Lunar Rover Competition

Critical Design Review

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Background Research

The Mission

The Moon has been central to human curiosity and explorations since the 1960's where the space race and John F. Kennedy's ambitious speech accelerated technological advances, ultimately leading to Apollo 11's successful landing in 1969. Missions to the moon; both manned and robotic have remained in close proximity to the equator, (not travelling further than 40^0 in latitude) as it is generally flatter than the Moon's mountainous North and South Poles [1].

The South Pole of the Moon is of great interest to researchers and the space community due to the possibility of frozen water. As a result, in 2010 the European Space Agency, proposed a robotic lunar mission, in which a lander would remain at the rim of the Shackleton crater whilst a rover would travel down into the crater and retrieve soil samples[2].

This ESA mission outline mirrors our aims within this project. In which a rover was designed to travel down into the crater, collect a soil sample and return to the lander at the crater rim. To achieve this, the Moon terrain and conditions, previous robotics missions, mechanics, electronics, programming and space standards are all considered.

Environmental Considerations

The Surface of the Moon

The Moon has a rocky cratered surface as a result of meteoroid impacts. Due to the lack of atmosphere, even small meteoroids impact with the Moon's surface, whereas on Earth they would be burned up in the atmosphere. Rock samples collected during Apollo found small rocks with tiny craters due to their impact. Unlike Earth, the majority of the Moon's ancient geological features are present as there are no bodies of water or plate tectonics to shape the surface[3].

The Moon's rocky surface is known as the Lunar Regolith, which consists of fine dust particles, glass spheres and rocks as a result of meteor strikes[4]. The soil is dry due to the lack of atmosphere and liquid water and therefore is inorganic[3].

The South Pole of the Moon

The South Pole of the Moon is of particular interest due to the possibility of discovering frozen water and other volatile compounds found in craters. Finding a source of water would be key to proposed ideas such as Moon villages, where the cost to transport water from Earth is very high. Ice would provide a supply of water, oxygen and fuel; essential for human habitation on the Moon[5]. Additionally, volatile compounds which can be found in craters could possibly date back to the beginning of the Solar system and would enable further research and understanding on lunar and solar system formation[6].

Mountain peaks and crater rims are beneficial for robotics missions that require high solar outputs and almost constant communication with the Earth. This is due to periods of extended sunlight that higher altitudes are exposed to. To accomplish this, the lander will have to accurately land as higher regions are usually smaller in area [1].

The bases of the craters are exposed to very little sunlight, due to the low sun angle. Often the only light they receive is from distant stars or the reflection from Earth. The temperature in shadowed craters typically remains at 24 K, which creates cold traps where ice may be present. Another factor which affects the sunlight specific

areas of the Moon receive is its tilt. The Moon's axis of rotation is tilted at 1.5° which causes very long days and nights of approximately 2 weeks[5].

Shackleton Crater

The Shackleton Crater is positioned almost central to the Moon's South Pole and is approximately 12 miles wide and 2 miles deep[7]. It has suitable characteristics for robotics missions as the rim of the crater is exposed to extended sunlight (solar power) and the crater itself is in almost permanent darkness creating cold traps[8].

Ice could have formed over millions of years from cometary fragments, where water vapour may have condensed and precipitated on the walls of the crater. The frozen water could then be protected from sublimation by dust settling and compressing the ice. It is estimated that ice could contribute to 22% of the crater's surface[9].

Previous missions have shown mixed results as to whether there could be ice present. NASA' s Lunar Reconnaissance Orbiter flew at an altitude of 30 km and mapped the crater using an infrared laser where it measured that the base of the crater is more refractive than others. However, it also found the walls of the crater to have a greater reflectance, which is unexpected as occasionally they are exposed to sunlight which would cause evaporation. Researchers believe that this may be a result of shaking from Meteoroid impacts, or the pull of the Earth[8].

Mission Specific Environmental Considerations

In planning for the final rover design, problems which may be encountered in the lunar environment must be considered. For example, if not properly protected, the rover will likely encounter problems with solar radiation and overheating due to the lack of atmosphere on the moon[10]. These, among other possible concerns, will be discussed, along with possible solutions[11].

Due to the lack of atmosphere in the lunar environment, there is no protection from solar radiation. Radiation can damage electronic elements by disrupting the crystalline structure of semiconductors, thereby shifting the operating voltage of components[12]. To protect the electronic components of the rover from radiation, these will be shielded using spot shielding (rather than a local shield) due to the tight weight constraint. Candidate materials for spot shields include aluminium and polyethylene[13], both of which can be acquired at relatively low prices, and so would be ideal for this rover.

A major problem faced by the Apollo missions was the effects of dust particles[14] with components on the lander suffering from interference, as well as decreased visibility. Although there is not a great deal which can be done to increase the visual field of our camera if lunar dust were to impede it, we can prevent this dust from interfering with our systems by ensuring all electronic and mechanical components are properly enclosed and shielded from dust. This should prevent any damage to our systems, and allow the rover to carry out its tasks effectively despite any lunar dust.

A problem encountered by many satellites operating in the vacuum of space is overheating. As there is not an atmosphere present, heat produced by electrical components will not be dissipated through conduction and convection, and will remain within the system. This leads to electrical components overheating and ceasing to perform their proper function. This problem could be remedied by including a cooling system in the rover, such as radiators, or a built-in system using stored cryogenics[15]. This would allow heat to be removed from electrical systems, preventing overheating, and allowing normal functions to continue.

Previous Rover Missions

While considering structural designs, past rover missions were examined to identify the different suspension and wheel systems used. This allowed a comparison and overview of the necessary technical specifications required to traverse across the lunar surface.

Lunokhod:

The first rover to land on the Moon was the Soviet Union's Lunokhod 1, in November 1970. It was directed remotely from Earth for 10 months, covering a distance of over 10km. Lunokhod 2 followed 2 years later in January 1973, it was operational for four months until overheating brought an end to the mission, it is thought that lunar soil could be the cause[16].

The Lunokhod rovers housed all the necessary electronics in one tub-like chassis, which was pressurised to an atmosphere of 1 bar. This reduced the cost developing specialised technology for space. Both rovers could travel over rocks of 40cm due to the 8-wheel suspension system. The wheels themselves were made from a wire mesh tire and titanium treads and had a brake system. The rover steered using a differential system, where one set of wheels would travel at a slower speed than the other, allowing the rover to spin around in one direction. The steering itself was reduced to prevent the rover becoming stuck in the lunar soil.

The rover's batteries were charged using solar panels on the inside 'lid' of the tub and radioisotope heaters kept the batteries warm, allowing the rover to withstand the cold 2-week long lunar nights[17].

Apollo Lunar Roving Vehicle:

The Lunar Roving Vehicle (LRV) was the first - and so far only - manned rover driven on the moon or another planet. It was designed for the Apollo missions to allow astronauts to travel farther from their landing site. As it was manned, the astronauts controlled it directly using navigation and direction systems. The navigation system showed astronauts their position relative to their landing site and the communication system consisted of a television camera, radio communications and telemetry.

The mechanical system itself consisted of wheels, traction, suspension and steering control [18]. The LRV was a 4x4 vehicle, where each wheel was powered individually by an electric motor and had dust guards and a mechanical brake. Front and rear steering motors allowed the LRV greater manoeuvrability. The LRV had 2, 36-volt non-rechargeable batteries, providing contingency as the LRV would function using only 1[19].

