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STELLAR

SPACE TECHNOLOGY FOR EXPLORATION
LUNAR LANDING AND ROVING

Critical Design Review of
North Carolina State University
Senior Design:

STELLAR Lunar Rover

May 5, 2008

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I. Introduction

The STELLAR rover team was commissioned in June of 2008 and tasked with creating an Earth demonstration model rover for Team STELLAR's pursuit of the Google Lunar X-Prize. The rover team is composed of graduate students at NC State University, led by Dr. Andre Mazzoleni.

Team STELLAR is an ongoing project between NC State University, the Advanced Vehicle Research Center and some other private engineers in the Raleigh area. Its ultimate goal is to land a roving vehicle on the moon and drive that vehicle for half a kilometer, performing other smaller tasks along the way so as to win the Google Lunar X-Prize. The X-Prize offers 20 million dollars to the first team to land a roving vehicle on the moon and drive for 500 meters.

The early rover designs were studied over the summer of 2008. During the fall of 2008 the system was run through computer testing and the components were selected and their connections were programmed. After finalizing nearly all aspects of the design the design team submitted a preliminary design review in December of 2008. In the spring of 2009 construction commenced on the STELLAR rover and was completed in late April.

II. Objectives

X-Prize Objectives

The X-Prize has several mandatory objectives and a few optional secondary objectives. The most important objective is the drive of half a kilometer. This distance is measured in total roving distance, not a straight line. (e.g. Driving 250 meters in one direction and 250 meters in different direction is as acceptable as driving 500 meters in one direction.)

The other primary objectives are to broadcast high-definition video and pictures. The video must be transmitted in real-time, though the rules do allow a delay if the rover is in transit. The rover is also required to send an information packet back to Earth as the first "email from the Moon." This will presumably be one of the easier objectives as it only demands a transmission of data.

There are 2 required images that must be taken on the moon. The rover must take a high-definition series of photographs that display a 360º panoramic view of the landing site. The rover must take a self-portrait, presumably, though not necessarily, using one of its onboard cameras. This self-portrait must show at least 40% of the rover's surface area.

Each of the optional, secondary objectives has a monetary reward if it is accomplished. One of the most challenging of these is for the rover to drive an exceptionally long distance of over 5 kilometers. This distance again is in total roving, not a straight-line path.

There is also a reward for photographing any man-made objects that are already on the lunar surface. These include Apollo landing sites, unmanned probes, and debris from previous rocket impacts. There are 43 known locations where man-made debris can be found on the moon. While any of these objects would be acceptable for the objective, the site that is targeted will be chosen based on a series of criteria.

The X-Prize offers a reward for surviving the 14 and a half days of lunar night, with no sunlight and near absolute-zero temperatures. This will be a very challenging objective as it may require the ability to shut down the rover for two weeks and then reactivate it remotely. There will be a need to reserve power and heat to keep the components from being compromised.

There is also a reward for finding water-ice. Incidentally, finding water-ice would have a profound impact for future missions and colonization efforts. Finally, if the rover uses a bio-inspired drive system, there is additional money offered.

Of these secondary objectives, the rover team is focused on creating a rover that can drive up to five kilometers and survive the lunar night. The cameras which will be mounted on the rover will be able to photograph any previous lunar missions, but their ability to do so will be determined by the landing site and not the rover design.

It is also important to note that the X-Prize requires that the mission objectives be completed before December 31st 2012. After that date, the prize money decreases by 5 million dollars and the contest is withdrawn at the end of the calendar year of 2014.

Earth Demonstrator

The rover team was asked to oversee design and construction of an Earth demonstration vehicle and to develop operating procedures for that vehicle. The rover that has been built is not intended to be launched. The construction materials are off-the-shelf and as such, are not suited to the vacuum of space, nor the harsh temperatures that are found on the lunar surface. This rover will be used to test concepts for a later vehicle that is space-rated. One of the primary goals of the team was to determine the capabilities of the system. The design team has explored procedures for driving on the surface of the moon, for photographing specific targets and for emergency situations that may arise with the spacecraft.

III. Early Designs

18-Wheeler

The STELLAR rover team was originally presented with a very large, very robust design for the rover. The design was based on previous concepts that were proven with tanks and all-terrain vehicles.

One of the advantages of the system was that it could conceivably negotiate over any obstacle that was not taller than its base. It would also have been capable of driving through thick lunar dust and soil. The six legs of the rover, each having three wheels, would have been capable of varying the height of the rover and the tri-wheel feet on the legs had the ability to rotate independently.

Ultimately, the 18-wheel design proved to be too heavy and too cumbersome. The constraints on the system were not acceptable and many of the aspects of the design were simply not necessary. Lunar soil and dust was not found to be more than 1.5 inches deep by any manned or unmanned missions. The rover's power systems were too heavily taxed and it was difficult to find motors which were small enough to accommodate the design while being powerful enough to drive the system.

