Concept Development

Team 11 – NASA/RASC-AL Robo-Ops

EML4551 – Senior Design - Fall

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1.0 Introduction

The objective of this project is to design and build a robot that can traverse terrain similar to that found on the moon and Mars. The robot must have an appendage capable of picking up rocks and a place to store the rocks. All control of the robot during the competition must be done remotely from the campus of the university, with the competition itself taking place at the NASA Johnson Space Center in Houston, Texas.

We will build upon efforts of past years' senior design teams which designed and built a hexapedal robot for the purpose of competing in the NASA Lunabotics competition. The intent of this project is to build an entirely new robotic platform for our competition. However, if we are not selected for the competition (only 8 teams are selected), our contingency plan is to adapt the existing robotic platform to the requirements of this competition and perform a mock run of the competition before the end of spring semester, paving the way for a team to build upon our efforts and make an even stronger case for entry into the competition next year.

2.0 Project Scope and Goal

The RASC-AL Robo-Ops competition website provides the following statement outlining the scope of the competition:

“RASC-AL Exploration Robo-Ops Competition (i.e., Robo-Ops) is an engineering competition sponsored by NASA and organized by the National Institute of Aerospace. In this exciting competition, undergraduate and graduate students are invited to create a multi-disciplinary team to build a planetary rover prototype and demonstrate its capabilities to perform a series of competitive tasks in field tests at the NASA Johnson Space Center’s Rock Yard in June 2013.”

In other words, the objective of this project is to design and build a robot that can traverse terrain similar to what is found on the moon and Mars. The robot must have an appendage capable of picking up rocks and a place to store the rocks. All control of the robot during the competition must be done remotely from the campus of the university, with the competition itself taking place at the NASA Johnson Space Center in Houston, Texas.

3.0 Problem Definition

The first problem being addressed in this report pertains to relating our robot's intended method of mobility to systems being used in actual planetary exploration (primarily NASA rovers and prototypes). The hexapedal platform intended for use is similar to recent Mars rovers in that it uses six independently-powered limbs to traverse its environment. The major difference is that this hexapod uses compliant legs instead of wheels. It will be shown in the sections that follow that legged mobility is superior when it comes to traversing extremely uneven terrain. The Mars Exploration Rover Spirit has been stuck in a surprise patch of soft sand on Mars since 2010, and NASA hopes that the current rover, Curiosity, won't suffer the same fate. NASA is currently exploring rover platforms that combine the best aspects of wheeled and legged mobility for future rovers. Also, all teams participating in the 2011 and 2012 RASC-AL Robo-ops competitions used wheeled rovers with great success (as far as mobility is concerned). Thus our major challenge will be fine-tuning our platform to exceed the capability of these wheeled rovers and prove the versatility of our legged platform.

The second problem to be addressed is the need for the rover to acquire and store material samples. Current Mars rovers utilize instrumentation that require precision-positioning over objects of interest for use. As a result, these rovers employ robotic arms having 5 degrees-of-freedom to maximize the precision of this instrument positioning. Many of the 2011 and 2012 Robo-Ops participants reported needing only three degrees-of-freedom mobility to effectively acquire and store material samples. One common downside to all these team's systems, however, is that they still experienced relatively slow sample acquisition speeds. This is partly due to the communications delay imposed by NASA, but low-precision is also a culprit on behalf of the systems they developed. This opens the door for exploration of potentially faster, more efficient solutions to sample the acquisition problem.

4.0 Previous Design Work

4.1 NASA's Rover Technology

Looking through NASA's current terrestrial rovers, both in-use and under-development, provides insight to the direction in which they are heading with new rover platforms. All the rovers NASA has sent to explore the Moon and Mars are/were wheeled platforms. But, based on what NASA has under development at its various research centers, the next generation of planetary rovers will most likely be based on legged platforms. The following discussion gives an overview of some legged rovers currently under development, and the two most recent and operational wheeled rovers on Mars.

4.1.1 NASA ATHLETE Prototype

ATHLETE stands for 'All-Terrain Hexapedal-Legged Extra-Terrestrial Explorer' ("The ATHLETE Rover", n.d.). According to the NASA Jet Propulsion Laboratory website, ATHLETE is envisioned to be used as a heavy-lift utility vehicle. It would support human exploration of planetary surfaces by unloading and transporting bulky cargo from stationary landers ("The ATHLETE Rover", n.d.). It would also be used to develop habitats for human explorers on other planets or moons.

Figure 1: NASA's Athlete Rover carrying a prototype habitat module. Image from the NASA Jet Propulsion Laboratory website.

The first iteration was constructed in 2005, could stand at a height of about 2 m, and had a mass of about 850 kg ("The ATHLETE Rover", n.d.). It moves using six limbs, each having six degrees of freedom (6-DOF), with a rotating wheel at end of each limb. ATHLETE is capable of both rolling and walking motion. The robot walks by locking its wheels and using each limb as a leg. This will allow the rover to roll on stable terrain, and walk over harsher terrain. The second, and current, iteration was built in 2009, and is literally twice the robot. It stands twice as tall, and is actually a combination of two "Tri-ATHLETE" robots ("The ATHLETE Rover", n.d.). Each Tri-ATHLETE is a three-limbed robot that can connect to special payload and combine into a hexapod.