The thermal protection system was essential in protecting the LRV from both the extreme temperatures and the dissipated heat from on-board equipment. When the vehicle was moving it disturbed lunar dust, to limit damage to components parts of the LRV were sealed. Heat from these sections was collected and the astronauts had to manually uncover the equipment [18].

Yutu:

Yutu is China's Lunar Rover which landed in December 2015. Yutu was configured of 6 independently powered wheels, 4 of which had independent steering. The rover was equipped with infrared imaging, a communication antenna, panoramic cameras and a robotic arm to drill and collect lunar soil.

Like the Lunokhod rovers, it was powered by solar energy by two foldable solar panels. The structure was covered in gold scales to deflect sunlight and therefore reduce the temperature and radiation that the rover experienced. Due to the very low temperatures during lunar nights the rover showed mechanical abnormalities and eventually the wheels and solar panels were no longer operational[20].

NASA's Mars Rovers:

NASA has designed and launched a series of rovers to Mars for exploration. The first was Sojourner in 1997, followed by Spirit and Opportunity in 2004 and Curiosity in 2012. Each rover traversed the rocky environment using a rocker-bogie suspension configuration, allowing the other wheels to remain under load and in contact with the ground while travelling over rocks and debris[21].

Sojourner was termed a micro-rover with 6 wheels, the front and rear wheels have independent steering which allows the rover to turn on the spot. The rover was solar powered, backed up by additional batteries. Any equipment not able to withstand the temperature of Mars was stored in a warm electronics box[22].

The Spirit and Opportunity rovers were both operated remotely from Earth and were expected to last 90-days. However, both outlived this by several years. They were field geology robots which made remarkable discoveries about the likelihood of water on Mars[23].

The Curiosity rover resembles Sojourner, Spirit and Opportunity, however; it is powered using a nuclear battery (using radioactive plutonium). This battery system allows the rover to be continually powered rather than relying on solar energy which is unavailable during the night or the Martian winters[24]. The rover also has 17 different types of camera, each accommodate a different function. It is able to collect, prepare and process soil samples as well as analyse the planet's atmosphere[25].

Design Specification

Mission Specification	1) The rover shall travel down a 30° slope, into a crater. 2) The rover shall be able to travel across rocky terrain, maneuvering 5-40 cm obstacles. 3) The rover shall travel over a 60 m straight. 4) Rover shall accurately reached the sample collection site. 5) Rover shall collect up to 500 g of the specified sample. 6) The rover should withstand a vibration test, comparable to a Falcon 9 launch.
Structure	1) The structure should be rigid to withstand applied stresses (experienced during the vibration test, and when travelling over the uneven surfaces) 2) It should be strong to support the rover. 3) The rover shall fit in a 30 cm cube container. 4) The rover weight shall be less than 5kg. 5) The centre of gravity should be considered for stability.
Command & Control	1) The rover is to be remotely operated, an onboard camera system can be used where there is no direct visibility of the rover 2) The rover should attempt to reconnect if signal is lost
Power	1) The rover shall use a removable, non-lead acid battery. 2) The battery must be removable. 3) Good battery practice should be followed. 4) The battery shall be protected from reverse connections, short circuits, over voltage, under voltage, overheating, and overcurrent.
Propulsion	1) Using power from the battery to run the motors, the rover should be able to travel the distance specified above. 2) The rover should have sufficient power to overcome the previously mentioned obstacles.
Materials	1) The rover shall use lightweight, cost-efficient materials, able to resist stresses due to the rocky terrain and vibration testing it will experience. 2) Thermal expansion coefficients should be considered in the selection of materials. 3) Materials for shielding and protection of components shall be carefully selected in order to ensure protection from radiation and thermal cycling.
Safety	1) There shall be no live voltage greater than 12V carried on any exposed point or area of the rover during its operation. 2) Electrostatic discharge should be considered, to avoid hardware loss. 3) There must be an external kill switch which isolates the battery power from the rest of the rover that is easily accessible in the event of an emergency.

Technical Specification

Weight	5 kg
Length	30 cm
Width	30 cm
Ground Clearance	approx. 15cm
Maximum Speed	0.25 m/s
Power Supply	15V Li-on battery
Range	120 m

High Level

Systems Breakdown

Control

This section will discuss the various hardware and software solutions which, once implemented, will allow the final product to navigate challenges with the aid of environmental sensors. Further, this section will describe the microcontroller which will interface with the aforementioned sensors, as well as interfacing with cameras, motor drivers and the kill switch.

Sensors

The first such environmental sensor is a rotational sensor or rotary encoder, this, in combination with a GPS tracking chip, allows the operating base to collect information on the rotation of the rover's wheels and their current direction and location, information which in turn can be combined with pre-existing information regarding the rover's dimensions to eventually create a programmable method of measuring distance crossed[26] by the rover as well as providing a way to instruct said rover to move across specific distances. Moreover, the rover will be equipped with a combination of infrared and ultrasonic[27] sensors arranged in a 'skirt' around the front of the rover as well as a 360 degree camera to relay information regarding its surroundings back to base. This information can then be filtered through SLAM (simultaneous localisation and mapping) algorithms for accurate obstacle avoidance and surface mapping[28] allowing autonomous movement in cases where the 360 degree camera will not be functional or useful such as the loss of connection to ground control or low power. During normal operation, however, the rover will receive instructions to move from ground control where the base will be equipped with the means to allow manual control over rover movements & actions such as a Joystick, though PC mouse or keyboard will also be able to achieve this. The rover will further be equipped with a small scale to be added to the sample collector allowing accurate weight measurement.

Microcontroller

A Raspberry Pi 3 will be used as the rover's microcontroller as its complexity allows for better multitasking and more processor intensive programmes to run on the finished rover. The Raspberry Pi has a recommended input voltage of 5 V and a recommended input current of 2 A. This means it cannot be directly connected to the battery without causing damage. In order for the battery to be able to power the Raspberry Pi, a 5 V regulator must be integrated into the circuit. A regulator has a pin for input (from the battery source), one for a ground connection and one for the 5 V output (regulated output that can be fed directly into the Pi). The capacitors can be included in the circuit to reduce the "line noise" (random fluctuation in electrical signal).

The regulator chosen is the L78S05CV. It can regulate an input ranging from 10 V to 35 V to give an output voltage of 5 V (so the proposed input of 15 V would be regulated).

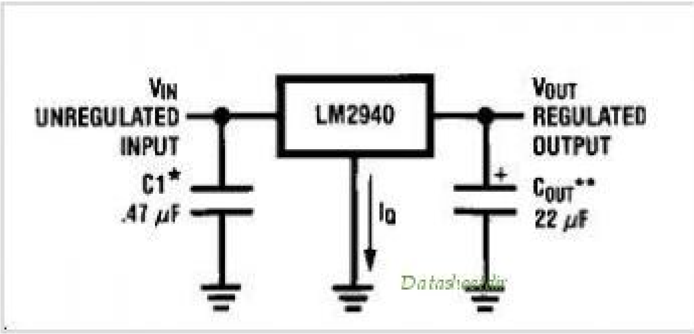


Figure 1: An example circuit for a similar regulator [29]

Point to note when configuring:

1. The regulated 5 V output voltage must be checked to ensure it is actually giving the correct output using a multi-meter to avoid damaging the Pi.
2. The pin roles must be checked before actually making any connections to avoid setting the circuit up incorrectly and causing damage to the Raspberry Pi.
3. The regulator will dissipate the excess voltage as heat, the website for the regulator claims the temperature will not exceed 125°C, but a heat sink may be necessary depending on which regulator is chosen[29].

