University of Maryland at College Park
Dept. of Aerospace Engineering

Persephone Remote Exploration System

2014 RASC-AL Robo-Ops Technical Report

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1. Introduction

Persephone, the University of Maryland's rover for the 2014 RASC-AL RoboOps competition, was derived from Demeter, UMD's rover from 2013. In Greek mythology, Persephone was the daughter of Demeter, who was in turn the daughter of Rhea (the UMD RoboOps entry from 2011 and 2012). The design of Persephone meets all the requirements of the competition including the 1m x 1m x 0.5m stowed configuration dimension constraint, a weight of less than 45 kg, the ability to navigate over 10 cm tall obstacles and 33% grade slopes, as well as the capacity to pick up irregularly shaped rocks via a controlled manipulator system.

2. Main Body Structural Design

The main body for Persephone had to follow several general requirements. The overall structure was designed to minimize size and mass, provide protection for electronics, and reduce attachment complexity for the components of other subgroups.

2.1. Minimization of Size and Mass

2.1.1. Dimensions

There are several different components of various sizes that make up the main body structure. The main frame of the main body consists of 1" x 1" x 1/8" hollow 6061 aluminum tubing and 1" x 1.5" x 1/8" hollow 6061 aluminum tubing. The side panels consist of 1/32" 3003 aluminum sheeting. The brackets that support the tube connections are made of 2" x 2" x 1/8" 6061 aluminum 90 degree L-brackets, each of which is 1" wide.

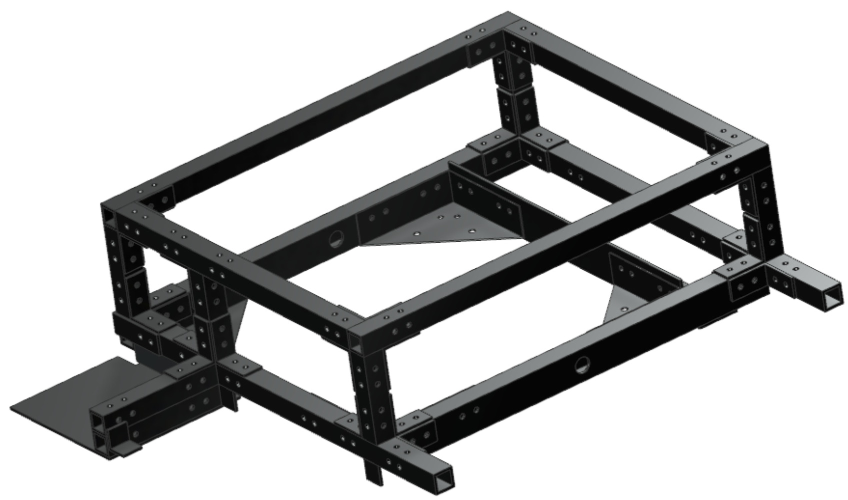

Figure 1. Main Body CAD Side View

2.1.2. Mass

The final mass of the main body is approximately 12 pounds, or 5.5 kg. This does not account for the rivets. The team was able to minimize this mass by using lightweight material, specifically 6061 and 3003 Aluminum, for the majority of the main body. The main body consists of 1/8" hollow 6061 aluminum tubing, with 1/32"

3003 aluminum sheets for side panels. The basket attachment frame is constructed with 1/16” hollow 6061 aluminum tubing, while the basket container itself is a nylon fabric bag.

2.2. Electronics Protection

Persephone’s electronics are mounted to a 16” x 16” x 3/16” electrical-grade fiberglass panel within the main body. This material was chosen to due to its lightweight mass, excellent tensile and impact strength, and overall good electrical insulation characteristics. This panel is protected from the outside of the rover by 1/32” side panels. The battery is also mounted within the main body, but sits in a section that is separate from the electronics. The electronics are protected from high frequency vibrations with bolt-down rubber vibration isolator mounts. There is one vibration damper bolted to each of the four corners of the electronics panel. These specific dampers are characterized by 5/16"-18 thread and a 75 pound capacity. Due to their high weight limit, the dampers will protect all electrical elements sufficiently.

2.3. Component Integration

In order to integrate the different components successfully, the main body provides various structurally sound mounting points. The components that needed to be integrated are the electronics board, the battery, the arm, the basket, the camera mast, the primary rocker axle, and the differential bar. Due to the size of the rivet gun used, special care was required during the manufacturing process to ensure that component integration was successful. Additionally, placeholder bolts were initially used to ensure correct alignment.

3. Drive System

3.1. Motors

Persephone uses a simple four-wheel-drive design with skid steering. Four reversible 12V gearmotors (AM Equipment 218-2001) are mounted at the base of the legs, providing a continuous torque of 4.3 N-m and a peak torque output of 18 N-m. With a wheel diameter of 15.2 cm, this equates to 30.8 N continuous drive thrust per wheel, with a peak thrust of 129 N.