ATHLETE is equipped with the ability to utilize modular tools. Each limb can attach a tool at its wheel hub, and use the wheel's mobility to power the tool and/or manipulate the tool using the entire limb. Thus each limb can become an independent manipulator. The ATHLETE robotic platform is still under development at NASA's Jet Propulsion Laboratory (JPL) at the California Institute of Technology ("The ATHLETE Rover", n.d.).

4.1.2 NASA Scorpion Prototype

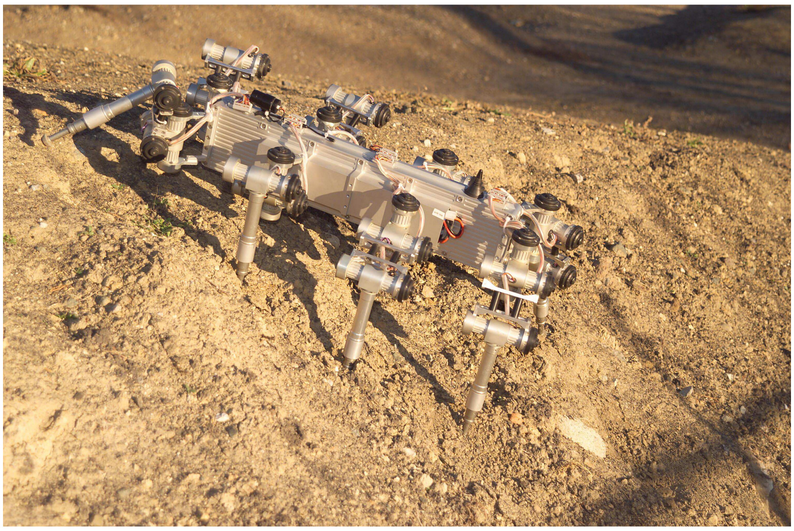

Figure 2: NASA's Scorpion Rover Prototype. Image obtained from NASA's Ames Research Center website.

Scorpion is an octopedal legged robot under development at NASA's Ames Research Center and was designed to mimic the mobility of a scorpion (Bluck, 2005). Its purpose is to explore small crevices and extreme terrains that larger wheeled platforms can't access. Ames researchers plan on implementing a model of the inner ear on Scorpion to improve its balancing capabilities (Bluck, 2005). The Ames Research Center web page for the robot also lists a camera, ultrasound/sonar sensors, as well as touch sensors at the ends of Scorpion's legs to allow the robot to sense its environment. No documentation of the implementation of other tools was found.

4.1.3 NASA Mars Exploration Rover (MER) and Mars Science Lab (MSL)

The MER and MSL are planetary rovers that successfully landed on, and are currently exploring Mars. The MER rovers nicknamed Spirit and Opportunity were launched in 2003 to explore the history of water on Mars, and both rovers successfully landed on the Martian surface in 2004 ("Mars exploration rovers", n.d.). Opportunity is still operational and continues to send valuable data to NASA to this day. Spirit, however, has been stuck in soft sand since 2009 and its mission was officially ended in 2011 after spending its last years as a stationary platform ("Mars exploration rovers", n.d.). The MSL rover is nicknamed Curiosity, was launched in 2011 and successfully landed on Mars in 2012. Its mission is to explore the possibility of the existence of microbial life on Mars ("Mars science laboratory: curiosity", n.d.).

Figure 3: NASA's Curiosity Rover, which is currently exploring Mars. Image obtained from NASA's official website.

Both platforms are wheeled rovers utilizing the 6x6x4 wheel formula. This formula states that the rovers have six powered wheels, and four of them are used to steer the vehicle (Seeni, A., Schafer, B., Hirzinger G., n.d.). Both platforms also employ the rocker-bogie suspension system. This suspension allows for all six wheels to maintain contact with the ground, even over obstacles. The MSL and MER are capable of overcoming obstacles that are as tall as their wheel diameters, and maintaining even wheel pressure on soft surfaces (despite the MER rover Spirit being hopelessly stuck in soft sand) (Seeni, A., Schafer, B., Hirzinger G., n.d.).

Figure 4: Early MER prototype testing near NASA Dryden Research Center. Image obtained from NASA's official website.

Both rover platforms are equipped with mast-mounted cameras for a panoramic view of its surroundings, and to monitor systems on the rover itself. Cameras are also mounted at all four sides of the rovers, and at end of their respective robotic manipulators. Their sample acquisition systems consist primarily of a 5-DOF robotic manipulator (robotic arm). Their end-effectors contain multiple tools pivoted about a "wrist". The MSL arm can reach 2.2 meters and its end-effector has 5 tools. The MSL can also store and study samples both internally and externally ("Mars science laboratory: curiosity", n.d.).

4.2 Previous successful teams from Robo-Ops competition

The team thought it would be useful to look at previous year's designs at the competition to see which designs worked best at the competition site. Looking at the top three teams from the 2012 competition, some insight was gathered as to what a successful design would require. The final reports and video feeds from the competition, from each team, were reviewed and analyzed for relavant information and criterion.