The Raspberry Pi will be mounted to a breadboard so the connections between the GPIOs (General Purpose Input/ Output pins) and the other components (like the kill switch).

As for the external kill switch to immediately disconnect the battery from the circuit in the event of an unexpected situation i.e. a collision or fire. A program will be written so that when a command is given from the user, one of the GPIOs will produce a HIGH signal and the switch will be triggered.

Robotic Arm

The robotic arm moves using a 360° servo motor. The servo is digital so it is programmable and will be able to be connected to the Raspberry Pi. It will receive input, 5 V and a ground voltage by connecting to the Pi's GPIOs.

The lid for the container will be motorised using a small linear actuator designed to be used with a Raspberry Pi and it will be fixed to the underside of the lid. This type of motor comes with various strokes (how far the motor can move) are available so a suitable one shall be selected depending on the size of the container. This motor will receive input, 5 V and a ground voltage by connecting to the Pi's GPIOs on the breadboard.

All sensors, including the capacitive sensor under the container, will be connected to the battery, ground and will be connected to an input pin of the Raspberry Pi.

Motors

The connection to the motors can be established using a L293D motor driver chip allowing the Pi to send signals to the wheels and control the rover movement without damaging itself. The L293 motor driving chip can withstand voltages up to 36 V and a maximum of 2 A, which the means it can handle the 5 V and 2 A given out by the Raspberry Pi.The chip can withstand temperatures of up to 150°C, which means it will not be damaged by the maximum temperature on the moon of 123°C. It also has built in heatsinks, meaning the temperature of the chip always be within a range that does not cause damage.

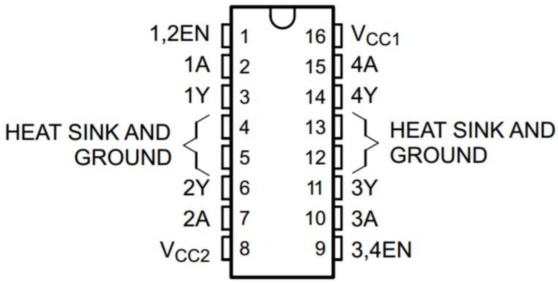


Figure : Labelled pins for the L293D motor driver chip

The chip has 16 pins, all labelled above in Figure. Pin 16 will have the Raspberry Pi supplying a constant input of 5 V, this will be used for the chip's internal logic translation. Pins 2, 7, 10, 15 will be connected to the Pi's GPIOs and are used to receive input from the Pi. Pins 3, 6, 11 and 14 will also be connected to the GPIOs but will instead feed the output back to the Pi. Pin 9 is an enable line and will also receive an input of 5 V from the Pi. Pins 4, 5, 12 and 13 are the aforementioned heat sinks and also act as ground.

Communication

This section will describe the solution arrived at to allow wireless communication between the operating base and the rover. In this case, the operation base will consist of a standard PC with two monitors; one to receive and display all data transmitted by the 360 degree camera (powered independently from the battery) onboard the rover, and the other to allow interaction with ground station control software. Further employed will be a Virtual Reality headset, paired up with the existing video live stream to allow a more nuanced understanding of the rover's current environment.

The rover will be able to communicate with the base and receive instructions from it by connecting the Raspberry Pi 3 which comes with 802.11n Wireless LAN and Bluetooth 4.1 (including Bluetooth Low Energy), to a wireless network originating at the base. This option provides significantly less interference than radio communication would, although it may limit communication range somewhat. At the base, the offline private network is formed using a signal booster alongside an ad hoc network created on the base PC. Ground control can also take advantage of the Raspberry Pi's Linux OS to remotely SSH into the rover and execute programs stored as needed.

Drive

Locomotion

Locomotion is the process of movement, regardless of whether a rover has wheels, legs, tracks, is limbless or hops. Legged robots are developed from insects while limbless are similar to snakes and reptiles [30]. However for accuracy a wheeled rover is usually superior. Since this is a key part of the mission brief a wheeled rover was chosen.

Suspension

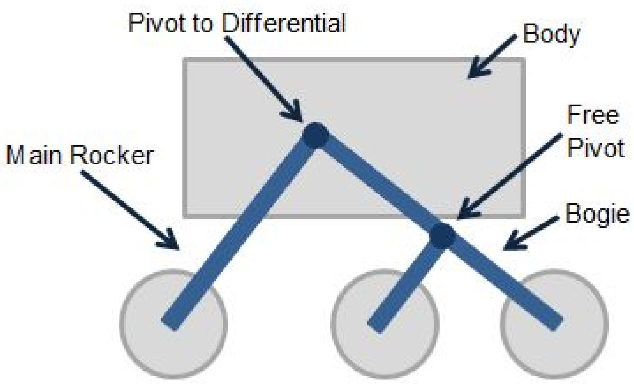
For travelling across the rocky lunar surface and up inclines, suspension is essential for locomotion. The suspension must be lightweight and equally distribute the rover's weight at all times, to maintain stability.

Rocker-Bogie Mechanism

A rocker-bogie system allows the load on each wheel to remain equal and has strong climbing capabilities. The rover will be able to traverse rocks and obstacles 1.5-2 times greater than the wheel diameter, as a result maximising the wheel dimensions is key to exploiting climbing ability. The relatively low speeds typical of rocker-bogie mechanism are compensated by the accuracy and obstacle avoidance they provide.

The suspension incorporates a main rocker and a bogie, connected by a free pivot. The design ensures that all suspension and joints are a reasonable distance from the wheels, to prevent the rover from getting caught on external obstacles.

The design requires a central counter-rotating differential to connect the left and right hand side of the rocker-bogie. It provides stability, as when one side moves across an obstacle the differential will work to push the opposing side in the opposite direction. The differential is a simple configuration, with gears from each pivot and another to connect the motion. The central differential is mounted inside the main body and contained in housing to protect electronics and contain heat. The small amount of heat generated by the differential could prevent lubricants from hardening in the cold moon environment [30].



Rocker-Bogie Mechanism

Drive Train

Along with the central differential the drive train is required to convert the motor's torque output to the wheels. Our design mounts an individual motor in each wheel, to reduce the need for moving drive shafts and additional gear systems. The wheel hubs used to transfer the torque are designed to be compact and lightweight, to be contained in the inner wheel.

Steering

To simplify and provide accurate steering, skid steering was proposed. This operates much like a crawler, where the motors from either side of the rocker-bogie are connected in unison. Steering can then be conducted by differentiating the speed of the motors between the two sides.

Compact Storage

In order to maximise the rover dimensions and fulfil the mission requirements, a method to fold the rover into a smaller storage package for deployment was considered. This was done to maximise the rovers obstacle traversing capabilities and to ensure that it remained stable while climbing the 30° slope. The wheel size determines the rovers obstacle clearance, while the distance between the rocker and bogie dictate its stability whilst climbing up slopes. Therefore, the rover was designed to promote the highest stability, unfortunately the trade-off is the maximum dimension. The rover will be approximately 40 cm long rather than the specified 30 cm.