After a few weeks of analyzing the design and needs of the spacecraft, the 18-wheeled rover was dismissed.

Spherical Rovers

Based on previous experience with similar systems, the rover team did a survey of spherical rovers. Spherical rovers tend to be lighter weight, and easily compacted. Some of the designs that were studied were inflatable and could be put into a very small container for transport to the lunar surface. This has advantages for other aspects of the mission. Part of the rover team's considerations is to determine how the rover design will affect other aspects of the mission plan.

Spherical rovers are very stable. They can assume nearly any orientation and continue to function properly. They are also mechanically very simple. The basic spherical rover propulsion system is just a simple pendulum with a motor which shifts the center of gravity forward, letting the rover's own weight push it along its path.

The disadvantages of spherical rovers are that they do not provide many hardpoints for attaching cameras and sensors. There is also very little room on a spherical rover for installing redundant systems. Also, spherical and other non-traditional shaped rovers have yet to be tested in space and therefore their performance cannot be anticipated.

It was decided, after careful analysis of a variety of designs, that a more traditional design was better for mission safety. The rover team determined that a small, wheeled design was and is ideal for its reliability and its known behaviors. Wheeled rovers have been used on the Moon, Mars and hazardous environments on Earth. They are a proven technology and the problems associated with them can be predicted and accounted for.

IV. Shrimp Rover

Overall design

The shrimp design is a six wheeled rover. The wheels are arranged in a rhombus/hexagonal configuration as shown in figure 1. It should be noted that in Figure 1, the front of the rover is on the right.

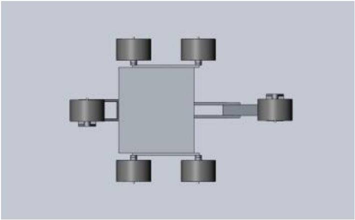


Figure 1: Wheel Arrangement

The four central wheels are mounted on two bogies, one on each side. The back wheel is fixed to the frame vertically, though it can be rotated horizontally. The front wheel is mounted on a fork that is free to rotate and to rise up to climb over an obstacle. This configuration allows the rover to climb over hazards up to two times its wheel diameter. The climbing sequence is shown in figure 2.

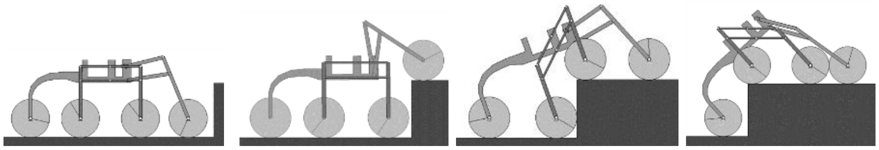


Figure 2: Shrimp Rover Climbing Sequence

The main advantage of this design is its ability to climb over any conceivable obstacles that would be encountered on the moon. Also, the known reliability of wheeled rovers is incorporated into this design making it ideal for the given mission.

The basic tenants of the Shrimp design were developed by an outside research team. While the original design shares many features with our model, the original was not designed for extraterrestrial missions. As such, the design team has made a number of changes, both in scale and capabilities. The frames of the two designs are similar, but the components that power and control the robots are very different.

The design team had a goal to keep the final weight at less than 20 kilograms (44.09 lbs.) and the overall length as short as possible. This was done in order to allow for the transport vehicle to have as few requirements as possible. The working drawing of the STELLAR rover can be seen in Appendix A and the isometric view of the spacecraft is shown in figure 3.