4.2.1 Worcester Polytechnic Institute (WPI)

The team from WPI won the Robo-Ops competition both years it has taken place. During last year's competition, they successfully collected fourteen samples, the most of any group. Their sample manipulator consisted of a hybrid scoop-pincer attached to a two degree-of-freedom arm. The gripper mechanism reduced the amount of precision needed to acquire samples, and the low-degree-of-freedom arm used the rover's wheels to compensate for the arm's limited reach. To aid with the sample collecting, there was a camera placed on the front of the rover that was able to see through the clear part of the claw to insure the sample had been collected.

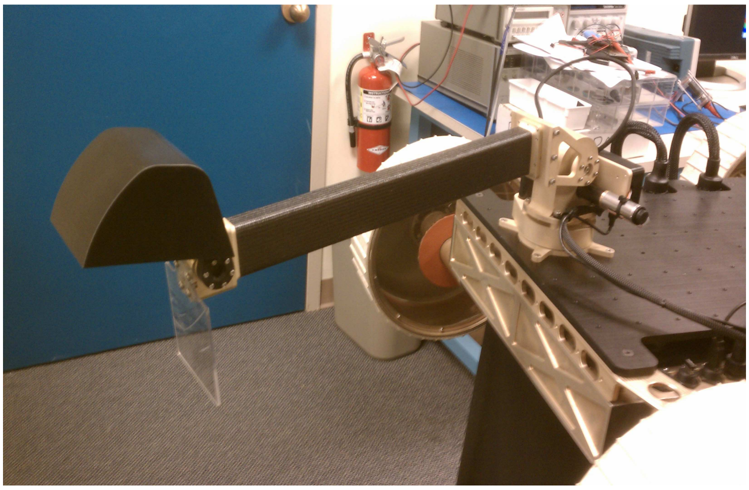

Figure 5; WPI's arm and claw design for the 2012 competition.

One of the benefits of this design was the size and storability of the arm. When the arm was not in use, it was resting on the top frame of the robot, keeping the center of gravity low. It also helped that the arm was able to quickly go from its stored position to a position either in front of the robot or above the sample storage compartment. Another large benefit was the clear image from the front camera of the rock being within the scoop before dropping the payload in their collection bin and stowing the arm again.

A large drawback of this type of arm, for our purposes, is that they used the robots wheels to move the arm forward and back. Since we will be competing with a legged robot, fine adjustment forward or backward will be difficult. Another disadvantage lies in the scoop system used, the team collected other small rocks and sand along with the desired samples. This can add up by the end of the competition and weigh the robot down. While this design was able to collect many samples, the control of the arm once it was in the front of the robot seemed to take a fairly long time. It would certainly be useful to explore solutions that may reduce sample collection time.

4.2.2 California Institute of Technology (Caltech)

Caltech's design consisted of a six degree of freedom arm with a pincer type gripper mounted at the end. This was the most degrees of freedom used for an arm of any group at the competition which aided in their second place finish. During their sample acquisition, they had a video feed of several cameras to help with positioning the sample well within their pincer gripper.

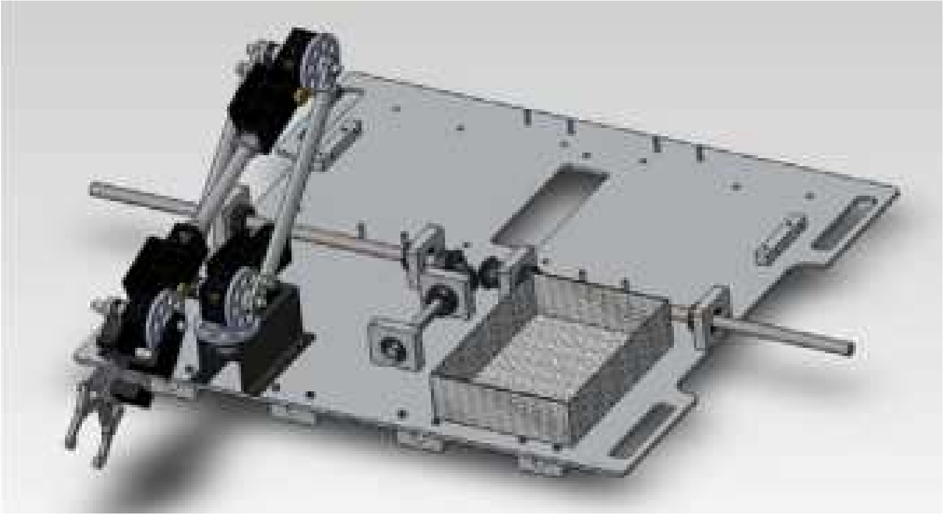

Figure 6: California Institute of Technology's arm and gripper for the 2012 Competition.

The main advantage of this design is the ability to move the gripper in many ways to select the sample. If the desired sample is tucked between rocks, this design would be best for just trying to collect the sample without having to move rocks. The pincer gripper allows the team to only pick up the desired sample and not collect sand and other debris with it.

The main disadvantage of this arm is the control algorithm needed to use it in a time-efficient manner. To move the arm in a simple planar motion, the user has to adjust several motors. Unless an advanced control algorithm is in place (such as the model-interface mimicry system used by the team), this process would take too long. Also the pincer gripper has its disadvantage of having to be precisely in the correct place to hold on to the sample, unlike a scoop.