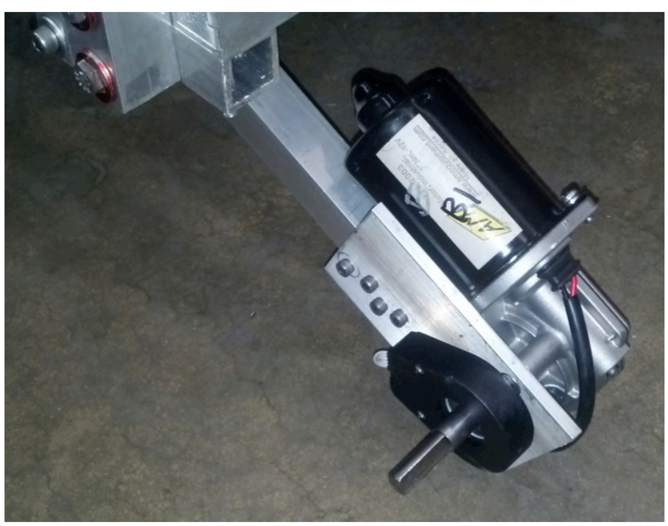

Figure 2. Motors with Attached Encoders

3.2. Wheels

There are two versions of tires used on Persephone. The first are traditional pneumatic tires 25.4 cm in diameter and 7.6 cm wide. Pneumatic tires will provide some vibration absorption and acceptable performance in most terrain. Persephone will be capable of moving at a speed of approximately 1.1 m/s on these pneumatic tires. The second set of tires are 27.9 cm in diameter and 15.2 cm in width. These tires feature diamond patterned tread that will be effective on both loose sand and gravel. The tires are puncture proof and provide more surface area than any previous design. The wheels are manufactured out of PVC with aluminum spokes to provide structural support and a mounting point for the hub. Due to the increase in diameter for the second set of wheels, Persephone will be capable of travelling at a speed of approximately 1.2 m/s.

Figure 3. Pneumatic Wheels

Figure 4. Treaded PVC Wheels

3.3. Rocker Suspension System

Persephone uses a rocker suspension system. This system is the preferred type of suspension for traversing extreme environments as the rocker design keeps all four wheels in contact with the terrain while traversing rugged features. Keeping all wheels in contact with the ground allows the rover to evenly distribute weight and traction while providing full forward locomotive force. The rocker system also provides the benefit of averaging the angle between the highest wheel and the rover body - a rigid wheel system would tilt the camera and arm twice as much as the current design.

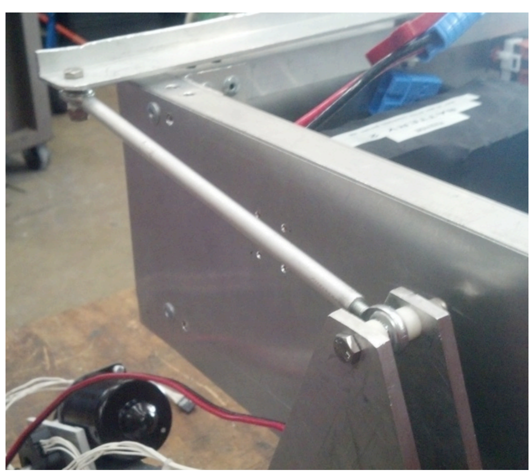

Figure 5. Rocker Bar Suspension System

Rocker systems, similar to the popular rocker-bogie systems, are composed of one "rocker" on each side of the rover. Each rocker is comprised of two legs fixed together at an angle of approximately 120 degrees, which pivots on an axle that extends through the frame of the rover. Each rocker is connected to a pushrod, running from the rocker gusset plate to each end of the differential bar on the back of the rover. The push rod has a ball-joint on each end to preserve the multiple degrees of freedom necessary for rocker operation. The differential bar mounts to the rear frame of the rover, pivoting on a vertical axis. As one rocker pivots on the axle, its push rod pivots the differential bar. This effectively causes the rover body to rotate to half the angle that the first rocker pivoted relative to flat ground. All four wheels stay in contact with the ground with comparable weight distributions, which optimizes traction while traversing rocky and hilly terrain.

4. Camera Mast Design

In order to meet the project's dimensional design constraints, the mast team chose to construct a mast that would self-deploy from a stowed configuration. The team also wanted to maximize the height of the mast while increasing camera stability, so a gimbal was added to reduce any unwanted vibrations.

Figure 6. Mast Assembly CAD

4.1. Cameras

The main mast camera is a Point Grey Cricket IP Security Camera with a Fujifilm YV3.3x15SA-SA2 lens. The auxiliary cameras are Logitech C920 Webcams with auto-focus/auto-iris capabilities to assist arm manipulation. Two of the auxiliary cameras are placed on the chassis providing a view of the arm's range of motion, and the third is placed on the underside of the arm about halfway between the wrist and the elbow joints.

