_d - \dot{\mathbf{q}}) \; + \; K_p \, (\mathbf{q}_d - \mathbf{q}) \qquad (3)$$

where the d subscripts indicate desired quantities and K_v and K_p are diagonal gain matrices. This controller is referred to as the computed-torque method which is well-known in the field of robotics. Software referred to as "Autolev" was used to develop the equations of motion. This software also has an automatic code generation feature that outputs simulation code formatted as a Matlab ".m" file.

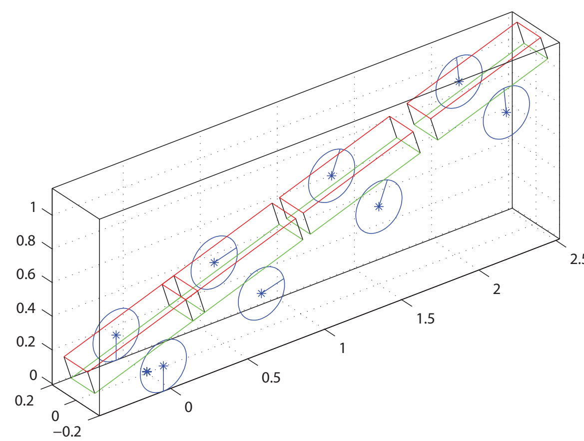

Figure 6: Simulation of base. (units=meters)

The base was simulated moving straight up an incline of 18° and coming to a stop on the incline. This scenario should require the maximum output from the drive motors. The simulation code was run in Matlab using an adaptive numerical integrator `ode45.m`. A motion capture from a Matlab animation of the base is shown in Fig. 6.

The torque and power obtained from (2) during the simulation is shown in Figs. 7 and 8. The maximum speed up the incline for this simulation is $0.43 m/s$ $(0.96 mph)$. The chosen motor is rated at 750W, 2600 RPM, shown as the dashed curves in Figs. 9 and 10, plotted against the required torque and power in Figs. 7 and 8. In Figs. 7-10, the requirements on both motors are identical so only a single

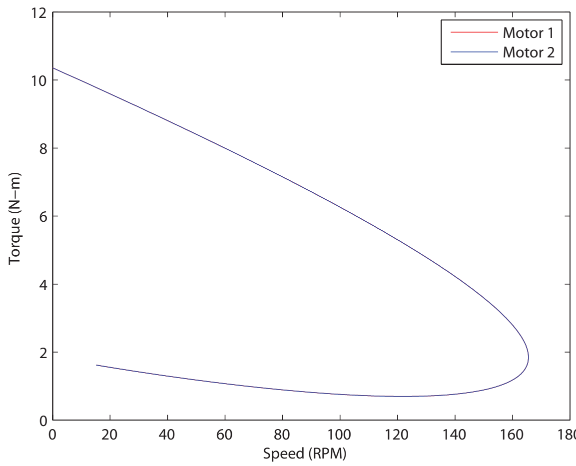

Figure 7: Base torque vs. speed.

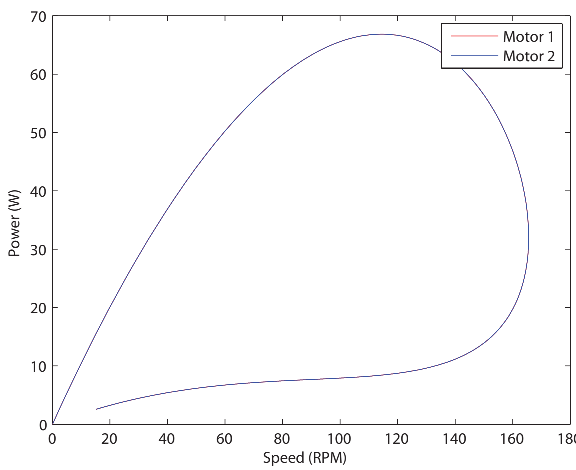

Figure 8: Base power vs. speed.

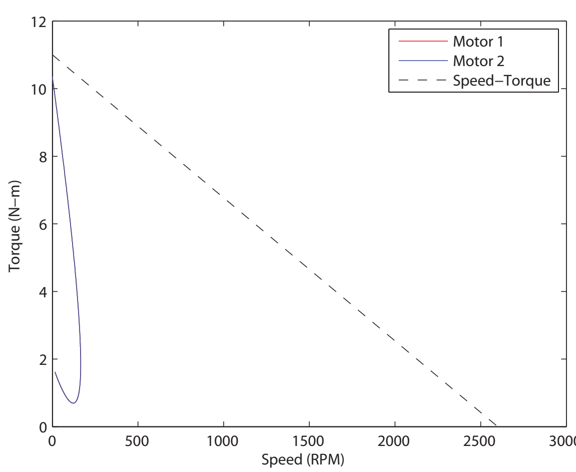

Figure 9: Available base motor torque.