To counteract this mechanical spring lock mechanisms are applied to allow the rover to remain in a folded position whilst simulating its journey to the moon. Once it arrives at the crater, the mechanism would deploy and lock into place and remain in the extended configuration for the remainder of the mission. This fulfils the requirement for the rover to fit in a 30 cm cube whilst allowing the greatest stability and wheel diameter.

For simplicity the mechanical mechanism was considered rather than actuators. The mechanism works by having a two piece hinge, the springs in the mechanism provide power to deploy the members and prepare the rover or the mission. Trigger locking mechanisms are used to deploy and lock the structural members in the operational configuration. This mechanism is known to be stable, lightweight and resist torsional forces[32]. There are other mechanisms comparable to this, which may be examined or altered to accommodate the existing design and motor wires.

Currently the rocker will have the hinge mechanism, allowing it to fold into the bogie. This may be adjusted at a later stage following additional tests, research and calculations.

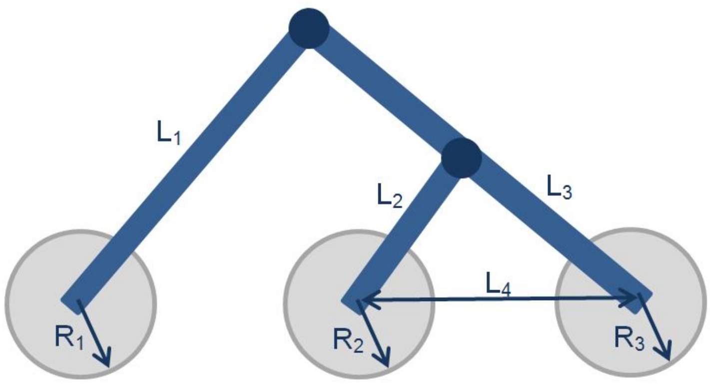
Dimensions

The rocker- bogie dimensions for the structural members and the wheel diameter are essential to ensure that the rover is able to carry out the mission specifications[31].

The rocker-bogie mechanism allows the rover to travel over obstacles approximately 1.5-2 times the wheel diameter[32].

Wheel Diameter:
The mission specification states that the rover will be presented with obstacles from 5-40 cm. Realistically, based off of constraints the wheel diameter was set as 8cm.
Therefore the rover will be able to travel over obstacles ranging from 12-16 cm maximum.

The structural lengths are defined as L_1, L_2, L_3 and L_4. To simplify the design the wheels have an equal radius: $R_1 = R_2 = R_3 = 4$ cm



The distance between each of the wheels was calculated to ensure that there is an appropriate clearance.

Length of L_4:
L_4 is the clearance between wheels 2 and 3, as shown in the diagram.

$$L_4 > R_2 + R_3$$

Therefore: $$L_4 > 8 \text{ cm}$$

As L_4 is the distance from the centre of each wheel, to calculate the clearance between the two wheels, radii must be subtracted.
L_4 was set to 14 cm to allow for 6 cm wheel clearance.

Length of L_2 and L_3:
For simplification it was assumed that L_2 equaled L_3.
The triangular inequality must be satisfied:

$$L_2 + L_4 > L_3$$
$$L_3 + L_4 > L_2$$
$$L_2 + L_3 > L_4$$

From the inequalities, it can be found that L_2 and L_3 must be greater than L_4.

$$\text{Allow } L_2 = L_3 = x$$
$$L_2 + L_3 > L_4$$
$$2x > 14$$
$$x > 7$$

Therefore L_2 and L_3 equal 9 cm. This satisfies the triangular inequality.

Length of L_1:

$$L_1 - R_1 > R_2 + L_2$$
$$L_1 > R_2 + L_2 + R_1$$
$$L_1 > 4 + 9 + 4$$
$$L_1 > 17 \text{ cm}$$

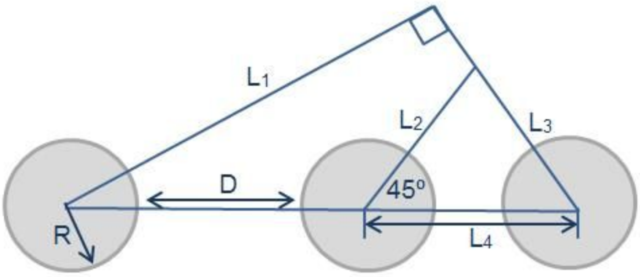
Therefore the L_1 = 20 cm.

Distance between wheel 1 and 2 can be found using trigonometry:
As $L_2 = L_3$ the wheel makes a 45°angle with L_4,.

$$\text{Sin}(45°) = \text{opp/hyp}$$
$$\text{hyp} = 20/\sin(45°)$$
$$\text{hyp} = 28.3 \text{ cm}$$

Lastly, to calculate the distance, D between wheel 1 and 2, L_4 and R_3 are subtracted.

$$D = \text{hyp} - (R_3 + L_4)$$
$$D = 10.3 \text{ cm}$$



The approximate clearance between the rover electric housing and the surface can be calculated to outline the rover's capabilities.
Assuming that wheel 2 is positioned directly below the central pivot, the height, H from the wheel centre to the pivot can be calculated.

$\cos(45°) = H / L_1$

$H = L_1(\cos(45°))$

$H = 14.2$ cm

Therefore there will be approximately 15-16 cm clearance between the ground and the central pivot.

These dimensions are preliminary and may be altered to improve the rovers efficiency later.

Wheels

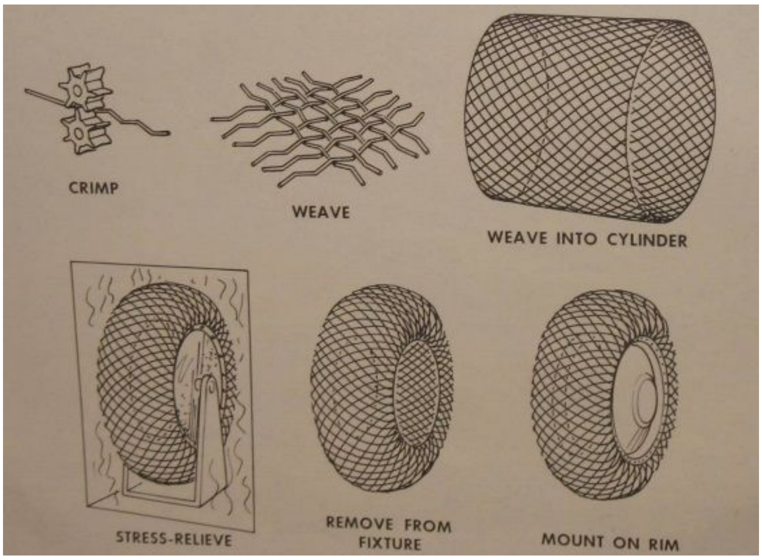
In order to effectively traverse the lunar environment, the rover must have wheels which can travel across the loose, soft surface of the moon, and are able to deform enough to pass over obstacles, and have enough traction to travel up the slope.

A design which fits our requirements well is that of wire mesh wheels, in a similar style to those used on the Lunar Roving Vehicle (LRV)[34]. These wheels consist of a solid metal wheel hub, with a tyre of woven wire mesh. This wire mesh is able to deform and reposition when it experiences a load, meaning the wheels would be able to effectively travel over obstacles. The wheels also include a stiff inner frame, which acts to prevent over-deflection of the wheels, which could cause damage or permanent deformation. Part of the tyres is covered with thick tread strips, in the form of metal chevrons, which increase the traction of the wheels, as well as allowing them to travel effectively over the soft lunar surface[35].