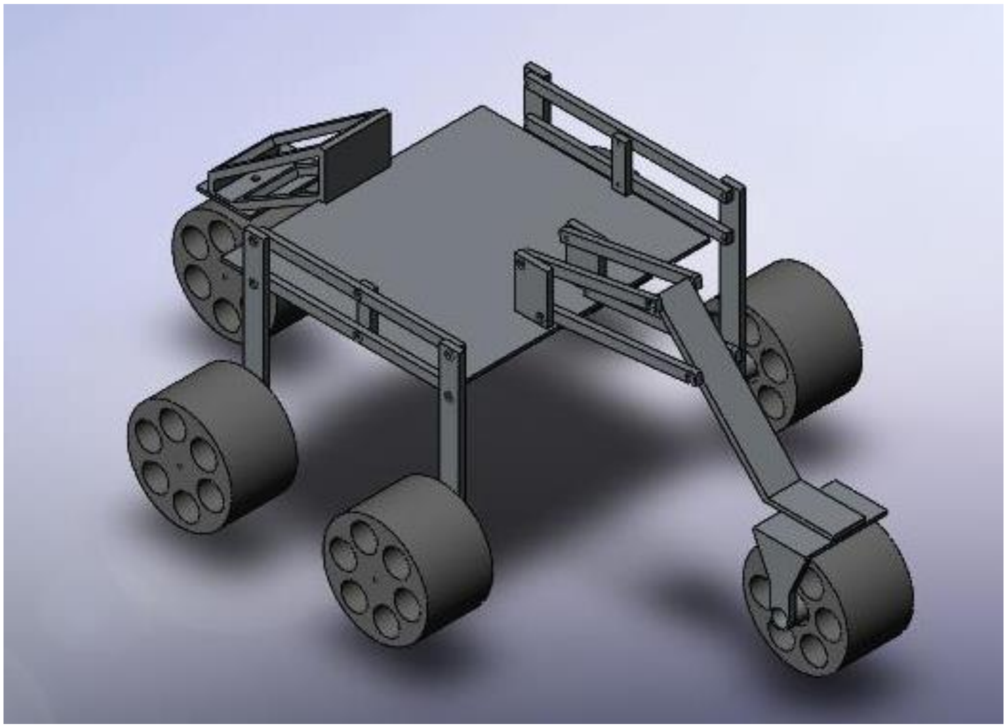


Figure 3. Isometric view of the STELLAR rover (without components)

V. Controls

Laptop Control System

The earth demonstrator rover is controlled remotely via commands issued from a laptop computer. The laptop is connected to the rover through a 2.4 GHz wireless router that is mounted on the rover’s baseplate. PWM generation will be done by a GPUX PWM driver. This device connects to the computer via a USB 2.0 port and converts a digital signal into a PWM signal. A 4-channel USB server connected with an ethernet cable to the wireless router will provide the connection between the GPUX and the laptop. In this configuration, all software is located on laptop, allowing the controllers to update the mission software during driving operations if necessary.

The GPUX is a four channel PWM driver. In order to use the PWM most efficiently, two signal splitters are used so that three drive motors can be controlled by one PWM signal. This means that all six drive motors can be controlled with only two of the four channels on the GPUX. A third channel is used in conjunction with a splitter to control two servos that will be used for steering. This leaves one PWM channel open for use with the camera mast though it can be fitted to serve other hardware, as mission requirements demand.

The Keyspan USB server has four USB 2.0 ports. One is used for the GPUX PWM driver and the other three are available for additional components.

The wireless router contains four Ethernet ports, allowing for up to three additional Keyspan USB servers to add additional cameras and/or GPUX drivers as necessary. A schematic of the control system is shown in Appendix A and the source code for a basic control program is listed in Appendix B.

The laptop controls allow the operator to have a consistent, clean interface for controlling the vehicle. This was done to eliminate operator error and to add an element of realism because actual ground control operations are handled with software commands given through a standard computer interface. The system is programmed in C Sharp and uses the standard command interface. The system has basic commands such as left, right, forward and reverse. Once a direction is set, the operator inputs a power percentage which is communicated to the motors. At this time, the commands are being refined to achieve maximum efficiency.

VI. Power

Power Requirements

The components requiring power include the router, USB hub, PWM generators, motors, and servos. The router requires a 12V supply, the motors require 7.2V, and the rest of the components will be powered through the USB hub using 5V. Due to lack of documentation for many of the components (a common problem when components are cannibalized from previous projects), a power budget had to be developed over the construction phase of the project.

Power Systems

To ensure a safe delivery of power, independent power systems have been utilized. Because the hub and the components that it will be controlling draw a small current, they are assigned a single system through the on board lithium-ion battery. There are two onboard battery packs with 4 AA batteries in each. One is used to power the servo motors on the front and rear wheels, the other is used to power the onboard computer systems.

As more sensors and equipment are added to the rover, more power systems will be added to accommodate the upgrades.

VII. Motors

Motor Requirements

To estimate the torque required for the rover, a mass of 25 kg was assumed (overestimating the maximum of 20 kg for a factor of safety) with a wheel radius of 0.08 meters. The equation

$$T = \frac{R(\cos(\theta) * m * g * \mu + \sin(\theta) * m * g)}{n}$$

was used to calculate the torque required per motor, where T is torque required, R is the radius of the wheel, m is the mass of the rover, g is the acceleration due to gravity, n is the number of wheels, μ is the coefficient of friction, and θ is the angle of incline. From this equation it was determined that a motor with a torque rating of 5 to 7 N-m would be ideal. Appendix C shows the results of this calculation for various angles of incline and coefficients of friction.

Motor Selection

After exploring a number of different options for the rover's motors, the design team selected the HG62 geared motor, commercially available from robotics retailers. This motor meets all the needs of the project. Its stall torque is 660 oz-in, which comes in at just under the ideal of 5 N-m. The motor's gearbox is just over 1.5 inches square and the entire motor weighs less than 17 ounces. At four inches in length it fits securely into the custom wheels that were created.

The small size, low cost and low power requirements combined with the abilities of the motor to turn each wheel efficiently made it the best available choice for the design team.