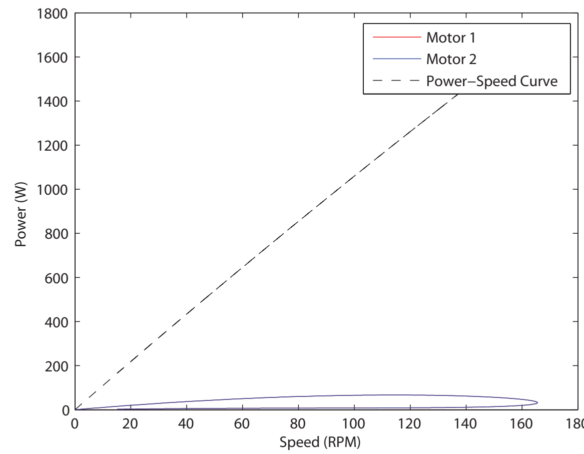

Figure 10: Available base motor power.

line appears. Although the initial torque requirement is high, usually it is far from the peak torque. The speed required is never near the maximum rotational speed. Thus this motor should be able to accomplish the mission. However, the speed of the base can be reduced if unmodeled aspects of the base and the environment increase the torque requirments.

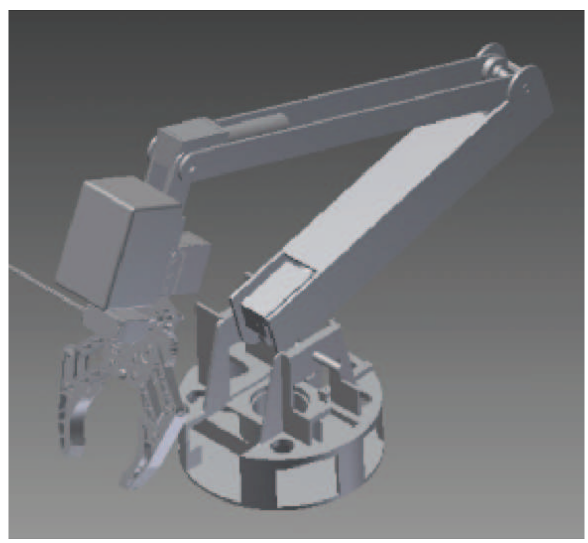

Figure 11: Additional view of manipulator arm.

2.2 Manipulator Arm

The manipulator arm shown in Figs. 3 and 11 was designed to provide enough dexterity and control to pick up objects. It can be extended to provide a workspace of 0.60 m from the rear of the rover. The arm has four degrees-of-freedom (DOFs). The base of the arm rotates about a vertical axis almost 360°. The other three DOF are formed by two links and

Figure 12: Gripper.

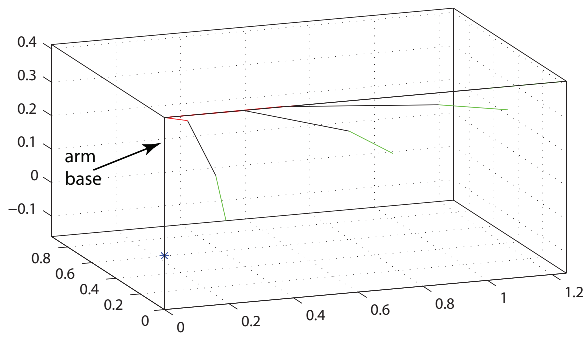

Figure 13: Simulation of arm. (units=meters)

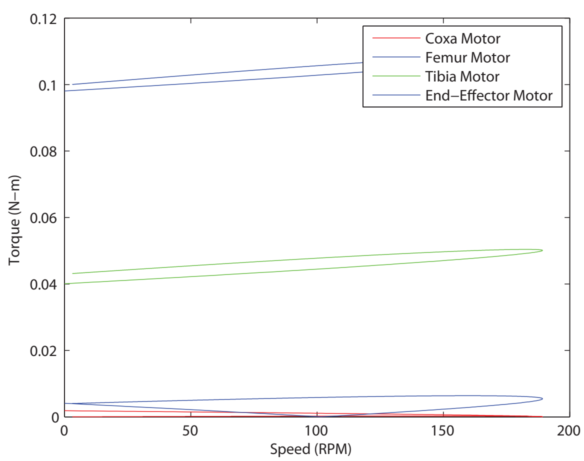

Figure 14: Arm torque vs. speed.

an end-effector with revolute joints. This allows the manipulator to pick up and place rocks into its collection bin. In addition, the manipulator can be used to shift the rover's center of gravity when traversing sloped terrain.