4.2. Gimbal

The gimbal is an ASP 3-Axis Nex-GH5 controlled by an AlexMos microprocessor. This gimbal allows for pan-tilt camera manipulation as well as providing vibration isolation. The structure of the gimbal is large enough to accommodate the dimensions of the Point Grey camera. In addition, the motors can supply torque sufficient for the camera mass.

4.3. Mast

The mast is comprised of a base, linear spring, gas spring, mast arm, gimbal attachment plate, and stow strap. The base, mast arm, and attachment plate are made of 6061 Aluminum with dimensions of 1" x 1" x 1/8" x 21.75", 3/4" x 3/4" x 1/16" x 19.5", and 6" x 6" x 1/8", respectively. The gas spring is rated for 30 lbf and the linear spring is rated for 6.6 lbs per inch of compression, which will yield 10.96 lbs for our configuration.

4.4. Mast Assembly

The stowed configuration of the mast assembly had to fit within 6.8 inches in height. The height restriction in conjunction with the large gimbal assembly necessitated an 8-degree angle between the mast arm and the base. With this configuration, the mast could not self-deploy with only the 30 lbf gas spring due to the added gimbal and camera mass. The team's solution was to add a linear spring to the assembly to raise the mast arm to a large enough angle to allow the gas spring to complete the self-deployment. The mast will be deployed when the stow strap, which is attached to the gas spring, is released from underneath one of the wheels when Persephone drives forward.

5. Manipulator System

The manipulator was designed to be used in a number of different configurations and provide variable reach. A 5 degree-of-freedom manipulator was chosen because it best models the articulation of a human manipulator. Using servomotors, rotations can be achieved in the following manners: shoulder yaw, shoulder pitch, elbow pitch, wrist pitch, and claw actuation. This design is a compromise amongst complexity, maneuverability, and structural weight factors. Using a forearm and upper arm of equal lengths of 36 cm, an overall reach of 76 cm is achievable. The manipulator can also pick up rocks as close as 11 cm from the main body. Equal length manipulator links were selected because this optimized the ability for the manipulator to reach sufficiently far away from and close to the main rover body, while also being convenient lengths for stowage and depositing of rock samples.

5.1. Manipulator Assembly

To better describe the manipulator system operations, some of the key aspects of the system will be defined. The rotating base of the manipulator, including the base point discussed earlier, is now described as the "shoulder" joint. The next actuation point is the "elbow" joint, and the final actuation point located at the end of the manipulator is the "wrist" joint. The links between the shoulder joint and the elbow joint are now the "bicep" links, and the links bridging the elbow and wrist joints are the "forearm" links. Figure 7 below depicts the joints and the links in the manipulator.

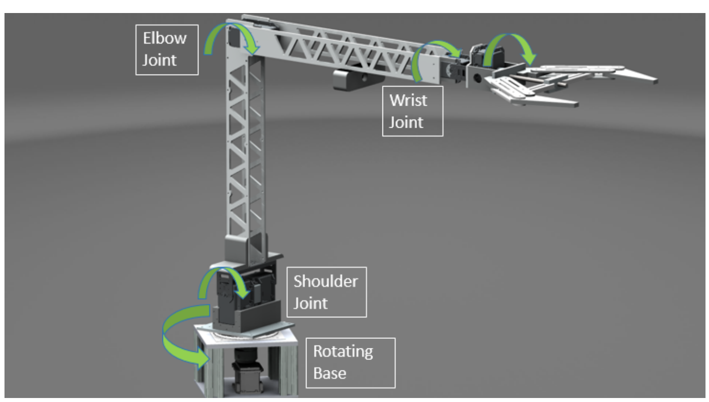

Figure 7. Joint locations

The pitch actuation at the shoulder is accomplished with a double MX-106 servo system and corresponding bracket. An important factor in choosing is double servo system lies in the MX-106 design, which allows one of the servos to be "slaved" to the other. In short, both servos follow the same commands simultaneously. The elbow pitch actuator is another MX-106 servo, oriented perpendicular to the rotation plane. At the wrist joint, a smaller MX-28 servo with accompanying bracket is utilized for wrist pitch. The bicep links are attached to the shoulder bracket via two L-shaped brackets, while the MX-28 servo is integrated at the wrist through a combination of metal and delrin mounts. The dual-MX-106 shoulder servos are secured to a u-channel via two end caps, and the u-channel in turn is bolted down to the rotating base.