Wheel CAD Model

Wheel Manufacturing

The outer mesh frame of these wheels will be manufactured using piano wire (tempered high-carbon steel), which will then be attached to a stiff inner frame, around a hub of aluminium. The piano wire will be woven into net-like mesh cylinders, which will be heat treated before being attached to the inner frame and the aluminium hub. Tread strips will be added to the wheels, partially covering the wire mesh, to give additional protection to the wheels, as well as to increase the traction, and provide a better surface to traverse the soft lunar surface. This process will be fairly simple, allowing for manufacture to be carried out within the team, meaning resources will not be wasted outsourcing manufacturing of wheels.



Process of manufacturing wire mesh for wheels

This process will give a wheel which can perform well on the soft lunar surface, which will also be able to deform when passing over obstacles[36], and when travelling up the slope, giving an increased performance in these areas. To increase the traction of the wheels, they will be manufactured with a wide tire, increasing the area of contact with the ground, and include thick metal tread strips along the outermost surface, to give extra traction. These will assist in traversing the slope, as will the wheel's ability to deform[37].

Six Wheeled Rover

The extra set of wheels in a six wheeled rover (in relation to a four-wheeled rover) allows for greater traction, to provide greater forward thrust. We aim to incorporate a six-wheeled rocker bogie opposed to four wheels, as the extra wheels reduce the normal force, as the weight is distributed across greater surface area. The rear wheels must have enough traction to push the front wheels up and over an obstacle larger than the diameter of the wheels itself. Without traction the wheels will slip and the forward thrust will be reduced, making it unlikely the front wheels would remain in contact with the obstacle[35].

Materials

Metal was chosen for the rover's suspension and chassis. Plastics such as, polycarbonate, HDPE and Corex sheets were considered for their strength. However, an alloyed metal will be able to withstand the rugged lunar environment to a higher degree. The material chosen will have to withstand extreme temperature changes which would deform and melts a plastic. Although plastics may be easier to manufacture, the plastics would not cope with the abrasive lunar dust [38].

Aluminium has traditionally been used in space application and was selected because it is lightweight and strong [39]. At low temperatures, aluminium's strength increases rather than deteriorates which is essential for the lunar environment [40]. Aluminium has a high linear thermal expansion coefficient, which is a disadvantage that must be considered. It's resistance to stress and ability to be easily manufactured are key characteristics which make the material desirable for our applications [41].

The structural members of the suspension will be made from hollow tubes. Hollow circular tubes are beneficial due to their high bending stiffness (of 4.3) and torsional resistance (of 62.0) which allow it to support the rover weight to a greater degree than flat rectangular bars [42]. Overall, hollow tubes are a better choice for designing a lightweight, rigid suspension system.

The material will be further considered in the next development stage.

Motor Selection

To determine a suitable motor for the rover applications, several assumptions were made. The minimum velocity at which the rover is expected to travel across the terrain was 0.25m/s. Using this value, the time the rover will take to travel 60m - as specified in the mission requirements - was estimated:

$$\text{Velocity} = \frac{Distance}{Time}$$
$$\text{Time} = \frac{60}{0.25}$$
$$\text{Time} = 240 \text{ seconds}$$

The wheel diameter and the minimum velocity were used to calculate the minimum angular velocity of the motor.

$\omega = \frac{v}{r}$ $\omega = \frac{0.25}{0.08}$ $\omega = 3.125$ rad/s	*Where:* ω = *Angular Velocity* *v = Linear Velocity* *r = Radius*	*Assumptions:* *v = 0.025m/s* *r = 0.08m*

The RPM of the required motor was determined:

$$\omega = \frac{2\pi}{60} \; x \; RPM$$

$$RPM = \frac{60}{2\pi} \; x \; 3.125$$

$$RPM = 29.9 \; Rev/min$$

As this value was calculated using ideal conditions a motor of 30-45 RPM was found to compensate.

Possible motor: http://uk.rs-online.com/web/p/dc-geared-motors/8347647/ [43]

http://docs-europe.electrocomponents.com/webdocs/133e/0900766b8133eaea.pdf

The 951D SERIES 12mm dia. SPUR SUB MINIATURE GEARED MOTOR, has a RPM value of 45[44].

Collection

Material collection will be achieved by the use of a robotic arm, which will fold out from the front section of the rover, and feature a clamshell bucket attachment. The sample container will be located within the main body of the rover, positioned with a capacitive sensor beneath it, which has the ability to notify the Raspberry Pi when 500g of the sample has been deposited within the container.

The sample container will be accessed via the top surface of the rover. The container will be protected by a plastic cover, which is motorised, and can be manoeuvred to give access to the container when required. When the rover has reached the sample site, the Raspberry Pi will be used to communicate with the motor chip driver to trigger the cover sliding mechanism, moving the plastic cover so that it slides within the container, giving external access to the container, where the sample will be deposited.

When the sample container has been opened, the robotic arm will be extended from the rover using a 360^o servo, and moved so that the clamshell attachment is positioned over the sample site. A second servo in the robotic arm's joint will move the top section of the arm (with the clamshell bucket attached) downwards to the sample, and when the sample is reached, a third, more constrained servo will close the clamshell bucket around a portion of the sample, before the arm is manoeuvred back up to the position of the container, and the sample released into the container.

The robotic arm will be manoeuvred back to the sample site, and will continue transporting the sample to the container until the sensor identifies that 500g of the sample material is present in the container. At this point, the Raspberry Pi will be notified to stop material collection, and will communicate with the 360^o servo at the base of the robotic arm, triggering the arm to fold back into its position stored against the body of the rover. The Raspberry Pi will then be used to communicate with the motor to trigger the sliding cover mechanism to close, ensuring that the sample container would not be exposed for the journey back to the landing site. Once the robotic arm has been folded away, and the sliding cover closed, the material collection process is complete.

Power

The Battery

A 15 V 2200 mAh lithium-ion battery was chosen to power the lunar rover. This type of battery was chosen because it has a relatively high energy density[45] and a high power to weight ratio in comparison to other battery types[46]. Lithium-ion batteries can withstand a moderate amount of movement and can be turned upside down without which makes it more likely that it will survive the landing simulation than for example a lead acid battery.

The proposed battery has internal circuitry built-in, like most modern batteries, to protect it from as over-charging, over-current, over voltage, under voltage and over temperature. This means that battery protection is a lesser, but still important, consideration..

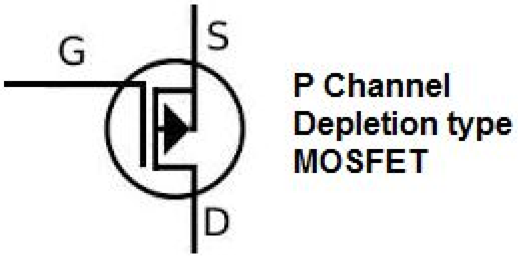
The dimensions of the battery are 70 mm x 38 mm x 38 mm which is compact enough to fit within our chassis and abide by the competitions guidelines.

The battery is quoted to last up to 2000 cycles. Lithium-ion batteries only last so many recharges is because eventually chemical reactions occur within the battery that reduces the battery's charge capacity due to a formation of solid on the negative end of the battery.