A color, box camera [req5.2] is mounted on the end-effector as shown in Fig. 11. This allows a wide field of view without moving the rover. The camera and other sensor data, such as its position and orientation, will be fed to an onboard computer to allow for accurate movement. The end-effector, shown in

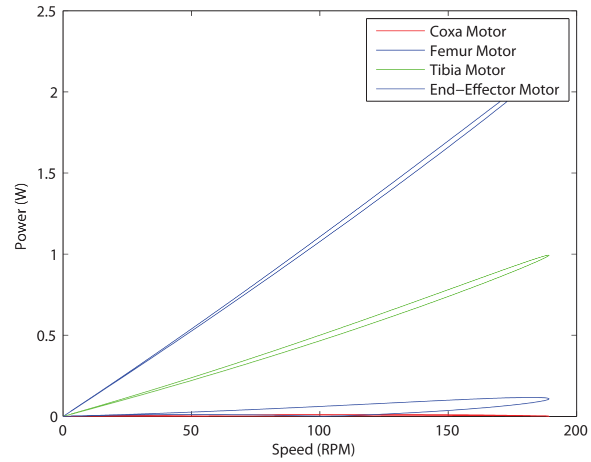

Figure 15: Arm power vs. speed.

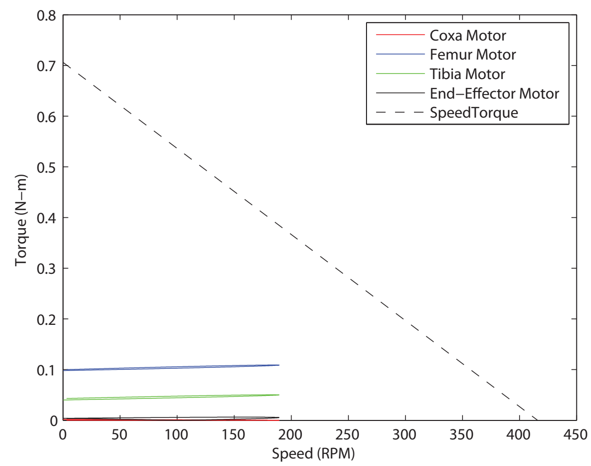

Figure 16: Available arm motor torque.

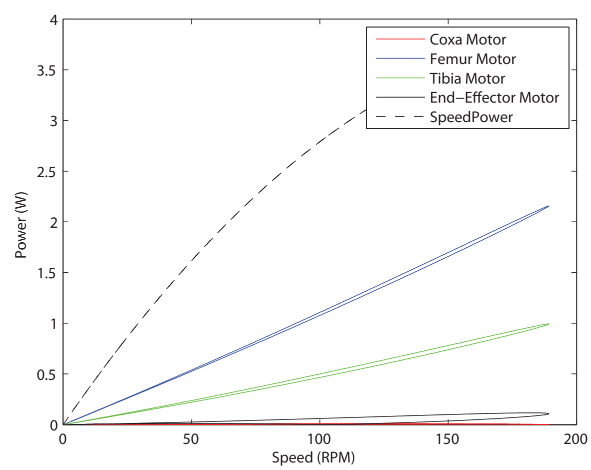

Figure 17: Available arm motor power.