4.2.3 University of Maryland

The University of Maryland placed third in the 2012 Robo-Ops competition. Their arm design utilized a four degree of freedom arm and a two-way clamp as the claw. They had multiple webcams mounted to the body of the robot and used these to aid in their sample acquisition process.

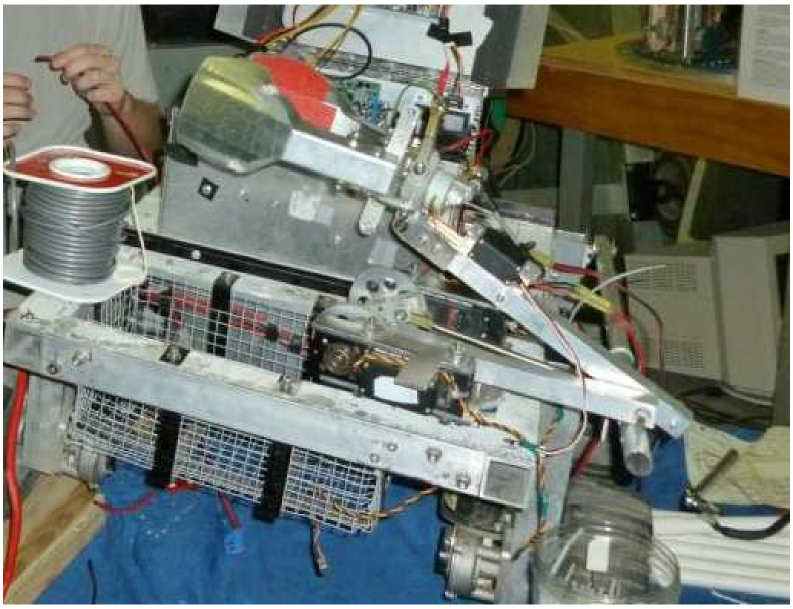

Figure 7; University of Maryland's arm and gripper for the 2012 Competition

The advantage of their clamp design was that they did not have to be as precise as Caltech when picking up the sample as they surrounded it with wide pads lined with soft material to increase friction. This would make the process a bit faster but has its disadvantages as well. The four degrees of freedom of the arm did not have to be aided by the moving of the robot to move in the x, y and z plane in front of the robot. This arm was also able to fold away quite well as to not have any effect on locomotion.

The disadvantage of the claw was that it would be able to pick up more than just what is desired. It is also heavier due to the size of its "hands", and required stronger motors. The arm has a control disadvantage, as it too requires complex control to move in a planar motion. In order to drop the rock from the gripper, it has to be released while the gripper is sideways which might introduce problems in the rock missing its storage bin.

5.0 Objectives to Improve

The main objective to improve for the collection process is to reduce the time required collecting and storing samples. This requires a clear vision system, a simple control algorithm and an efficient gripping device. The communication with the robot has to be simple and quickly executable, which involves the selection of the main computing system on board the robot. The vision system has to provide a clear view of the area under the arm as it is acquiring samples and not take away too much of the onboard computing power such the control of the arm is affected. Developing the control algorithm to be simple for the user will benefit the time of acquisition significantly. This would involve automating part of the control algorithm as well as finding a way to make manual manipulator control intuitive. Being able to use a gripping device that does not have to be precisely placed each time a rock is collected will help considerably in lowering the collection process time. This might mean undesired samples will be collected along with the desired samples. The team may have to either find a way to actively or passively remove the undesired samples or make sure the platform can handle the extra weight.

6.0 Design Criteria

The Decision Matries, below, show analysis of options for manipulator and computing hardware selection. The criterion, therein, are based on measurable performance parameters and the system needs outlined in the team's previous "Needs Assessment" report. Sample gripper concepts are still being evaluated.

Robotic Manipulator Decision Matrix								
	Rank	Weight	2-Axis		3-DOF		Pulley	
			Value	Score	Value	Score	Value	Score
weight/size	5	10.7	9	0.964	7	0.750	8	0.857
cost	7	3.6	8	0.286	8	0.286	8	0.286
controllability	1	25.0	9	2.250	5	1.250	5	1.250
invasiveness	6	7.1	9	0.643	9	0.643	9	0.643
reliability	3	17.9	9	1.607	9	1.607	7	1.250
autonimity	4	14.3	10	1.429	6	0.857	6	0.857
reach	2	21.4	6	1.286	8	1.714	8	1.714
		Total	8.464		7.107		6.857	

Table 1: Decision matrix for robotic manipulator selection.

	Cost	Power Consumption	Wireless Communication	Computing Power
Raspberry Pi	$35	3.5W	USB 3G/4G, USB WiFi, SSH	N/A
Arduino	$50	~1mW	WiFi	16 MIPS
ITX	$200	150W*	Same as Pi	128,000 MIPS**

Table 2: Decision matrix for computing hardware selection.

7.0 Individual Tasks and Concepts

7.1 Arm Concepts

7.1.1 Pulley Arm Concept

This arm concept design utilizes a pulley mechanism which moves a gripper along a track. Figure 8, below, shows the arm itself as a track which can be raised and lowered in reference to the ground, as well as pivoted about its base. The three degrees of freedom of the arm allows for a large reach area. When an object is picked up by the gripper, the arm can fold back over the robotic platform where it can release the object in to a collection-bin located on the top surface.