5.2. Servo Selection

Using an iterative selection process, servos were chosen to meet the torque requirements at each joint of the manipulator. The torque required by the servo at any joint can be found using the following equation:

$$\tau_{net} = \sum_{i=1}^{n} m_i g r_i$$

When m_i is mass of each component, r_i is the distance from the component to the joint, and **g** is the acceleration due to gravity. By assuming the components to be point masses at their center of mass, the required torques can be calculated. Working from the end effector back to the shoulder, servos at each joint could be properly sized. Dynamixel servos were chosen for their high stall torques and relatively low masses. One Dynamixel MX-28T servo was used for the wrist pitch and end effector joint, which has a stall torque of 2.5 N-m. The elbow pitch uses a Dynamixel MX-106T, which has a stall torque of 8.4 N-m. The shoulder yaw uses a 6 N-m max stall torque Dynamixel MX-64T servo. Finally, the shoulder pitch is required to support the greatest torque throughout the manipulator, so a double MX-106T servo configuration is used with a maximum stall torque of 16.8 N-m. The initial calculations governing the servo selection are expressed in Appendix A.

Using a similar calculation, the shoulder yaw servo maximum required torque could be calculated. While driving over level terrain, the rover will not place any torque on this shoulder yaw servo. It is only when the rover is at an angle θ (on a slope) that the shoulder yaw servo will experience an outstanding torque. This modified torque equation becomes:

$$\tau_{net} = \sum_{i=1}^{n} m_i g r_i \sin(\theta)$$

The overall moment of inertia of the manipulator also affects the maximum angular acceleration of the yaw servo. This was calculated by:

$$\alpha = \frac{\sum \tau_i}{\sum m_i r_i^2}$$

Where the denominator represents the total moment of inertia for the manipulator about the shoulder. These results are shown in Appendix B.

5.3. Base-Plate Assembly

The base plate assembly integrates Team Persephone's manipulator assembly to the body of the rover and allows for a full 360-degree rotation in the yaw direction. It was designed to be easily modifiable, because throughout the design process, we will need to be able to disassemble the components for potential modifications and to access the MX-64. The base plate assembly comprises of a top and bottom layer plate, T-slots, an oldham coupling, turntable, and MX-64 servo represented in Figure 8 below.

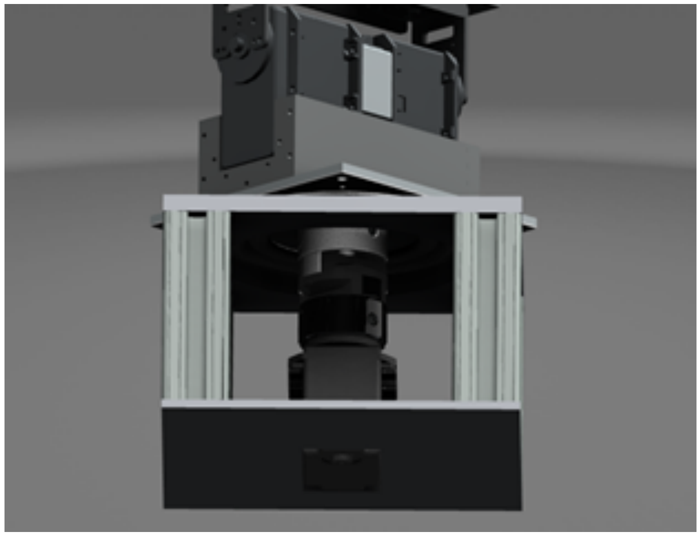

Figure 8. Base-plate assembly

An Oldham coupling is integrated into the base plate assembly as a safety measure in order to protect against possible torque damage to the MX-64 servo during operation. The coupling is attached directly to the horn of the MX-64 by screws passed through counter-bored holes in the coupling. The coupling is also attached below the top base plate that rotates along with the turntable, and again counter-bored holes and screws are used. Should the rotating table experience any lateral loads, the coupling will slip, absorbing the applied side forces and preventing damage to the delicate gears inside the servo, while still transmitting torque from the servo.

The rest of the assembly was designed around the focus of rigidity and support. The aluminum t-slots selected for the legs of the rotating base are lightweight, high strength, and easily integrated into the design. These serve not only as supports, but as standoffs to create the right sized standoff between the top plate and the MX-64. The turntable chosen for rotation is listed as having a 300 lb load capacity (McMaster Carr, 2011). It is installed at an angle of approximately 35 degrees on the base plate because doing so does not affect its actual actuation, while enabling easy access to the components of the base plate which attach to the four T slots. The bottom plate is attached directly to Persephone's chassis, and there is a slot for the MX-64 to be attached. The plate underneath the turntable has a corresponding hole machined out of it to allow the Oldham coupling to pass through.

5.4. End Effector

Our manipulator/end effector is a claw that is actuated with a lead screw design. The lead screw is rotated using a MX-28 servo. The end effector is designed to have a grip width of approximately 24 cm. This parameter is roughly double the size of the average rock found in past competitions, which ensures that the end effector has a large enough range for grabbing. However, the actual width created after assembly comes out to be slightly less due to weight constraints – between 20 and 21 cm. In terms of actuation, multiple designs were considered. Due to shipping time constraints, the servo was chosen before the design of the end-effector was completed. Therefore, the team had a baseline torque to design around. The driving factor in the design is the mechanical advantage in the system to maximize the force applied on the rock given the safety restrictions on the MX-28. The end effector configuration can be seen in Figure 9 below.