Fig. 12, is a two prong gripper purchased from VEX

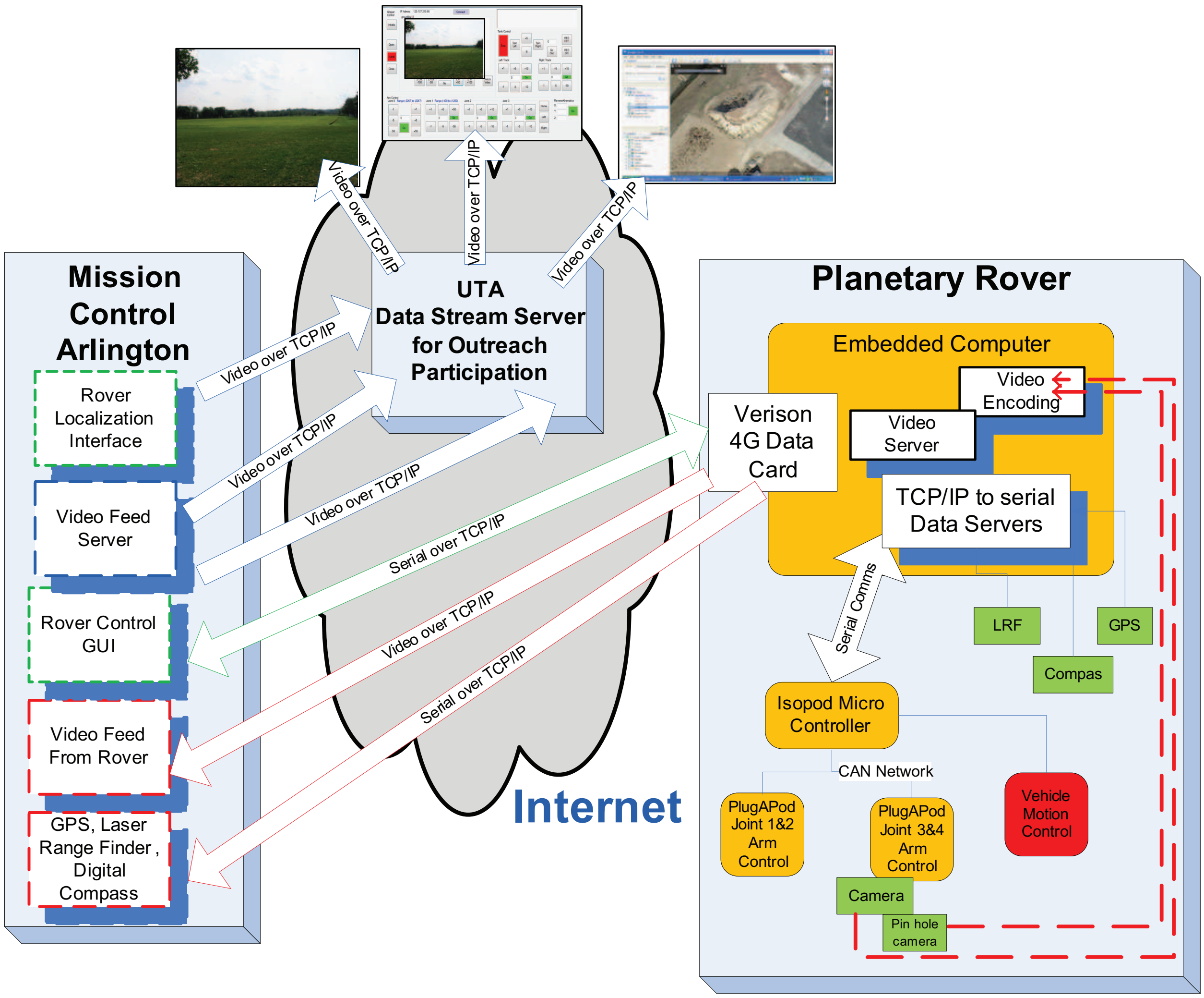

Figure 18: System control architecture.

Robotics that can manipulate rocks up to 9 cm in diameter and having a mass up to 175 gm [req5.1].

A motor sizing analysis was performed for the arm similar to what was done for the base drive motors. The equations of motion for the fixed-base arm were developed and had a form similar to (1). However, $\mathbf{q} = [q_3\ q_4\ q_5\ q_6]^T$ and there are four motor torques. The mass properties of the arm and all components attached to it, including motors, were included in the model. A computed-torque method controller, (2) and (3), was simulated to generate motor torque data.

The simulated movement of the simplified arm is shown in Fig. 13, where it moves from the back of the rover to the ground to pick up a rock. The required torque and power for this motion are given in Figs. 14 and 15. The identical motor is used for each joint and its capabilities are plotted as dashed lines in Figs. 16 and 17 which show there is plenty of motor capacity beyond what is required for the mission.

3 System Control

The System Control Architecture in Fig. 18 can be broken down into three major sub-systems: planetary rover controls, the Mission Control Arlington (MCA) command and control facility, and the UTA Data Stream Server that will be responsible for hosting three live video feeds generated during UTA's RASC-AL operations at the JSC. The first video stream will be of the raw video footage captured by the rover. The second will be an image of the vehicle control interface that will be used by the MCA team to drive the vehicle and operate the robotic arm. The third will be of MCA Rover Localization Interface that will update the rover's location while performing the mission. Each of the three major sub-systems will be described in greater detail below.