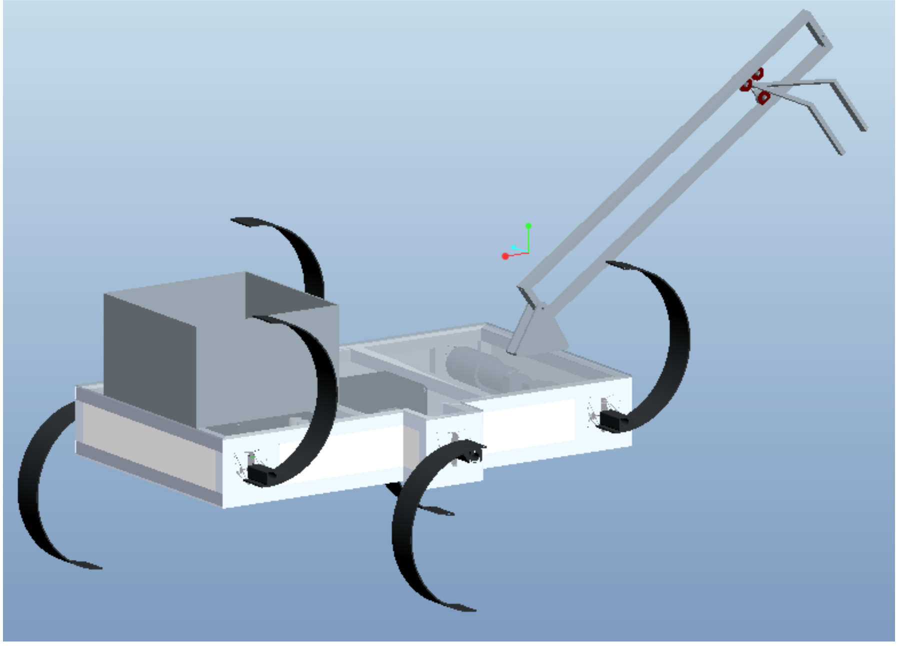

Figure 8: Pulley Arm Concept on the robotic platform with storage box.

One of the benefits of this design is that almost any gripper/scoop design can be implemented on the arm. This allows for modifications to gripper designs to be easily made if design problems arise. Also, the three plane operation allows for a wider range of gripper positions when reaching for an object as opposed to an arm which operates in two planes.

On the other hand, a downside to this design is that the pulley system is open to the elements. Debris can potentially become lodged in the track and seize motion of the gripper. This design also requires more complex control algorithms as opposed to an arm which operates in two planes.

7.1.2 Three Degree of Freedom Manipulator Concept

This robotic manipulator concept is a 3-DOF arm consisting of all revolute joints. It was evaluated that this is the minimum mobility necessary to manipulate specimens as required while maintaining versatility in how samples can be acquired. The joints are equivalent to a 2-DOF "shoulder", and a 1-DOF "elbow", with no "wrist" joint before the end-effector; servo or stepper motors may be used at each joint.

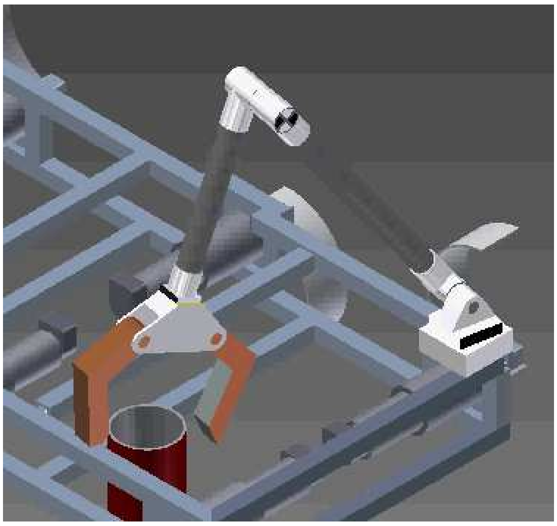

Figure 9: Robotic arm concept model generated using Autodesk Inventor Professional 2012. Gripper shown is generic and does not accurately represent gripper concepts generated.

Some key advantages of this concept is that its mobility allows access to a sample stowage compartment placed anywhere on the rover, and operate around any other instruments on top of the rover. Also, this arm can be mounted in front of or on top of the rover without jeopardizing its function. It is very compact in its stowed configuration, thus it easily meets the dimensional stowed rover configuration requirements.

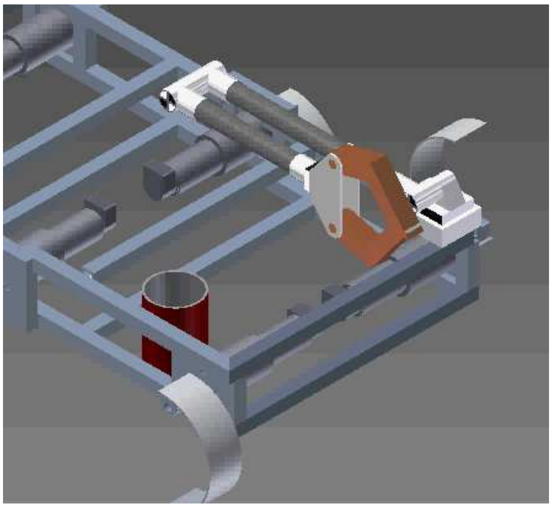

Figure 10: Robotic arm concept in stowed configuration. Model generated using Autodesk Inventor Professional 2012. Gripper shown is generic and does not accurately represent gripper concepts generated.