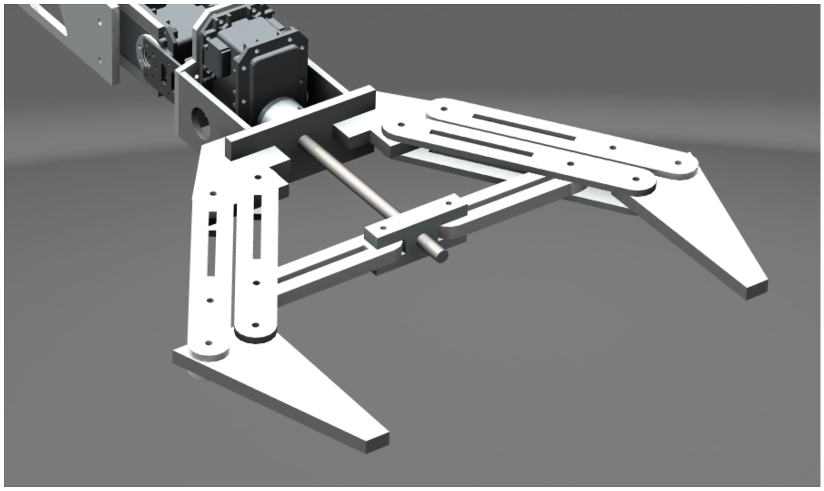

Figure 9. End effector

Attached to the lead screw is a traveler, which moves a linkage system up and down, in turn opening and closing the claw. This traverser converts the rotational motion from the servo and lead screw into a linear motion, which can then drive the opening/closing motion of the claw. The servo for this design is placed underneath the lead screw, which eliminates the need for an intricate servo housing, cutting down on the 10 cm design for the scissor design. The team selected a stainless steel 1/4" – 20 thread lead screw for the design because it had an ideal thread count for the traversing mechanism and it added less mass to the end effector. It was determined that only 1.5 inches of linear movement on the lead screw would be required for our claws to open and close with the 20 thread count. There were concerns about sand and rocks getting stuck in our screw, but the servo is powerful enough to crush small pebbles. Additionally, we can implement a cleaning washer easily if concerns arise. One last design feature is the interchangeable nature of the "finger" pieces of the end effector – because of the simple geometry, there is the possibility to add components onto the end effector. Such additions could be used to increase the grabbing area of the end effector, or used to provide extra contact area via a plate/teeth.

6. Software/Communication

6.1. ROS Implementation

All of the software involved with Persephone is implemented using ROS (Robotic Operating System), which provides a simple messaging system between components. This allows the team to easily communicate between systems, receive telemetry, and additionally offers an easy-to-use protocol to send commands to the onboard computer. All components, from the wheel motors to the sensors, have a corresponding ROS node, which allows the team to interact with these components easily.

6.1.1. Dynamixel Servos

Persephone's arm is built using Dynamixel Servos, which provides much finer control over set angles and telemetry regarding the state of each servo. Because we are using these Dynamixel servos, we will be utilizing proprietary hardware to interface with them, namely the USB2Dynamixel converter. Additionally, we were provided a pre-built ROS node, which interfaces with the servos directly, giving us a simple method of setting joint angles and complete feedback on the status of each servo.

6.1.2. Jaguar Motor Controllers

The drive system uses Jaguar Motor Controllers to set the wheel speeds, which is interfaced with a CAN (Controller Area Network) bus. By using CAN with the Jaguars we are able to use several different methods of setting speeds, and we can additionally receive feedback about the motors. Unfortunately, there is no particularly easy way of interfacing with the Jaguars on a Linux platform, other than constructing properly formatted binary messages according to the data sheet and sending them out over a serial connection. By sending these messages out over the serial connection, the first Jaguar automatically converts the message to the CAN and relays it to the following Jaguars in the daisy chain.

Once we were able to construct these binary messages and statically send out these messages over RS232, we were able to build our own ROS node around this. Our node listens to a wheel speeds topic, constructs a message formatted properly using this data and sends it out over the RS232 connection. Additionally, we have built a ROS node, which takes messages sent from the Jaguars and converts them into ROS messages and broadcasts them out. We can then listen to at our control station to have status information about the Jaguars.

6.1.3. Arduinos

We are using a single Arduino Mega to interface with miscellaneous sensors throughout Persephone. Most notably, we will be using an IMU to communicate the orientation of Persephone and a temperature sensor to ensure the surrounding space of the electronics is not overheating.