A pair of joints are controlled by a Motorola-based microcontroller. Numbering from the base to the

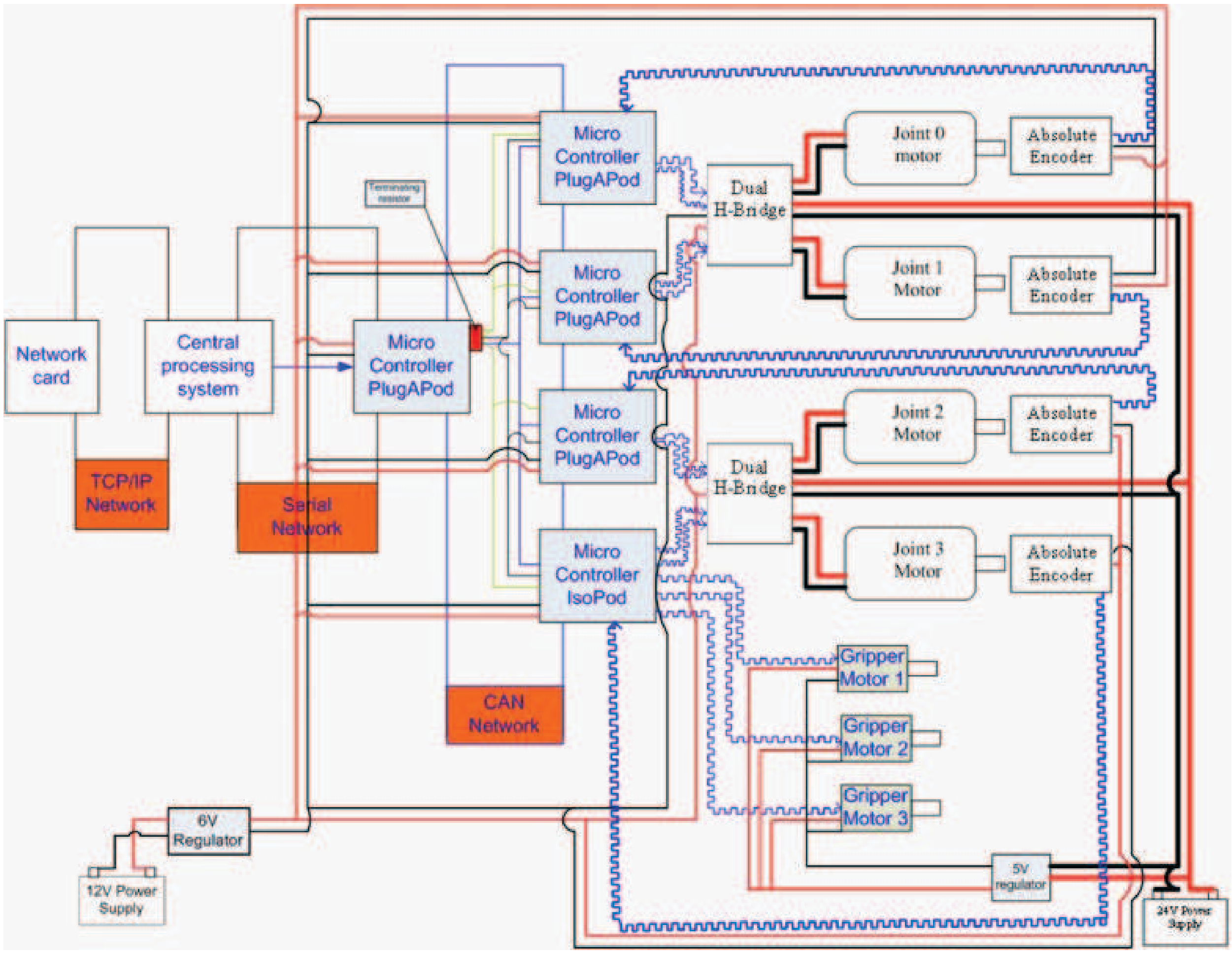

Figure 19: Wiring diagram of rover arm and gripper.

tip, joint 0 and 1 are controlled by one microcontroller, and joint 2 and 3 are controlled by a second. Each joint will also include an absolute encoder that provides feedback on the position of the arm. Each microcontroller is encoded with PID controllers that output a Pulse Width Modulation (PWM) command signal to their respective joint motors. Each of these controllers is also programmed to wake up when power is turned on, thereby requiring less programming knowledge from the user, Fig. 19. Microcontroller level programming also includes the ability to listen to mid-level programming, i.e. Controller Area Network (CAN) protocol. The CAN protocol provides the link between multiple low-level microcontrollers and the mid-level microcontroller.

The mid-level controller provides a link between microcontroller-based programming and higher level programming, Fig. 20. It consists of three major components:

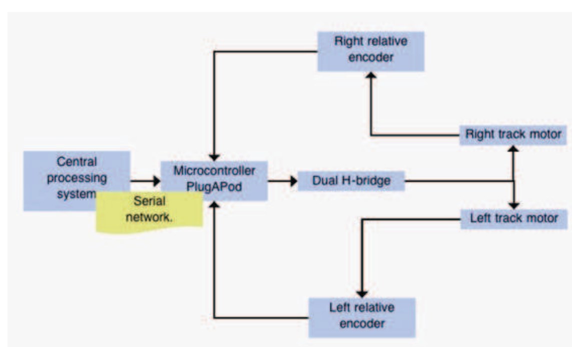

Figure 20: Rover track control flowchart.