Figure 4: HG62 Geared Motor

VIII. Chassis

Frame

The rover frame is made of aluminum and low density polyethylene. The side rails and legs ensure stability and robustness. Aluminum was used because it has a high strength to weight ratio, is affordable and easily procured. The mounting plate, or base, is constructed from a low density polyethylene. This material is readily available and has a high strength to weight ratio. Due to the complex layout of components on the base, a material that is easy to cut and manipulate is necessary. The aluminum rails were assembled using locking nuts and bolts. The base is attached using L brackets.

Wheels

Each of the rover's 6 wheels are powered. The HG 62 geared motors are located inside the wheels with the motor shaft attached to the leg. This provides the maximum clearance for the rover while also protecting the motors from impact and debris. The wheels themselves are molded from a two-part foam called A-B foam. This material, once mixed, expands to 25 times its original volume and has a density of about $3.6e^{-5}$ slugs/in^3. A single mold was created to ensure each wheel is as similar as possible. This mold also serves to introduce tread as needed for the lunar surface and a center sleeve for the motor to reside. The mold is 180° to allow for ease of use. After the half-wheels were created, they were combined with an adhesive and cured. A computer model of the mold is shown in Figure 5.

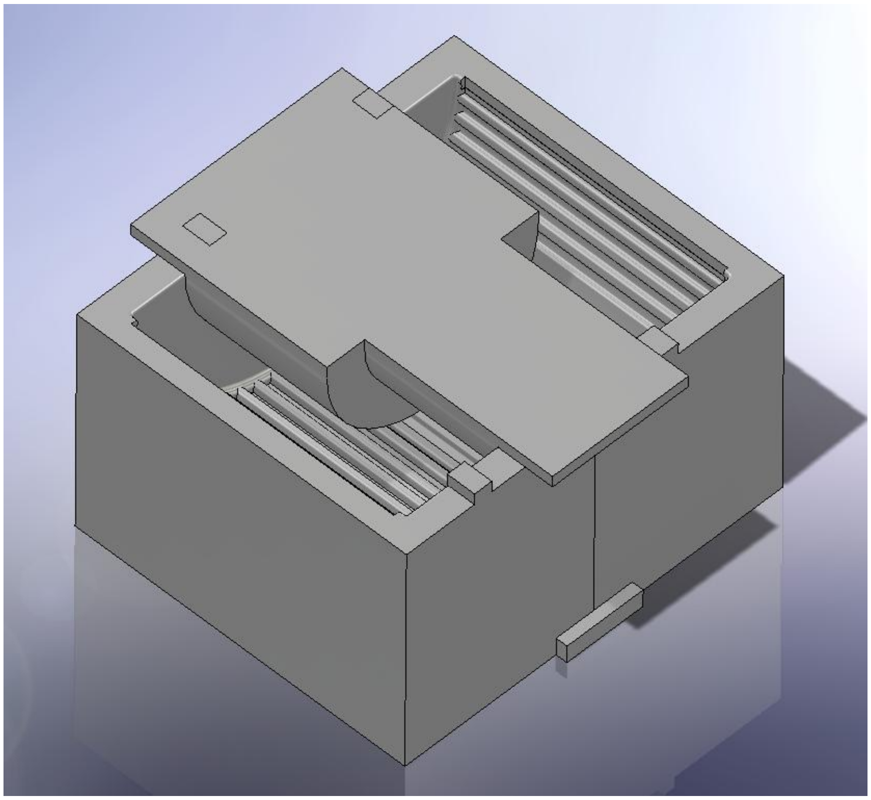


Figure 5: Half-wheel mold

The void space in the mold was created to allow room for the motor, bearings and clearance space for rotation. The outer hull of the mold includes ridges to provide traction for the wheels during movement over uneven or unstable surfaces.

The techniques for constructing and extracting the wheel halves from the mold had to be developed over the course of the project. Several initial failures led to the team lining the mold with a sheetwrap for each new half wheel. This allowed for a much easier extraction, though there was a drawback in that the sheetwrap became incorporated into the foam. This has not been an issue with driving or wheel rotation, though it was an unexpected side effect of the construction process.

Several of the rover wheels were painted with black spray paint, but when problems developed with shrinking during the drying process, the practice was abandoned for lack of positive benefits to the overall design.

Initial estimates of the weight of each wheel without the motor installed came out to be .2327 lbs. (.1056kg) and .4827 lbs. (.2189kg) with the motor. With six wheel-motor assemblies this consumes 2.8962 lbs. (1.314kg) of the overall weight budget. This is significantly the lightest option possible for this rover.

Because the foam is not a purely isotropic material, further testing must be performed to ensure structural integrity. If such testing shows problems, internal spokes can be included as necessary to gain internal strength. The entire configuration can be seen in Figure 6.