A major downside to this design is the complexity in controlling and/or automating the system. The number of motors that would be employed for the arm joints, and whatever gripper mechanism is implemented, would require some relatively complex control algorithms to simplify the control scheme to something more user friendly.

7.1.3 Planar Arm Concept

This concept addresses the question: Is there a difference between a robotic arm designed for a wheeled robot and one designed for a legged robot?

A wheeled robot is "planar" in that it cannot adjust the vertical position of its body; on the other hand, it is clear that a legged robot is non-planar because it can adjust the height and even the angle of its body by manipulating the orientation of its legs. This arm concept takes advantage of this fact by removing the vertical degree of freedom generally found in robotic arms and instead utilizing the legs of the robot to adjust the vertical position and angle of the end effector. The result is an arm that is very simple to control, requiring only two linear motion axes. The figure below displays the axes of motion for this design (marked in red).

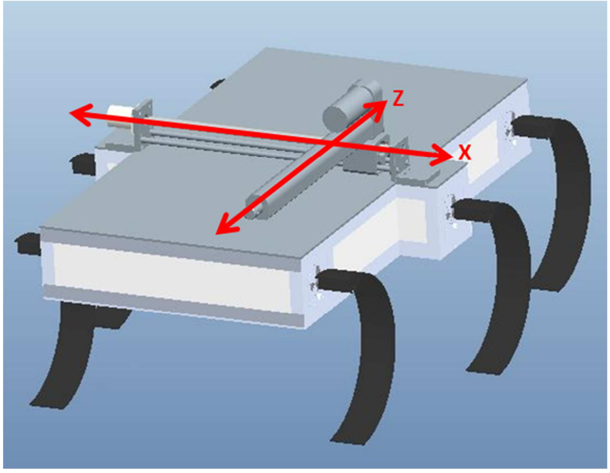

Figure 11: Depiction of the two axes of motion the Planar Arm Concept operates on.

The robot initiates the extraction process by lowering the plane of arm motion to the plane of the sample using the legs. In the above case, the sample (red ball), is located on flat ground so the robot simply lays all the way down, this is expected to be the case a majority of the time during the competition from examination of footage from previous years. The robot then positions the claw or end effector over the sample, captures it, and returns it to the storage container on the front of the robot. A scoop/pincer hybrid claw is shown above for demonstration purposes and is not the only possible claw configuration for use with this arm design. This sample extraction process is depicted in Figure 12 on the next page.

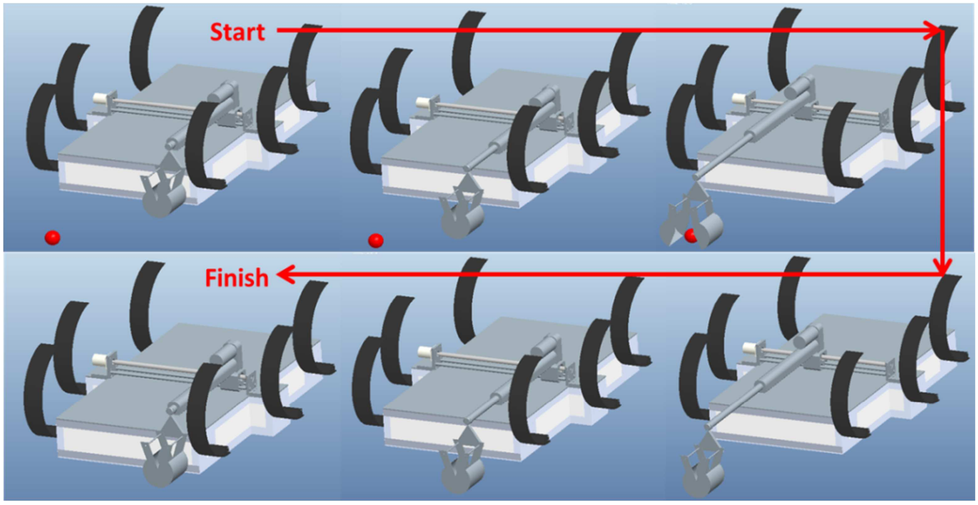

Figure 12: Step-by-step depiction of the Planar Arm Concept's sample extraction process.

Advantages

The operator will be controlling the robotic arm remotely and will guide the arm based on a low quality and low frame rate video, which will be delayed by several seconds. Every degree of freedom added to the arm will exponentially increase the time required to collect a sample with the arm, and as such, this arm has a significant advantage over the other proposed designs with respect to ease of control.

The number of motors or actuators required for the operation of an robotic manipulator is directly related to its weight, cost, and reliability. This design has the fewest number of required motors of the designs studied, thus it may have a slight edge in these categories (depending on specific hardware used). Also, the plane of the arm is located just above the top surface of the robot, which keeps the center of gravity low and results in a more stable robot. Finally, the end effector can be used to easily push away undesired rocks to isolate the target sample.