6.2. Communications

6.2.1. Interface Pages

To interact with ROS on the rover, there is a set of control pages, built using HTML, CSS and Javascript. User input is taken from joystick and key-presses using inherit Javascript methods and using the Chrome Joypad API. Further using Javascript, the user input is formatted according to how it is expected in ROS. Finally, by opening a websocket, sending a ROS message is done by publishing JSON formatted strings over the websocket. The user input for controlling the wheels is either one or two joysticks. In the first case, there is an algorithm that takes advantage of the X and Y-axis of the joystick, and converts those into the proper left and right side wheel speeds. Conversely, if the user selects to use two joysticks, one joystick will be controlling the left side and one will control the right; this is similar to the controls for heavy machinery using skid steering. The arm is controlled using one joystick, which sends velocity commands to an inverse kinematics solver; because of this, the user does not need to control the arm joint by joint; the arm operator can instead move the joystick to the right to move the arm's tool tip (grasp point of the end effector) to the right, and so on for all directions.

6.2.2. Onboard Communication Hardware

The robot contains two CLEAR 4G cellular modems, which connect to the Sprint wireless network and provide a connection to the robot over the internet. One of these devices is connected to the main computer by Ethernet, allowing the base station to connect to the computer by SSH or the rosbridge protocol. The fixed cameras are attached to the main computer and transmit video through its data connection. The other modem is connected to the mast camera, which allows a direct IP connection to its video stream. The CLEAR network should allow for each modem to upload at 1 Mb/s; data from the previous year's team indicates a time delay of approximately 2 seconds.

Data sent from the robot includes status information from the motor controllers, orientation information from the IMU, and video feeds. All of the cameras onboard the robot support h.264 compression, freeing up processing power on the computer for other tasks and reducing data (Mace, Alexander, Lee, & Toris, 2014) streaming requirements by 50% (Wenger, Hannuksela, Stockhammer, Westerlund, & Singer, 2005).

The rosbridge protocol allows JSON based commands to be sent to the ROS software controlling the robot (Mace, Alexander, Lee, & Toris, 2014). In this way, a web browser based interface can be used to command

and display information from the robot. The browser displays the status of the motors, the fixed camera feeds, and the heading and orientation of the robot. To manage the limited bandwidth, only one fixed camera feed is transmitted at a time. Controls on the interface change which camera is active. The mast camera feed is accessed separately by the camera's IP.

6.2.3. Flow Diagram of Persephone Components

Below is a diagram showing the flow of communications between the different components involved with Persephone.

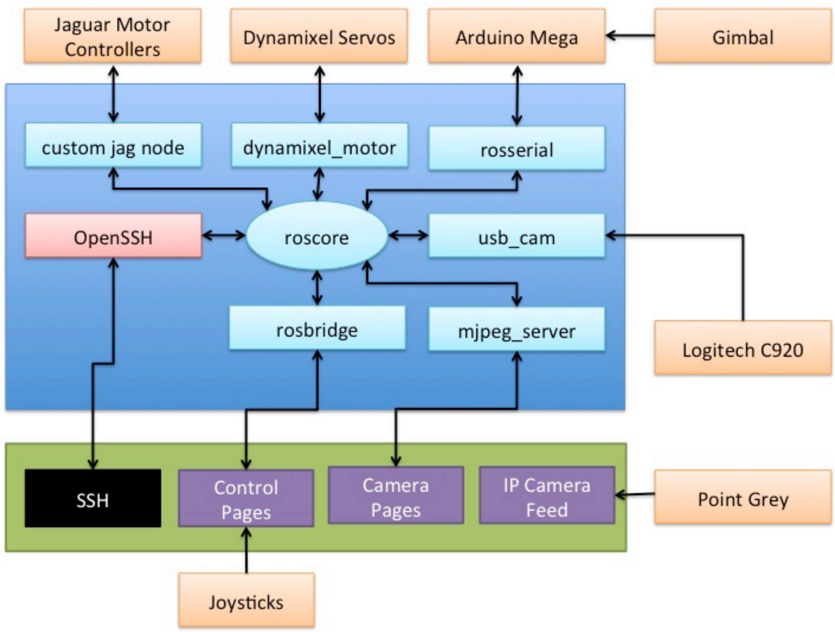

Figure 10. Persephone Flow Diagram

7. Technical Specifications

7.1. Mobility

Table 1. Technical Specifications

Maximum Speed	1.2 m/s
Maximum Obstacle Size	Roughly the size of the wheel (14 cm)
Rated Payload	~300 in^3
Operating Time	~67 minutes
Wheel Thrust	30.8 N continuous drive thrust per wheel, peak thrust of 128.8 N

7.2. Computing and Control

Computing on Persephone is handled by an Intel Core i5 2510e, 2.5GHz processor on an AIMB-273 Motherboard by Advantech. The computer is supported by 4Gb of DDR3 RAM and a 64Gb SSD by SanDisk.