Higher level Communication This component listens to higher level commands through a serial port and distinguishes these commands as CAN or drive wheel commands.

Drive wheel command protocol This section sends PWM signals to the H-bridge which controls the drive wheels. These drive wheels are also connected to independent relative encoders to provide feedback on their speed and position.

CAN command Protocol Here, arm control commands are processed and transmitted through the CAN bus.

The mid-level microcontroller is connected to the Windows XP embedded PC which handles higher level communications. At this level the camera data is processed and the main communication link with the Verizon data card is established. The PC runs multiple servers, as in Fig. 21 namely: the camera server, camera control listener, control listener, and accessory feedback listener.

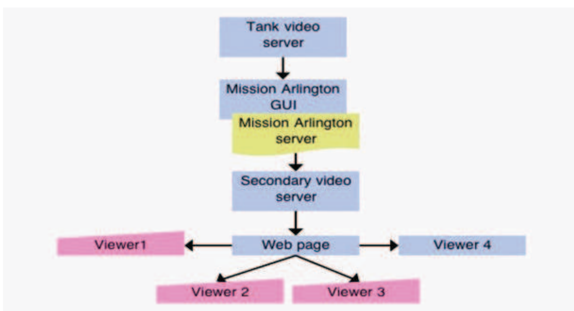

Figure 21: Video output flowchart.

The camera server provides a live video feed to the MCA GUI. The MCA PC will also be running a live video server but it will be transmitting the live screen capture of the video feed and the GUI control. This will reduce the load to the limited bandwidth provided by the Verizon data card in case of multiple hits on our website. This video will be captured by a secondary server and then transmitted to our website. This will reduce the bandwidth issue due to multiple hits on our website and reduce any risk of video delays to MCA.

The camera control listener provides a communication link from MCA, as in Fig. 22, to the rover to control the camera. This program listens to a predetermined port of the telephony network to redirect control commands to the camera on the rover through the VISCA command protocol. The control server provides the main communication through the telephony network to control the rover and the arm. This program also listens to a different predetermined port to redirect the commands to the rover to control its motion and the arm. An accessory feedback listener is also listening to a predetermined port on the rover that gathers various data like GPS data, Compass data and laser range finder (LFR) data, and transmits the latest recovered data to the Mission Control Arlington GUI only when requested, reducing the bandwidth usage.

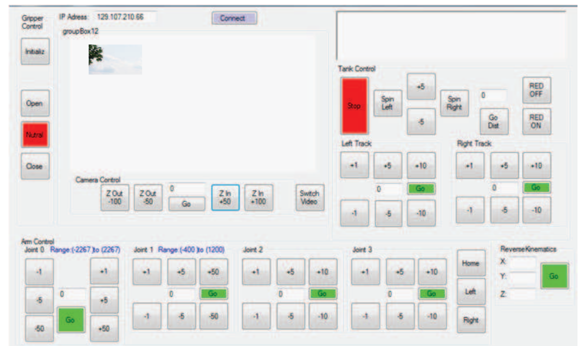

Figure 22: Mission Control Arlington platform control user-interface.

4 Fabrication

4.1 Rover Body and Tracking

The majority of the body will be manufactured using pre-preg fiber glass. There are two layers of fiber glass with Blown PVC plastic foam in the middle. The foam provides rigidity and strength. The various parts of the body will be made individually, cut using a laser cutter, and connected like a jigsaw puzzle. Keeping this in mind, the contact area is designed to have extrusions to account for assembly.

The wheel components are fabricated with a 3D printer which uses ABS plastic as the raw material. The designs for these components are loaded into the Dimension 3D printer in .STL format which stands for stereo lithography. The printer head is then allowed to warm up to 240°F at which point the material starts purging out in a systematic layer pattern. This 3D printer uses two sets of materials: one is for support and the other is the build material. The process usually takes 6 to 24 hours depending on the resolution, complexity, and size of the object.

4.2 Manipulator Arm

The manipulator arm is made using rapid prototyping material and a carbon fiber composite. The first joint, or base of the arm, is rapid prototyped for quick and easy manufacturing. The link on which the gripper is mounted on is also rapid prototyped. The production of a rapid-prototyped part is a relatively simple procedure. First, a solid model of the desired part is made using the solid modeling software Autodesk Inventor. The file type is then converted to an .STL file so that the part can be fabricated using the Dimension 3D printer.