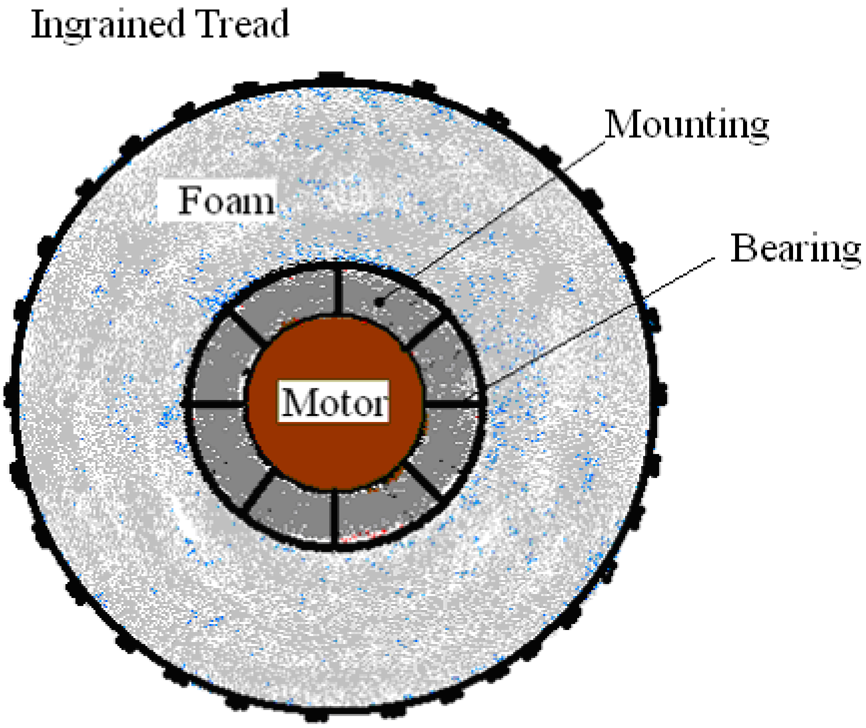


Figure 6: Wheel Cutaway

Building Materials

With the rover being a proof of concept vehicle, the design team attempted to keep costs low by using cheap and easily obtained materials. Aluminum bars and angles are the main structural component for the rover. The polyethylene which was used was found commercially with dimensions that were acceptable for the rover's design. Because the wheels' main requirements are shape and weight, foam was used to allow for custom shaping and very low density. With all of these building materials, nuts and bolts and other simple types of fasteners were utilized. This accelerated the build phase of the design greatly.

Aluminum and polyethlene have both proven to be effective for construction of spacecraft in the past and particularly of roving spacecraft. The design team has hundreds of man-hours of experience with both materials, in design and machining and was able to adapt the materials to from off-the-shelf applications to the rover design.

Component Layout

The base-plate houses the rover's power and sensor systems. These components include the control systems, the various power supplies, and the communications hardware. There were two important considerations for the layout of these components; one was the implications that arose from wiring the systems together, second was that the vehicle's center of mass had to be controlled so that the rover has maximum stability when overcoming obstacles. For this proof of design concept, this layout was accomplished through trial and error during the construction phase. This proved to be the most efficient method for this type of design.

A telescoping rod for the camera is mounted at the front of the baseplate. With upgrades in the coming weeks, the rod will be outfitted with a new camera and will be able to be raised and lowered to take pictures from a variety of heights and orientations.

IX. System Testing

Computer models were used for preliminary tests of the design. Computer models of the rover were built in a virtual environment and were tested to make sure that the basic tenants of the design (weight, shape, drive system dynamics, etc.) were acceptable. These early tests encountered some software difficulties, but observed no problems with the elements of the rover.

With construction complete, the rover is currently ready to be put through a series of real-world tests. These trials will determine the capabilities of the system in the areas of driving and climbing, navigation, communications and information gathering.

Driving and climbing tests will be the most important of all the analyses that the team makes. It is necessary to determine the types of obstacles that the rover can climb over and the ones that it must navigate around. The design of the rover was focused on climbing ability. As it is impossible to know the obstacles that the rover will encounter when it reaches the lunar surface, it was considered best to have a vehicle that is capable of climbing as much terrain as possible. When the rover encounters a large obstruction, the question will be whether to drive around or climb over the object. In order to answer this question, the team will test as many different shapes and surfaces as possible to determine the abilities of the system.

Rules will be developed based on these tests. The design team will determine the maximum climbing angle, the maximum height that the rover can descend from and the types of terrain on which the rover can maintain traction.

Descending from obstacles is an often overlooked aspect of the testing. It is useless to climb onto a rock or obstruction if the rover cannot descend the other side.

It is important to discover how much dust that the rover will kick up as it drives across the surface. The rover will be driven through test beds of various types of dust and soil and video will be taken. These tests will allow the design team to anticipate problems with dust and debris and to make any changes to prevent malfunctions on the moon.