Running Ubuntu 12.04, the computer makes use of numerous ports to coordinate the actuation and sensing of components around the rover. In particular, RJ45 (Ethernet) is used for connection to the CLEAR cellular router, and by extension the control station, while USB 3.0 connects the computer to the Arduino Mega (for Sensor I/O), Secondary Cameras (3x Logitech C920 Webcams), Sparkfun Razor IMU (Inertial Measurement Unit), and Manipulator Arm via USB-Dynamixel adapter

Motor control and feedback is handled by four MDL-BDC24s (Jaguar Motor Controllers) which communicate over a daisy-chained CAN bus. This network is accessed via Serial RS232 connections directly from the motherboard, and bridged internally by the first Jaguar in the chain. Each Jaguar provides live current and voltage monitoring, as well as supporting quadrature data from motor-mounted encoders.

7.3. Power Management

The rover is powered by a 20Ah 12.8V Lithium Iron Phosphate (LiFePO4) battery. This particular technology, while slightly less energy dense than other Lithium Ion Battery types, is notably more voltage stable throughout discharge and is highly resistant to thermal runaway. The battery allows discharge at a 100A rate, limited by a manufacturer included Protection Circuit Module (PCM).

Power from the battery is switched by a 100A automotive relay, which allows for hardware level power-safety measures to be implemented in the case of battery over-temperature. Additional 70A relays to the motors and arm allow for a dedicated kill-switch to shut off potentially dangerous actuation components as necessary while keeping the remaining systems online for diagnosis. An AndyMark Power Distribution Board is used to dispense DC power to the rest of the board, including the Motor Controllers, M4ATX CPU Power Supply, Arm, and Primary Mast Camera.

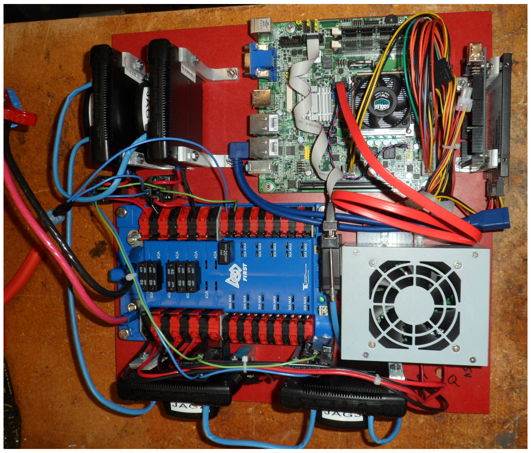

Figure 11. Electronics Panel

8. Testing Strategy

Testing of the wheels and suspension system has been conducted on flat and inclined sandy and rocky terrain. The rocker based suspension system was used with success by Demeter, a previous rover from the University of Maryland, and was modified slightly for use on Persephone. While the frame of Persephone was under construction, Demeter was used as a test bed for the two versions of wheels.

On Demeter, the pneumatic wheels performed well on flat ground and sloped gravel, but performed inadequately in soft sand. It was decided that for better performance, the surface area of the tire would need to be increased. From experience with Demeter's wheels, it was decided that the grousers should be less aggressive than last year's embodiment. This observation led to the construction of the second set of wheels, which are now undergoing final testing.

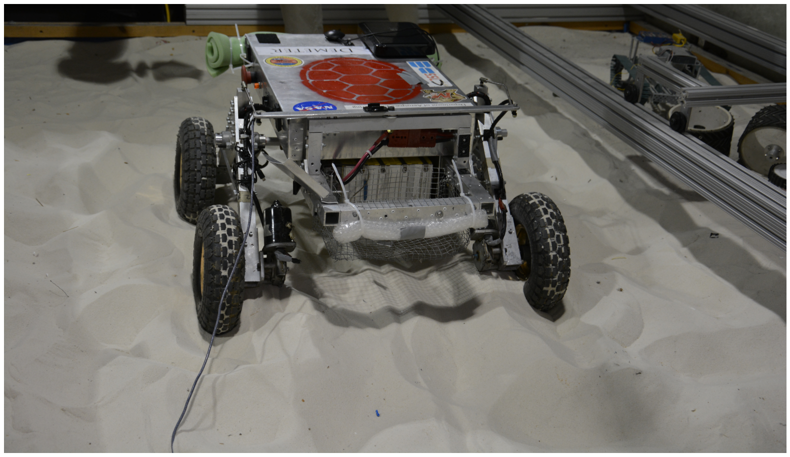

Figure 12. Wheel Testing in Loose Sand Bed

9. Overall Strategy

Persephone was designed to be an improved version of Demeter. The strategy employed by Persephone is to build upon the experience from the construction, testing, and success of Demeter. Successful systems, such as the rocker suspension, were unchanged. Systems that were found to be inefficient or in need of improvement were redesigned. For instance, Demeter's threaded rod push arms in the rocker bar system were undersized and buckled under normal operating loads. In their place, Persephone's rocker bar push arms are solid aluminum rods. The key theme was to increase efficiency across all systems and shave weight from the previous design. In addition, Demeter was left untouched to serve as a test bed for new software and mechanical system testing.