Shortcomings/issues

The design has several shortcomings and possible issues. The design requires that the storage box for the samples be mounted on the front of the robot, which would add to the length of the robot. As we are well under the maximum allowable dimensions specified by the competition, this is not an issue. Secondly, it is hard to predict how effective the legs will be in controlling the height of the robot, it may be the case that the robot is not stable at some intermediate positions between the prone and standing positions or that the resolution between these positions is too low for precise control. If this arm design is chosen, adequate control would be verified in the design of the electronics and a study would be performed to identify possible unstable positions.

7.2 Gripper Concepts

7.2.1 Pincer Style Claw

So called “pincer” style claws attempt to mimic the way relatively small objects are most commonly secured by the human hand. These claws generally consist of prongs or fingers which move towards each other to capture an object and prevent further motion through continuous application of force. This style of claw is good at picking up discreet objects but requires a relatively high level of precision from the manipulator it is attached to.

Figure 13: An example of a pincer-gripper. Image obtained from the Science in Seconds Blog.

7.2.2 Scoop Concept

There exist many versions of a “scoop” style sample/substance acquisition system, but they are all based on the idea of using the geometry (generally a concave surface) and the direction of gravity to capture and retain an object or substance. Scoops are generally used to pick up large quantities of a material and are not ideal for acquisition of discreet objects. Scoops can be operated successfully with much less precision than pincer style claws.

Figure 14: An excavator with the item of interest, its scoop, encircled.

7.2.3 Pincer/Scoop Hybrid

The scoop and pincer designs can be combined to form a claw that can pick up both discreetly and in bulk, is easy to control, and offers fairly high precision. A pincer/scoop hybrid claw moves two concave surfaces in a pinching motion to capture objects.

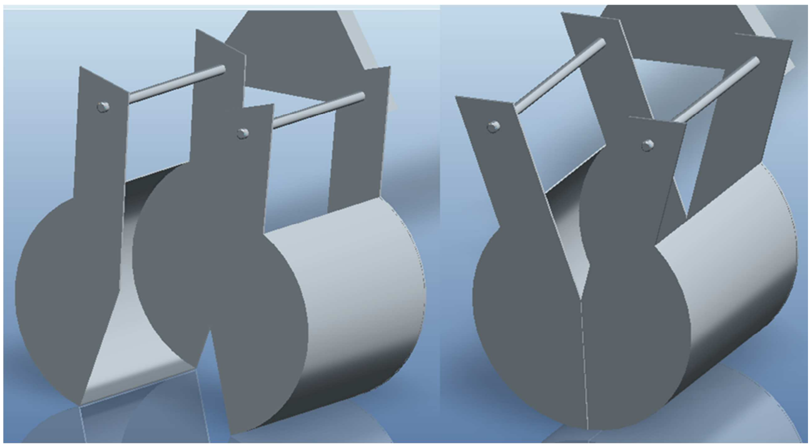

Figure 15: A solid model of the hybrid concept generated in Pro/Engineer software.

7.2.4 Universal Jamming Gripper Concept

This gripper concept utilizes not so common technique of picking up objects. Instead of having rigid moving members which grasp or scoop and object, this universal gripper conforms to the object in which it is grasping. The gripper consists of an ordinary latex party balloon filled with ground coffee. When the coffee-filled balloon is pressed onto the desired object to be picked up, the balloon and coffee conform to the object. At this point, a vacuum pump evacuates air from the balloon, solidifying the balloon, and thus gripping the object. This solidification is due to a “jamming transition” experienced by the coffee. When the air is vacated from the coffee filled balloon, the particulates of the coffee are pressed against each other causing them to resists slipping by one another or causing “jamming.”

Figure 16: The universal gripper conforms to the shape of any object it is lifting to allow for a delicate yet firm grasp

This concept is very beneficial in that the gripper will not have to orient itself to the object being picked up, but rather simply press against it. Conventional grippers require the target object to be oriented a certain way between the contact points to be picked up. This concept has several flaws when it comes to implementation in the competition. Although the universal gripper excels at easily gripping objects, it will also grip objects adjacent to the target object. The vacuum seal of the gripper can be compromised by sharp objects which can puncture the latex balloon. Also, the lack of need for orientation to the target object results in the lack of ability to un-wedge objects from tight spaces.

7.3 Camera Concepts

7.3.1 Internet Protocol (IP) Camera

IP cameras are typically used for surveillance purposes. For this reason, they feature the ability to pan and tilt. They also feature standard video transmission capabilities that can be remotely viewed from any personal computer (PC). These features are perfectly suited to the purposes of the competition. The standard pan/tilt ability of the camera would allow the rover operator to have a wide visual range. Another advantage to this type of camera is that it does not require any type of computational device; it is a completely standalone device. That is, it handles the video compression and processing by itself and then transmits the data. These cameras are also specifically built for outdoor use, which is where the competition will take place.

These capabilities do not come without a price, though, as IP cameras of this caliber are more expensive than standard webcams. Configuration of the device is also more complicated in that special care needs to be taken to ensure that all of the network values are correct. If the networking between the computer and the camera is not done correctly, then communication between the two would be impossible.