The rover will have to be able to communicate over vast distances, this includes both sending information back to its controllers as well as taking commands from those controllers and carrying them out. In order to test the communications capabilities in the system, a test will be run involving a radio balloon which should allow a signal from the rover to bounce and be relayed to a tracking station several miles away.

Once all of these tests are carried out and analyzed, then the design team will create a final list of procedures for operating the rover on the surface of the moon. For any situation where the rover encounters territory that it cannot drive around, the ground control team will have to use the onboard cameras to make decisions based on the terrain and the rover's current status. The situational tests that the rover will be put through will allow that future ground control team to have a better understanding before making critical mission decisions.

X. Science Component

The fully-developed space-rated rover will be armed with instruments for scientific discovery. A scientific aspect is important for the rover because, even among lunar probes, very few get a chance to look at the surface from ground level. To date, no probe has been able to photograph the surface from ground-level with the high definition photography currently available.

Helium 3

The design team is currently investigating Helium 3 detectors. Helium 3 has remarkable potential as a fuel source for future colonization efforts. On Earth, its equivalent cost as a fuel would be on the order of 40,000 dollars per ounce. While currently the technologies to process and use Helium 3 are still being developed, each new discovery indicates that it will be the primary power source for colonizing the solar system.

Helium 3 is a helium isotope with one neutron and 2 protons. It is only made in the core of stars like the sun. It is formed when a proton combines with a deuterium atom. Helium 3 is rare on Earth but should be more plentiful on the moon because solar winds can reach the surface of the moon more easily. The isotope is lighter than regular helium and is not radioactive. It is stable and may exist on the moon in quantities up to 30ppb. It is a gas found inside lunar rocks and soil.

While processing helium 3 requires facilities capable of burning thousands of pounds of soil, with only 220 pounds of He3 one could power a city the size of Dallas for a year.

Mapmaking & Geology

The control team will use the high definition pictures, taken both from the ground and from the approach to the lunar surface, to create the most accurate maps of the lunar surface ever made.

Geologists will be part of the control team and, following completion of the primary mission objectives, the STELLAR rover will use its onboard instruments to study the local geology. With the clarity given from STELLAR’s cameras, geologists will be able to gain new insights about the moon’s structure and history.

XI. Landing Site

While this is an Earth-demonstrator vehicle, the design team is constantly thinking about how the rover will fit into the larger mission plan. With that in mind, the team has developed a recommendation for the rover's landing site.

There are 62 possible former landing sites with man-made debris available to observe. These include Apollo landing sites, unmanned probes and crashed spacecraft. Of these sites, 4 are on the farside, making them inaccessible and 15 do not have precisely established coordinates.

Of the 43 known landing sites, 28 are unmanned probes, which vary in the type of terrain they have landed on, but in general should not be targeted because the man-made "footprint" of material they have left behind is relatively small. There are 9 sites which are crashed debris. These are third stages of Saturn V rockets from Apollo missions and crashed ascent stages from Apollo Lunar Modules. It should be noted that the debris from these crash sites may be so far embedded into the surface as to not be observable. These crash sites have specific known coordinates and in some cases have created small craters which could be targeted, but again, their relative size is small compared to the 6 Apollo landing sites.

Apollo 12

The Ocean of Storms was the target of Apollo 12 and was chosen because it was the site of a previous landing. Surveyor III was an unmanned space probe that had landed in that area previously and Apollo 12 was sent to rendezvous with it. This double landing site has a great advantage in that the there is the potential to find two spacecraft whereas at any other site, only one vehicle could be observed.

The Ocean of Storms has large open tracts of terrain which would be ideal for driving. The area does have several large craters, the most important of which is the Snowman crater formation where Surveyor III is located, but the photos show that these craters are relatively free of large rocks and boulders and have gentle slopes.