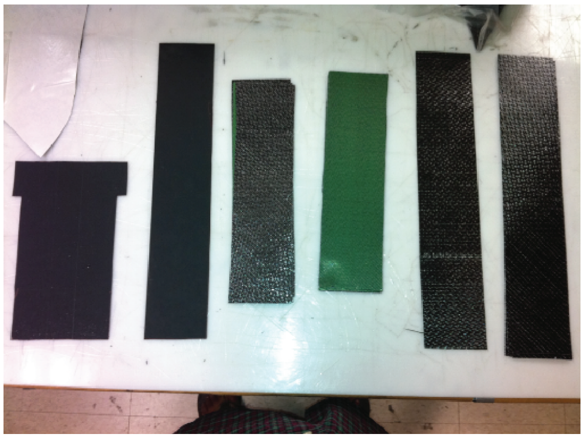

Figure 23: Templates of the arm links used for fabrication.

The remainder of the arm is fabricated using carbon fiber composite. This process is more complicated than rapid prototyping. For the production of any part with carbon fiber, first a mold is needed to wrap the layers of carbon fiber around it. The mold is generally made of aluminum. This mold should be able to resist temperatures of 350°F without alteration in its properties. This provides a solid base for the carbon fiber to cook in. The mold is then cleaned with acetone, followed by the application of sealer and resin. Once this is done, the mold is ready for the carbon fiber to be added, layer by layer on top of it.

A template is created of the flat shape of the final object as shown in Fig. 23. This template is traced in the carbon fiber rolls and similar shapes are cut at 0° and 45°. After the carbon fiber is cut in the desired shape, they are applied over the mold, generally on three sides. This is done to conveniently remove the part once it is ready. The mold with the carbon fiber is wrapped in a blue sheet of paper, and multiple components are vacuum bagged and ready to cook. The carbon fiber used is of grade 350. This means the fiber will cook and harden at that temperature. Once vacuum bagged, the whole bag is put in an autoclave where it is cooked at 355°F and 85 psi. At a high pressure and temperature, the carbon fiber hardens. Its strength depends on the number of layers used but the process ensures the finished product, similar to what is shown in Fig. 24, is light-weight and strong.

For the second link, 2 C-channels were made with an additional thickness near the joints. For each C-channel, 3 layers of grade 350 carbon fiber were used. The layers were at 0°, 45°, and 0°, respectively. The ends of the part had 4 additional layers for improved strength as these were high stress points. The two C-channels were then glued together to give excellent resistance against torsion. The third link is longer and slender and made up of one C-channel that is 15 inches long and a second one along its body that is 11 inches long. The two C-channels were glued together similar to the second link. Once manufactured, a dremmel tool was used to smooth the edges and achieve the desired dimensions. All other parts in the rover were purchased off-the-shelf or donated by the Autonomous Vehicle Laboratory (AVL) at the University of Texas at Arlington.

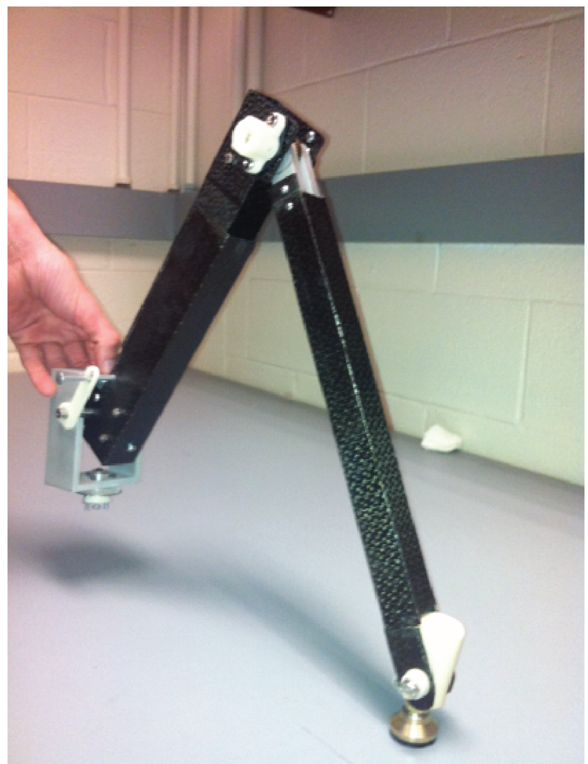

Figure 24: Fabricated manipulator arm using carbon fiber.

5 Testing

The remote operation of the rover will be tested in order to gain experience with the Verizon data card and to verify the control protocols required to command the rover. The rover will be taken to a remote site and commanded from Woolf Hall in order to debug the system.