Kill Switch

The kill switch is a necessary feature of the rover. It disconnects the battery from the rest of the circuit. This switch is activated when an emergency occurs like a fire or a collision.

The type of switch used is a p-channel MOSFET and it is set to depletion mode. A MOSFET is a transistor which has an insulated gate where the voltage across it determines its conductivity. The MOSFET has 3 terminals the gate, the source and the drain. The MOSFET being in depletion mode means that the transistor will conduct electricity without a voltage being applied to the gate. When a voltage is applied to the gate the conductivity of the gate drops and current can no longer pass through it thus cutting the battery off from the rest of circuit.



The labelled terminals of a p channel MOSFET

It is placed in series between the positive terminal of the battery and the other components of the circuit. The gate is connected to one of the Raspberry Pi's GPIOs. The source is connected to the 5 V power rail on the breadboard the Raspberry Pi is mounted to. The drain is connected to the ground of the breadboard.

A program will be written on the on the computer to activate the GPIO that the gate is connected to sending a HIGH signal down it (5 V). The switch could be set to activate when a certain button of the keyboard is pressed[48],[49].

Battery Safety

A faulty charger or a buildup of static electricity can do real damage to the battery's internal protection circuit, i.e. the circuit that protects the battery from such hazards as over-charging, over-current, over voltage, under voltage and over-temperature. This could cause the solid-state switches to fuse into an ON state. The battery may appear to function normally but none of the internal protection would work making the battery dangerous. This can be prevented by limiting the movement of components that could cause static electricity to accumulate and not to use materials that are prone to generating static. The battery's charger can be tested by safely using a multi-meter[50].

Lithium-ion batteries do not charge in temperatures less than 0 degrees Celsius. Even though there will be no outwardly indication and the battery will appear to be charging at sub-zero temperatures, deposition of metallic lithium will occur at the battery's anode This process is irreversible and worsen each time sub-zero charging is attempted. This can jeopardise the battery's safety as it can cause short circuits within the battery and makes the

chemical reaction within the battery unpredictable. This may be an issue if the battery needs to be charged on the dark side of the moon were temperatures can reach as low as -153 degrees Celsius. A resistive heating coil around the battery may be a solution to this, using a notional amount of stored power to allow it to recharge.

A branded battery is always a better option to buy as larger companies have to abide by high safety standards, that cheaper imports do not necessarily have to.[51]

Reverse battery installation can cause damage to the internal electronics of the battery. To protect the battery from reverse current a high value diode can be placed in parallel with the battery, only allowing it to flow one way, which also serves as protection from placing the battery in the wrong way.

A fuse is also inserted in series between the battery and all other components. In the event of a short circuit excessive current will try to pass through the fuse and the fuse will blow, breaking the circuit and protecting the components.

General Safety

Special care must be taken to wire the circuitry properly, any confusion in wire or component placement can result in shorting or damaging components.

Seeing as soldering will be involved to attach components to the breadboards, good soldering practice must be carried out. This includes:

1. Tinning the tip of the soldering iron.
2. Wearing goggles.
3. Being cautious of the heat coming off of the iron.
4. Only soldering in a well ventilated room.

No exposed areas of the rover will have a live voltage across it. All wires will be insulated to reduce the risk of shorting the circuit.

Good Battery Practice

All the wires connecting to the battery must be checked before the battery is switched on to avoid any short or open circuits (as this could cause damage to more delicate components like the Raspberry Pi).

The battery's terminals need to be checked for corrosion. Corrosion on the battery's terminals can be caused by environmental degradation (battery fluid coming into contact with the air), but this could would not apply to this rover due to the lack of atmosphere on the moon. Another cause could be over or under charging the battery and if this is found to be a cause the battery's internal circuitry would not be working correctly.

The battery must be checked before use that it is sufficiently charged otherwise the Raspberry Pi may not power or the motors may run slowly.

The battery must be allowed to discharge to 10% of its maximum value before it is recharged in order to prolong the battery's life as much as possible.

Software Specification

The following section will outline the software to be built to allow the final product to perform its variety of tasks. The first set of use cases cover the software which is needed for the rover observe, explore, collect and report, the second set covers the software to be use by ground control to allow communication, exploration and observation.

Structured Descriptions of Rover Use Cases:

Use Case One: Interface with Connected Devices

Description: The rover wishes to turn on and turn off external devices, it further wishes to be able to access a data collected by set devices

Preconditions: Rover must be on

Main Flow:

- Send signal to turn on a given external device
- Begin streaming recorded data back to rover
- Send signal to turn off a given external device when no longer needed

Use Case Two: Observation

Description: The rover wishes to record its immediate surroundings and return relevant information as well as videos and photographs back to to ground control

Preconditions: Rover must be on

Main Flow:

- Interface with 360 camera
- Begin streaming all camera input back to base
- Interface with external sensors to record environmental factors
- Send recorded reports back to base after every new reading

Alternative Flow: Low Battery

- Interface with single angle front-facing camera
- Interface with external sensors to record X environmental factors every X amount of time and take X number of photographs
- Send recorded reports back to base after every new reading

Use Case Three: Exploration

Description: The rover wishes to move around in it’s current environment, avoiding collisions or inversions and keeping track of its site of origin

Preconditions: Rover must be on

Main Flow:

- Record and store current location using GPS
- Receive movement input from ground control
- Move as instructed

Alternative Flow: No connection to ground control

- Interface cameras and IR and Ultrasound sensors
- Run camera and sensor input thru SLAM algorithm
- Use mapping returned to identify hazards
- Take the path with the least number of hazards

Use Case Four: Collection

Description: The rover wishes to move it arm, pick up and put down samples and accurately weigh collected material

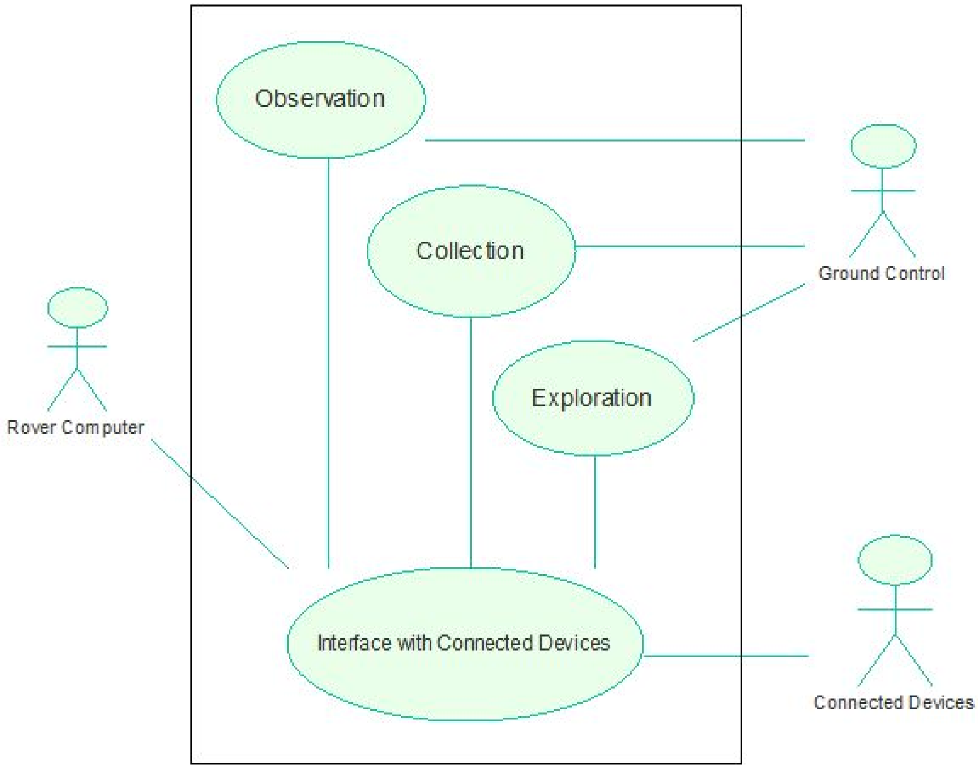
Preconditions: Rover must be on

Main Flow:

- Interface with front facing, single angle camera
- Wait for signal to move arm from ground control and follow commands
- Interface with sample container cover
- Deposit sample into the sample container
- Interface with scale
- Load sample in container keeping track of scale readings
- Wait for signal to move arm from ground control and follow commands

System Actors:

Rover Computer, Connected Devices, Ground Control.



Rover Use Case Diagram

Features:

- Continuous video transmission
- Obstacle avoidance
- Arm Control
- Communicates with ground control both through video, images and status reports
- Moves backwards and forwards and turn left and right
- Accurate Weight Measurement
- Receives instructions from ground control
- Sensor data analysis

Feature / Use Case	Interfaces with External Devices	Observation	Exploration	Collection
Obstacle avoidance			●	●
Arm Control				●
Communicates with ground control	●	●		
Moves backwards and forwards and turn left and right			●	●
Accurate Weight Measurement				●
Receives instructions from ground control	●		●	●
Sensor Data Analysis	●	●	●	●
Continuous video transmission	●	●	●	

Matrix of Use Cases Against Features

Structured Descriptions of of Ground Control Use Cases:

Use Case One: Observation & Reporting

Description: The user wishes to view a continuous 360 video transmission from rover cameras as well as analysing separate reports received

Main Flow:

- Receive video footage from rover
- Run video through virtual reality software to render 360 environment
- Receive data reports from rover and store them on ground control machines
- Analyze data for points of interest and rover performance tracking

Use Case Two: Exploration & Collection

Description: The user wishes to direct the rover's movement and arm maneuvering from ground base

Main Flow:

- Send directions commands using keyboard, mouse or joystick input
- Observe and analyse changes in rover environment
- Continue movement until arrived at goal location
- Send direction commands to robotic arm using keyboard, mouse or joystick input
- Command arm to collect needed sample

Use Case Three: Shut Down

Description: In case of emergency or unexpected circumstances, user wishes to remotely disable all rover activity.

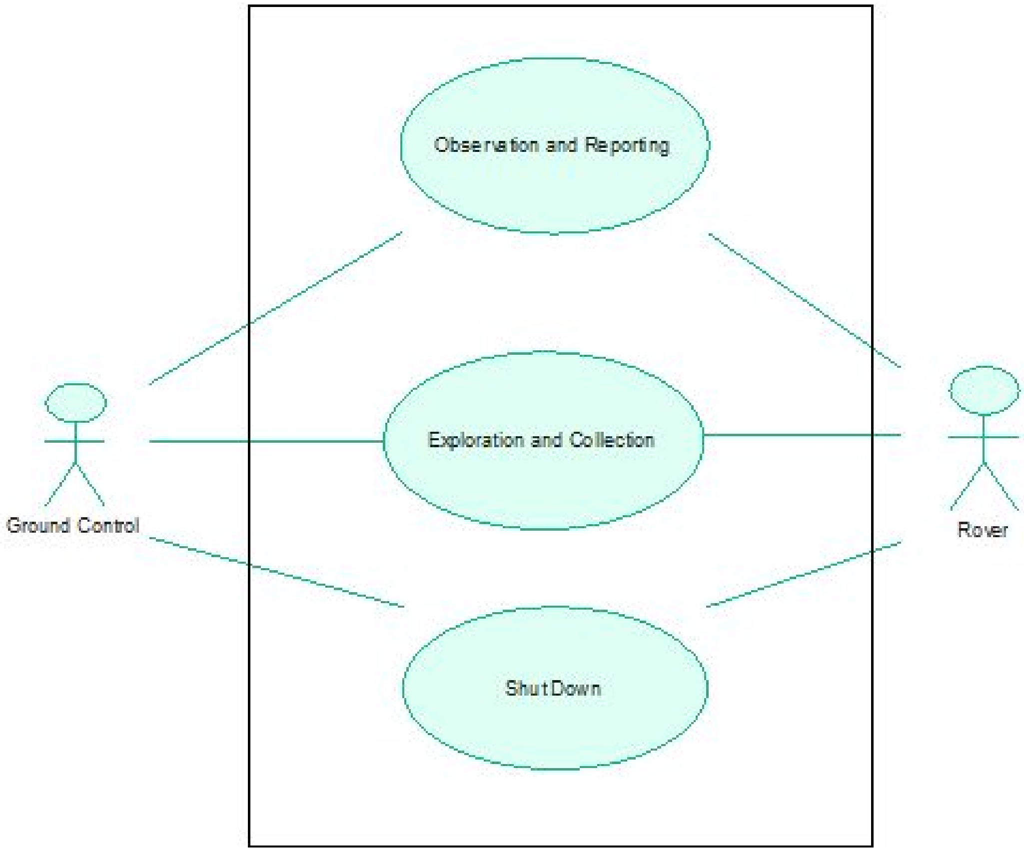
Main Flow:

- Observe rover for problems
- Send command for rover shut down

System Actors:

Rover, Ground Control

Use Case Diagram:



Ground Control Use Case Diagram

Features:

- Virtual reality video display
- Parse sent images, videos and status reports
- Take keyboard, mouse and joystick input to direct rover movement
- Take keyboard, mouse and joystick input to turn on/off rover