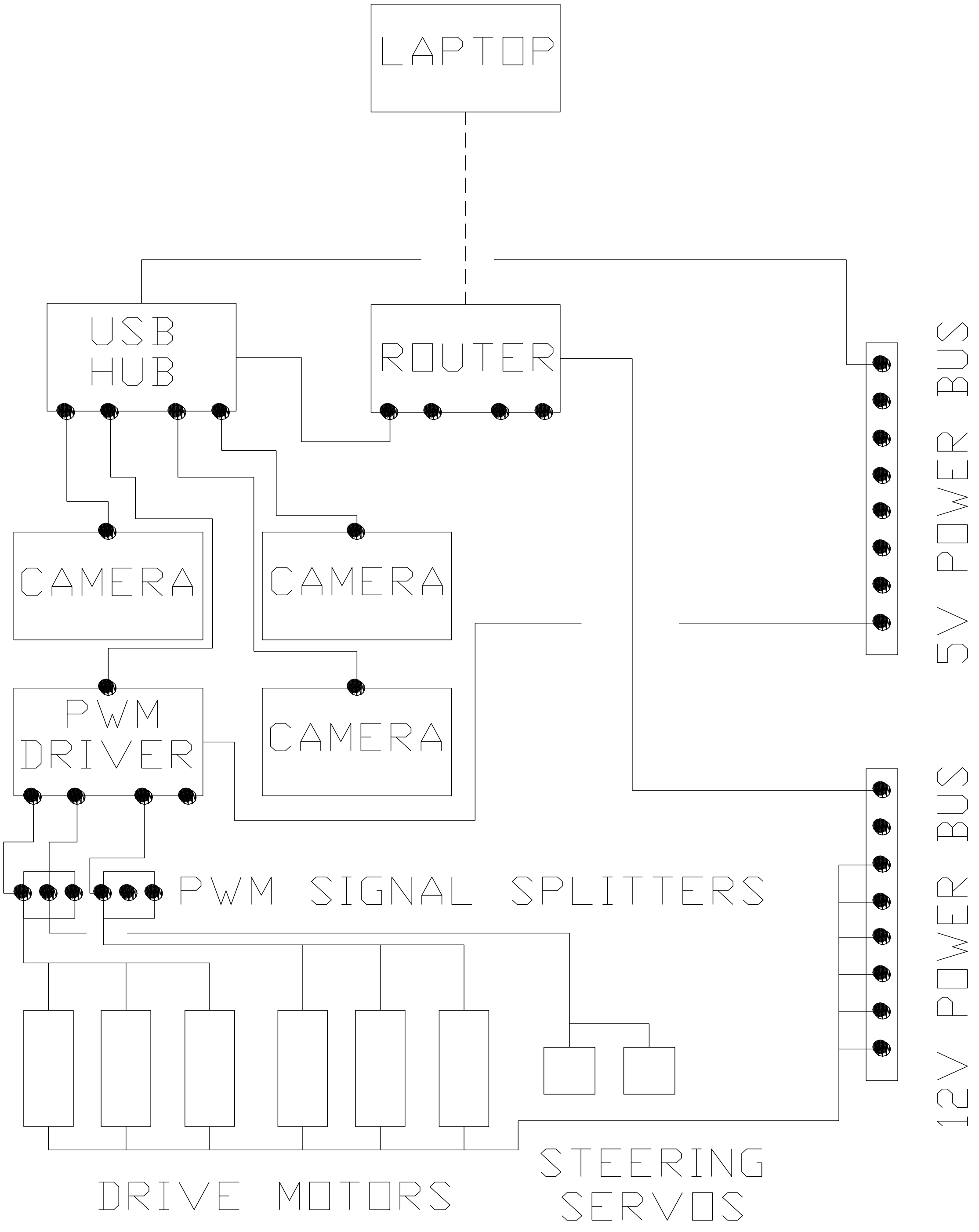
In the event that the lander cannot reach a pinpoint target, the Ocean of Storms has large amounts of open ground on which the rover could drive. Much of the surrounding area is suitable for the mission.

Apollo 12's landing zone in the Ocean of Storms has all the aspects of an ideal location to accomplish many of the mission's primary and secondary objectives. The site has both the descent stage from the lunar module Intrepid, as well as the Surveyor III unmanned probe.

The Ocean of Storms was the site of the first precision landing on the moon. It has a wealth of objects to photograph and it has good terrain for driving. Photography both from orbit and from ground-level confirms that there are not a great deal of boulders which will impede driving. The Ocean of Storms also has wide open spaces of relatively flat land. This is exactly the kind of terrain that is good for unmanned rovers.

The Apollo 12 landing site is relatively close to the lunar equator. This is important because landing in higher latitudes would likely require more fuel to achieve an orbit with a higher inclination. It is important to have as few burns as possible, not only for the cost of fuel, but to avoid adding unnecessary risks to the mission plan.