Figure 17: A typical IP camera (left) and webcam (right).

7.3.2 Standard Web Camera (Webcam)

The webcam is almost the complete opposite of the IP camera. It is cheaper and uses an onboard computer to handle video processing. There is also no need to worry about the correct network configurations since the onboard computer would take care of the communication aspect. As mentioned, this device would need an onboard computer for its data processing. This has the potential to consume more power than the standalone IP camera solution. The video streaming would also not be as straightforward since webcams are not set up to automatically stream as IP cameras are. Furthermore, webcams are not built for use outdoors. They are primarily social cameras for use with Skype and other software which, in most cases, does not involve the camera being used outdoors.

7.4 On-Board Computing Systems

7.4.1 Raspberry Pi

The Raspberry Pi is a Linux based computer that is about the size of a credit card and is a possible solution for onboard computing for the camera. It has a 700 MHz clock, 256 MB of random access memory (RAM), 2 USB 2.0 ports, an Ethernet port, and power is supplied via 5 V micro-USB port. There are already many peripherals that have been verified to be compatible with the Raspberry Pi; one of the most important being USB 3G dongles. The dongle would allow the Raspberry Pi to connect to a 3G network. Unfortunately the USB ports that are standard do not supply enough power for 3G dongles so a powered USB hub will be required. Since the operating system is Linux, communication with the Raspberry Pi is fairly straightforward with the ability to access its shell account. As long as the IP address is known, the Raspberry Pi can be communicated with and controlled.

However, the Raspberry Pi does not have enough pins to control all 6 motors in both directions and read every decoder. There are several pulse width modulation ICs and decoders available in the market but many of them require too many pins and those that are serial interfaced are not capable of handling 6 motors. Reading several decoders through a serial interface will introduce delays in our control algorithm. Therefore, the appropriate solution is to create the logic using an FPGA. This allows us to create the logic to control and read position from every motor in one compact design. The FPGA will have a serial interface which we will connect to the Raspberry Pi.

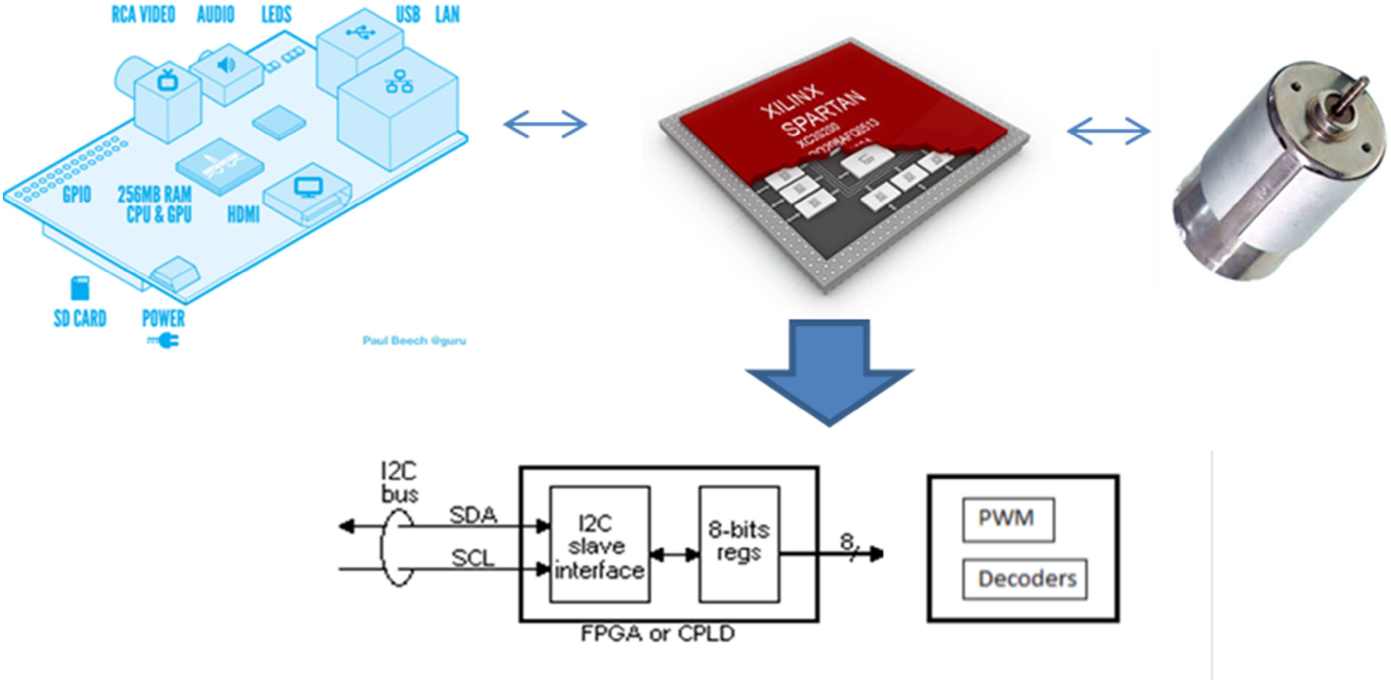

Figure 18: Functional diagram of controls hardware.

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