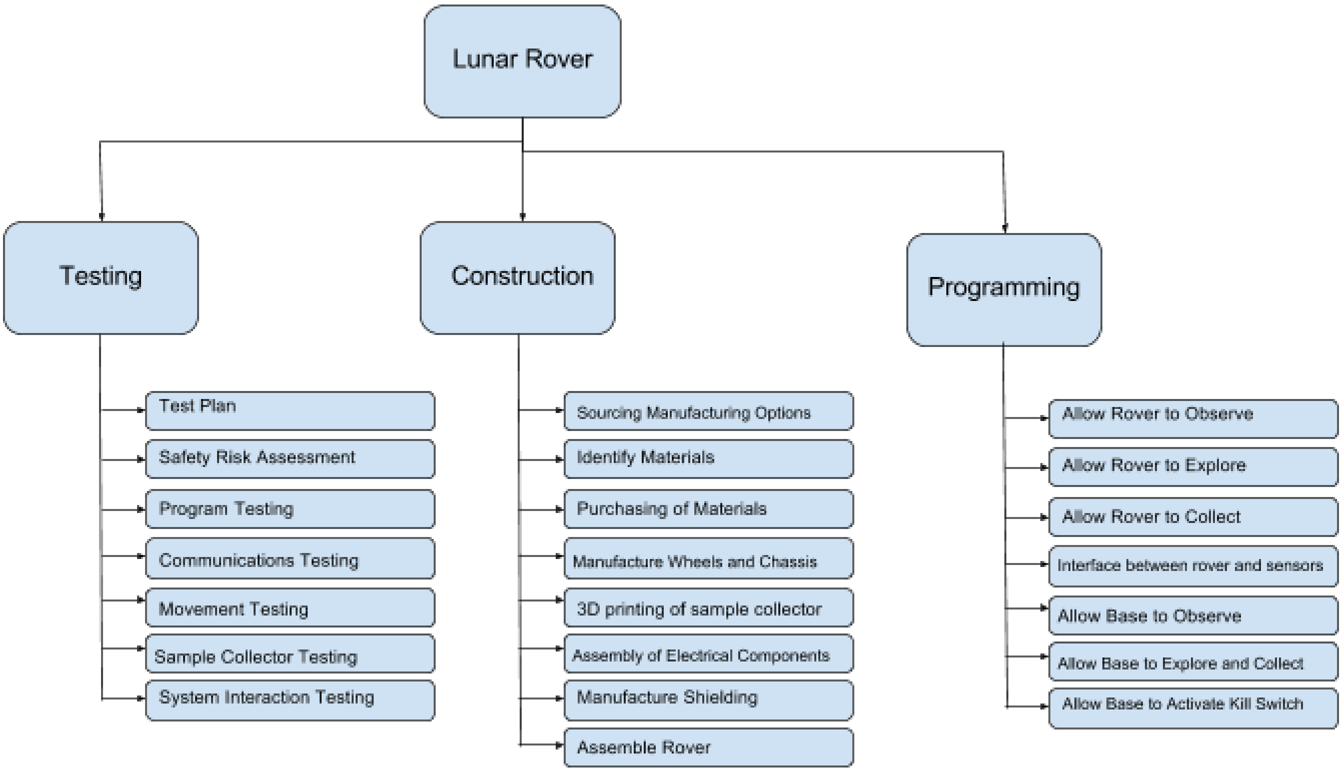
Feature / Use Case	Observation and Reporting	Exploration and Collection	Shut Down
Parse sent images, videos and status reports	●		
Take keyboard, mouse and joystick input to direct rover movement		●	
Virtual reality video display	●	●	
Take keyboard, mouse and joystick input to turn on/off rover			●

Ground Control Matrix of Use Cases Against Features

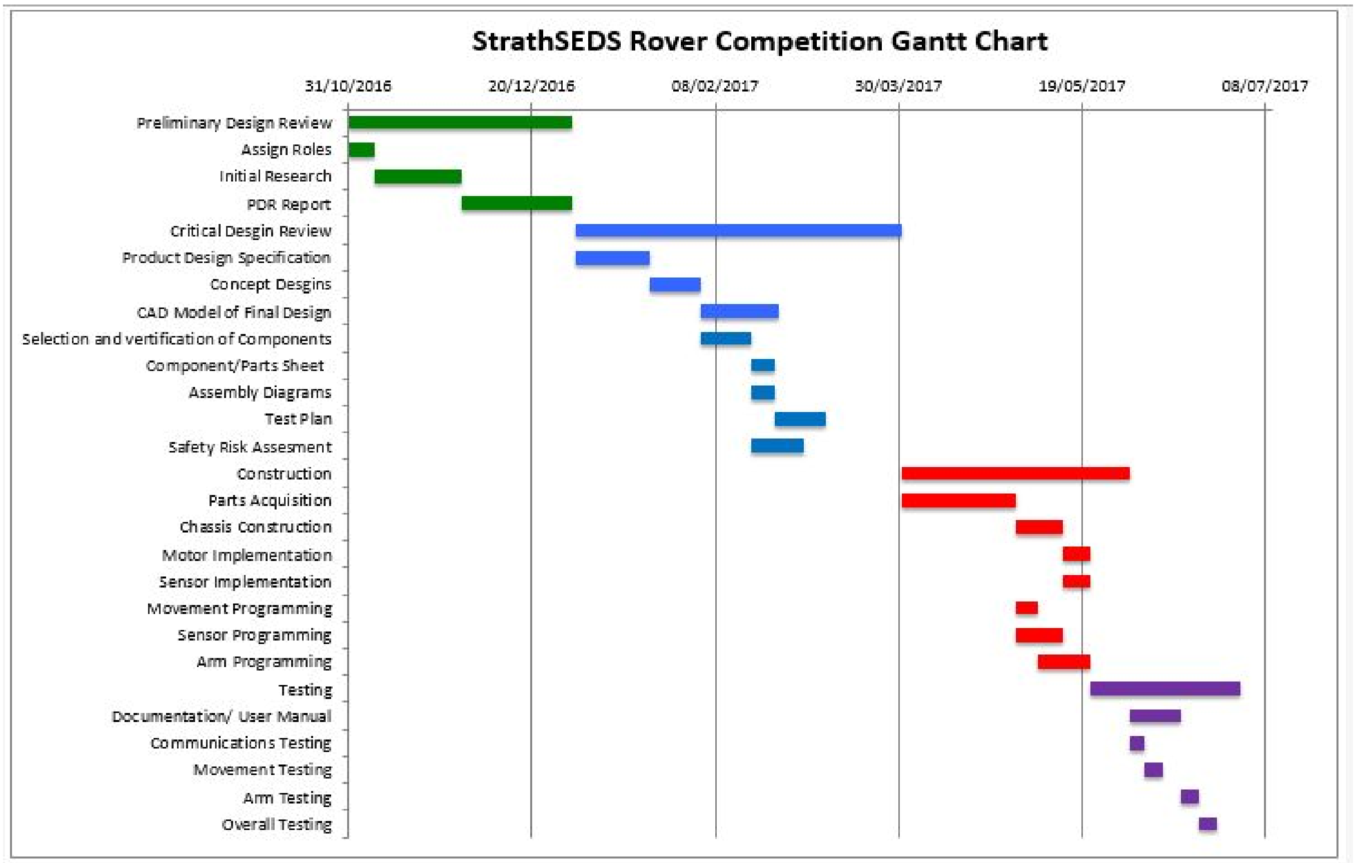
Budget

Items	#	Estimated Cost	Notes
Chassis	**1**	**£50**	**Self built within university facilities**
Motor	**6**	**£90**	**Geared DC motors**
Camera	**2**	**£230**	**One 360, one single angle**
Microcontroller	**1**	**£33**	**Raspberry Pi 3**
Ground Control	**1**	**£0**	**PC, Virtual Reality Headset, Extra Monitor (all already owned)**
Communications Link	**1**	**£0**	**Wifi Antenna, Router (already owned)**
Sensor Kit	**1**	**£80**	**Ultrasonic Sensors, etc.**
GPS	**1**	**£30**	**Offline Raspberry Pi 3 Compatible Tracker Chip**
Wheels	**6**	**£50**	**Wire mesh (should be able to self-build)**
Battery	**1**	**£50**	**Li-ion**
Motor Controller	**3**	**£20**	**L293D motor driver chip**
Sample Collector	**1**	**£40**	**Self built within university facilities**
Bolts/Screws etc		**£0**	**Salvaged / Already owned**
Wiring		**£0**	**Salvaged / Already owned**
Total:		**£673**	

Task Breakdown



Updated Timescales



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