For the competition, there were several important changes to be made from Demeter's manipulator design. The first changes was decoupling the motion of the forearm from the bicep and converting to a Cartesian control system. The goal of this change is to enhance the operation of the arm by the pilot by creating a more intuitive control method for the manipulator motion.

The next change was forgoing the scissor end effector and choosing the lead-screw actuation method. This helped reduce the mass, and also allowed for better integration of the end effector to the wrist pitch system. This more streamlined integration will help overcome obstacles in grabbing rocks. Rocks on top of other rocks as well as rocks under some sort of enclosure were encountered in previous years. Furthermore, using a lead-screw for actuation allowed for a wider claw grip. From previous competitions, many teams successfully utilized a small claw actuation, but limited visibility from camera feeds made it difficult to pinpoint the location of the rock. Our claw's large grip width allows gives the controller to pick up rocks as long as the claw is close by. This saves considerable time and saves the controller the frustration of angling the cameras/vehicle to get a more precise position.

10. Public Outreach

Our most important public outreach event of this year occurred on April 26 at Maryland Day 2014. Maryland Day is an annual festival held by the University of Maryland with informational displays, activities, food and fun for all ages. Persephone and her predecessor, Demeter, both made appearances at Maryland Day at the Space Systems Lab. While Persephone was only a static display and not operational due to a battery malfunction, Demeter was driven around a homemade obstacle course by hundreds of children, student and parents alike throughout the day. Maryland Day provided the team with the opportunity to talk to hundreds of visitors about Persephone, Demeter and the RASC-AL Rover Competition as well as the Aerospace Engineering department and university as a whole.

In addition, through our UMD Persephone Rover Facebook page, https://www.facebook.com/persephonerover, the team has been able to reach over 160 family members, friends and peers. This page includes photos of progress made throughout the semester and will continue to be updated for the duration of the competition.

Figure 13. Persephone and Demeter Rovers and Team Members at Maryland Day 2014

11. Budget

We would like to thank our generous sponsors: NASA/National Institute of Aerospace, the University of Maryland Aerospace Engineering Department, the A. James Clark School of Engineering, and the University of Maryland Space Systems Laboratory for their support in making Persephone possible. Our expenditures for fabrication and travel reached $15,269 this year, which was entirely covered by our sponsors. A breakdown of the costs incurred by each sub-team, as well as sponsorships, can be found in Table 2.

Table 2. Cost Breakdown and Sponsorships

Category	Cost (USD)
Chassis	740
Wheels/Suspension	1,088
Mast/Camera	983
Electronics/Power	4,697
Travel	4,958
Total	**15,269**

Sponsors	Sponsorship Amount (USD)
NASA/ National Institute of Aerospace	10,000
Department of Aerospace Engineering	2,500
A. James Clark School of Engineering	2,500
Space Systems Laboratory	269
Total	**15,269**

12.Works Cited

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13. Appendix A: Pitch Servo Torque Table

		Distance from servos (cm) (average)		
Component	**Mass (g)**	**Servo 3**	**Servo 2**	**Servo 1**
End Effector Camera	160	-	18	54
End Effector Claw	400	9	45	81
Largest Rock	215	15	51	87
End Effector Servo (MX-28T)	72	3	39	75
Wrist Servo (3) (MX-28T)	72	0	36	72
Link 2	200	-	18	54
Elbow Servo (2) (MX-106T)	153	-	0	36
Link 1	176	-	-	18
Shoulder Pitch Servo (1) (MX-106T x2)	306	-	-	0
	Required Torque (N-m)	0.69	4.00	8.80
	Stall Torque	2.5	8.4	16.8
	Req/Stall (Must be <50%)	27.6	47.7	52.4

14.Appendix B: Shoulder Yaw Servo Calculation Table

Component	**Mass (g)**	**Distance (cm)**	**MOI (g*cm^2)**	**Torque from slope (15 deg) (N-m)**
End Effector Camera	160	54	466560	0.219
End Effector Claw	400	81	2624400	0.822
Largest Rock	215	87	1627335	0.474
End Effector Servo (MX-28T)	72	75	405000	0.137
Wrist Servo (3) (MX-28T)	72	72	373248	0.131
Link 2	172.8	54	578534	0.236
Elbow Servo (2) (MX-106T)	153	36	198288	0.139
Link 1	172.8	18	130636	0.078
Shoulder Pitch Servo (1) (MX-106T x2)	306	0	0	0
Total	1723.6		6404000	2.24
			Req/Stall (Must be <50%)	37.3
		50% Max Stall Torque (MX-64T) (N-m)	3	
		Max Angular Acceleration (rad/s^2)	4.684	