Appendix A: Control Schematic



Appendix B: Source Code

```
using System;
using System.IO.Ports;
using System.Threading;


public class PortChat
{
	static bool _continue;
	static SerialPort _serialPort;
	static byte[] rbuffer;

	public static void Main(string[] args)
	{
		byte [] buffer;
		string message;
		StringComparer stringComparer = StringComparer.OrdinalIgnoreCase;
		Thread readThread = new Thread(Read);

		// Create a new SerialPort object with default settings.
		_serialPort = new SerialPort();
		buffer			= new byte[5];
		rbuffer	= new byte[5];

		// Allow the user to set the appropriate properties.
		_serialPort.PortName = SetPortName(_serialPort.PortName);

		_serialPort.BaudRate  = 9600;
		_serialPort.Parity   = Parity.None;
		_serialPort.DataBits  = 8;
		_serialPort.StopBits  = StopBits.One;
		_serialPort.Handshake = Handshake.None;

		// Set the read/write timeouts
		_serialPort.Open();
		_continue = true;
		readThread.Start();

		Console.WriteLine("Type V to read GPUX Version.");
		Console.WriteLine("Type MIN to set all ports to 1.0 mSec.");
		Console.WriteLine("Type MID to set all ports to 1.5 mSec.");
		Console.WriteLine("Type MAX to set all ports to 2.0 mSec.");
		Console.WriteLine("Type RAMP to ramp up and down ports A and D.");
		Console.WriteLine("Type QUIT to exit.");

		while (_continue)
		{
			message = Console.ReadLine();
			message.Trim();

			if (stringComparer.Equals("quit",message))
			{
				buffer[0] = (byte) ':';
```

```
            buffer[1] = 192;
            buffer[2] = 192;
            buffer[3] = 192;
            buffer[4] = 192;
            _serialPort.Write(buffer, 0, 5);
            _continue = false;
        }
        else if (stringComparer.Equals("min",message))
        {
            buffer[0] = (byte) ':';
            buffer[1] = 128;
            buffer[2] = 128;
            buffer[3] = 128;
            buffer[4] = 128;
            _serialPort.Write(buffer, 0, 5);
        }
        else if (stringComparer.Equals("mid",message))
        {
            buffer[0] = (byte) ':';
            buffer[1] = 192;
            buffer[2] = 192;
            buffer[3] = 192;
            buffer[4] = 192;
            _serialPort.Write(buffer, 0, 5);
        }
        else if (stringComparer.Equals("max",message))
        {
            buffer[0] = (byte) ':';
            buffer[1] = 255;
            buffer[2] = 255;
            buffer[3] = 255;
            buffer[4] = 255;
            _serialPort.Write(buffer, 0, 5);
        }
        else if (stringComparer.Equals("ramp",message))
        {
            for (int i = 127; i < 255; i++)
            {
                buffer[0] = (byte) ':';
                buffer[1] = 220;
                buffer[2] = 164;
                buffer[3] = 191;
                buffer[4] = (byte) (255 + 127 - i);
                _serialPort.Write(buffer, 0, 5);
            }
        }
        else
        {
            _serialPort.Write(message);
        }
    }

    readThread.Join();
    _serialPort.Close();
}
```

```
    public static void Read()
    {
        while (_continue)
        {
            try
            {
                _serialPort.Read(rbuffer, 0, 1);
                Console.Write("{0} ", rbuffer[0]);
                Console.Write("{0}\n", Convert.ToChar(rbuffer[0]));
            }
            catch (TimeoutException) { }
        }
    }
    public static string SetPortName(string defaultPortName)
    {
        string portName;

        Console.WriteLine("Available Ports:");
        foreach (string s in SerialPort.GetPortNames())
        {
            Console.WriteLine("    {0}", s);
        }

        Console.Write("COM port ({0}): ", defaultPortName);
        portName = Console.ReadLine();

        if (portName == "")
        {
            portName = defaultPortName;
        }
        return portName;
    }
}
```

Appendix C: Motor Requirement Calculation

Motor (RE25)	V (volts)	P (watts)	Efficiency	T (N-m)	Gear Head (GP32)	Ratio	Efficiency	Output (N-m)
118743	12	10	0.87	0.0291	116164	51	0.7	0.9038169
					116169	111	0.7	1.9671309
					116174	246	0.6	3.7367892
					116179	492	0.6	7.4735784
339150	12	20	0.79	0.0235	116164	51	0.7	0.6627705
					116169	111	0.7	1.4425005
					116174	246	0.6	2.740194
					116179	492	0.6	5.480388
118750	15	20	0.83	0.0206	116164	51	0.7	0.6103986
					116169	111	0.7	1.3285146
					116174	246	0.6	2.5236648
					116179	492	0.6	5.0473296

Appendix D: Financial Budget

Product Description	Vendor	Cost
Webots EDU dongle license	Cyberbotics Ltd.	336.00
GPUX USB to PWM driver Signal booster/ splitter	The Robot Market Place	103.95
Team Matrix pro-Lathe motor	Hobby Masters	19.99
Angle Aluminum (2) 1/8"	McMaster Carr	29.36
Aluminum plates, Steel brackets	McMaster Carr	83.14
AB Foam	Special Effect Supply Corp	54.42
2 Aluminum angles	McMaster Carr	29.36
Signal Booster 6 Main motors	Robot Marketplace	334.89
Mini Aluminum Hub 3 sets of 2	Robot Market place	43.46
Aluminum Bar	McMaster Carr	6.33
Ball and Roller Bearings (6)	McMaster Carr	146.34
Lantronix UBox	Neteon	108.00
		$1295.24

Appendix E: References

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Lunar and Planetary Institute. “Apollo 12 Mission.” http://www.lpi.usra.edu/lunar/missions/apollo/apollo_12/.

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