5.1 Tracked System

The Doug Russell Park, as seen in Fig. 25, located on the UT Arlington campus will be used to continue testing of the rover. This area was chosen after the careful consideration of all the anticipated challenges in the terrain for the competition. It was a viable option to choose this park because of the large space and different types of terrains available. This site contains enough undulation with approximate grades that match what will be expected at the NASA Rockyard. In addition, this site offers our team the ability to test the rover on both grassy and sandy surfaces so that it provides good information of how the rover will perform.

Figure 25: View of Doug Russell Park.

5.2 Manipulator Arm

The manipulator arm will be tested to determine its dexterous workspace. The use of inverse kinematics will ensure that it can easily move to a certain operational point without exceeding its joint limits and potentially harming itself. The arm and gripper will also be used to pick up test rocks to ensure that they can effectively manipulate objects.

6 Outreach

In an effort to inspire and educate the public, the team worked closely with various groups on campus to develop the following outreach initiatives: dynamic website, facebook page, team video, and participation in multiple outreach events.

6.1 Website

The intent of the website is to educate the public at large about the space program in general and the competition requirements and objectives while specifically targeting younger students to motivate them to continue learning about these topics. The graphic design was done by a local high school student and input was collected from pre-college sources regarding the layout of the site. The overall design plan called for multiple outreach sections with interactive content that caters to separate age groups, meant to engage the target audience. This portion of the plan was not implemented for this competition cycle, but it is intended to be added at a later date. It is also planned for future completion cycles that the team will document the design process in a video diary and publish this content here as well.

6.2 Facebook page

The intent of the Facebook page was to engage as much of the individual member's social network in our efforts by serving as a portal to our website and video publications. In addition, this form of social media has allowed our team to advertise its involvement in the competition to a much broader audience, invite people to our outreach events, and present any current information about the status of our progress.

6.3 Team Video

The intent for our team video was to convey three things: the multi-disciplinary team dynamic required of the design process for this competition, the driving force of NASA as a motivator and inspiration as individuals and as a team, and the importance of continuing to educate and inspire future generations into STEM fields and space exploration. This was accomplished through a blend of individual interviews and documentation of various competition components. None of this could have been accomplished without the contributions of Mr. John Mitchell, a student in the College of Fine Arts, through his generous donation of personal time and work, and the Film Department in the College of Fine Arts for allowing the use of editing equipment.

6.4 Outreach Events

One of the major initiatives for this team was to participate in as many events as possible allowing presentation of the rover design and education of people about the history and the future of the space program. Over the course of the last four months, our team was able to present in three events. The College of Engineering hosted the First Tech Challenge on March 5th, which allowed team members to interact with the student teams as volunteers and through a display set up in the competition area; see Fig. 26.

Figure 26: First Tech display.

The College of Engineering hosts Engineering Saturday three times a year. This is an event open to the general public that allows K-12 students to participate in interactive sessions presented by various groups and departments within the college. The team used this forum as an opportunity to give a brief history of the space program, the science behind the engineering, and our competition platform, see Fig. 27.

Figure 27: Engineering Day: Background Presentation.

As an interactive demonstration, we used RC model tanks which have been re-worked to act as semi- or fully autonomous ground platforms by the AVL, as seen in Fig. 28. The students worked as teams to first remote control the tanks from PCs via a wireless radio connection to learn the basic commands pre-programmed, and then to develop correction factors utilized in a semi-autonomous program designed to drive the tank in a straight line for a given distance. We also used the age-old game of "Whisper," or "Telephone" depending on where one grew up, to demonstrate the importance of network communications and delayed response time as well as general teamwork skills, shown in Fig. 29. For this activity, the students simulated the network chain between a "driver" and a "rover" to navigate a planned course.

Figure 28: Engineering Day: Student controlling the platforms.

Figure 29: Engineering Day: Telephone network demonstration.

The team also presented to the local chapter of the Association of Unmanned Vehicle Systems International (AUVSI) during their annual student competition meeting, in which the student teams fielded by the university present their solutions for their respective competitions which in some fashion incorporate autonomous systems. During this event, the team presented the final platform design and demonstrated the tele-operation interface which will be used during the competition.

Although the event takes place after the conclusion of this year's competition, the team will also be involved in the College of Engineering's annual Engineering Summer Camp program. Traditionally, the AVL sponsors the Interdisciplinary team project during which the campers must go through the engineering design process to develop a functional autonomous platform by designing a program to navigate an obstacle course. The students utilize the same RC tanks referenced above to complete this task and at the end of the week, they must present their work as a formal presentation as well as write a short paper. This year, the project has been redesigned slightly to simulate our competition field and objectives. The team will have a similar goal to identify and collect target objects while navigating an obstacle field. The team must utilize the knowledge they have gained over the course of a week to drive their platform efficiently with the programs which they develop. The unique aspect of this project this year is that all of this will be done via the wireless camera mounted on the tank from a location removed from the test field.