A Lunar Rover Design for a Future Crewed Lunar Base

Ayaan Naha

Received October 14, 2024
Accepted April 30, 2025
Electronic access May 15, 2025

A permanent lunar base is one of the later goals of the Artemis program from NASA. A lunar base will require significant robotic assistance to be properly built and maintained. This research aims to develop a teleoperated lunar rover design that can aid astronauts in maintaining and performing work around a lunar base. The necessity of this rover is due to the hazardous nature of lunar dust and cosmic radiation. Minimizing astronauts' time outside of a shielded environment is crucial for their health. The designed rover includes two modular robotic arms that can perform a variety of tasks, a nuclear power source to allow for power throughout the lunar day-night cycle, and a rocker-bogie wheel mechanism to ensure the stability of the rover. This paper focuses on each subsystem of the rover, detailing the design, what design choices were made, and why. This research introduces a modular, RTG-powered lunar rover designed to perform complex interdependent tasks in a harsh environment.

Introduction

The lunar surface is a harsh environment. According to a report from NASA on the impacts of lunar dust, the lunar dust is extremely fine and statically charged[1]. The static charge causes the dust to stick to almost anything it touches, including an astronauts suit and a lunar lander. In the same report, Apollo astronauts claimed in interviews that the dust would stick to their suits and get inside the lander, making breathing without a helmet difficult. This phenomenon could occur on a future lunar base if astronauts need to conduct frequent EVAs. The lunar dust could build up in the airlock and eventually in the base, which would be a safety hazard to the astronauts lungs. According to a paper from Kanako Hayatsu, the lunar surface experiences 570 mSv/yr of cosmic radiation[2]. For reference, a normal yearly radiation intake is 6.7 mSv/yr[3]. A lunar base would have to be heavily shielded to allow for the astronauts to live there for longer periods without high risks of cancer. Thus, minimizing their time outside the habitat is crucial for ensuring a lunar base can last a long time, due to the nature of lunar dust and radiation on the lunar surface.

As human presence is established on the moon through the Artemis program, robotics practices will need to adapt to fulfill the plethora of tasks that must be automated. Current rovers contain instruments that are specialized for specific tasks. For example, the Perseverance rover incorporates a robotic arm that collects and analyzes rock samples[4]. On a new lunar base, however, there will be a variety of unique tasks. Lunar robotics must be extremely versatile and adaptable to account for unforeseen circumstances and uncommon mission scenarios.

Due to the communications delay between the Earth and the Moon, mission control cannot control the rover in real time from Earth. There would be a 22-second communications delay, meaning it would take 44 seconds total to send a command and receive a confirmation message from the rover. On a lunar base, the robotics would need to be controlled directly from the base. Another limitation of current robotics on the lunar surface is the 14-day lunar night. Any robotics on the lunar surface would either shut down due to a lack of solar power through the night or require an alternate method of generating power through the night.

This paper introduces a lunar rover concept designed to aid astronauts on a crewed lunar base with various tasks, including habitat construction, repairs, cargo transport, exploration, deploying scientific instruments, collecting surface samples, etc. The rover will accomplish a variety of tasks through a dual robotic arm system with modular robotic hands. This concept would make the rover significantly more versatile than current rovers, which specialize in specific tasks and limit the capabilities of the system. The rover will be remotely operated by astronauts stationed on the base in real time. Finally, the rover utilizes an RTG for power, which will allow it to function reliably throughout the lunar night, when it may be dangerous for astronauts to go on frequent EVAs.

This paper will explore the different subsystems of this lunar rover concept, explaining the design decisions made, as well as the functions of each subsystem. Afterward, the design will be compared to other existing designs to determine the strengths and weaknesses of the design.

Methods

A requirements analysis is a necessary step in designing any system. To properly understand the design constraints for this rover, this section will describe 2 mission scenarios and define success criteria for each. These success criteria will be used to establish design constraints.

2a. Mission Scenario 1

The first mission scenario takes place in the early stages of a lunar base. The latest cargo lander brought a larger solar panel array to account for future energy needs as the base grows. Each segment of the solar panel array is approximately 6 meters long and 2 meters wide, weighing about 150 kilograms. These specifications make it impractical for astronauts to remove the array from the cargo lander themselves. The segments need to be transported about 500 meters to reach the installation location, over uneven, regolith-covered terrain. A dual-armed rover is tasked with performing this mission.

The rover autonomously drives to the cargo lander. An astronaut will control the rover remotely and begin removing a segment. One arm holds the panel while the other arm disconnects the segment from its mounting bracket. As the segment is pulled out of the cargo bay, the rover must occasionally allow the other arm to hold the segment as the first arm repositions to get a better angle. Once the segment is fully removed, both arms hold the segment at around an equal distance to ensure the segment is balanced and the load is not uneven on either arm. This would be impossible with a single arm. The rover would then place the segments into a transport cart specifically designed for holding large payloads. After loading 2 more segments, the rover begins transporting the cart. It holds the cart from the 2 handles on either side, specially designed to mate with this rover. As the rover moves over uneven terrain, it can dynamically adjust the angle of the cart to ensure stability over nearly any terrain. A single-arm system would not be capable of this. The rover itself can stay upright on most uneven terrainwithout external influence. Upon reaching the installation location, much closer to the lunar base, the rover removes each segment from the cart and lays them in the correct position for installation. The astronauts are now able to deploy the solar panels.
Success Criteria

- The rover can stay upright in uneven lunar terrain
- The rover can manipulate objects larger than itself with multiple arms.
- The rover can multitask with 2 different arms
- Astronauts can teleoperate the rover with minimal latency.
- The rovers hands are versatile enough to perform many different tasks

2b. Mission Scenario 2

The second mission scenario takes place in the mid-stages of a lunar base. Basic infrastructure, such as habitation, life support, and power generation, is now in place; the focus of the astronauts shifts to conducting scientific experiments. The rover is tasked with analyzing surface samples 1 kilometer from the base. The distance is close enough for the rover to be teleoperated with minimal latency but far enough that sending an astronaut would require significant time and resources (water, food, and air). The terrain in the area is rugged, with steep crater walls and loose regolith, making it ideal for geological exploration but dangerous for astronauts. A dual-armed rover is assigned to this mission.

The rover autonomously navigates to the survey location, avoiding rocks and boulders and using its arms to adjust its center of gravity when needed. Upon reaching the survey site, the astronauts take control of the rover. The rover extends one arm away from the crater while the other arm reaches down into the crater's edge and collects samples with a scoop. This keeps the rover balanced during the operation, which would be impossible with a single arm. The rover seals the samples in a container onboard the rover, and astronauts begin analyzing the samples remotely. One arm of the rover holds the sample container, while the other arm analyzes the containers contents using a spectrometer. After the initial inspection, the rover scoops out a hole, and the other arm places a seismic sensor in the hole. The rover could also deploy any other scientific instruments it brought along. Finally, the rover returns to the base with the samples collected so the astronauts can do a more thorough analysis.
Success Criteria

- The rover can navigate rough lunar terrain
- The rover can utilize a dual robotic arm system to dynamically adjust its center of mass for improved balance
- The rover can implement different types of end effectors, or robotic hands, to perform different jobs.
- The rover can carry cargo with it, such as scientific instruments and surface samples.
- The rover can be teleoperated at a distance of 1 kilometer with minimal latency.

2c. Design Constraints

Based on the mission scenarios above, the designed rover must:

- Be remotely controlled by astronauts with minimal latency
- Provide the astronauts with visuals of the surroundings

- Incorporate two robotic arms that are able to interact with the surrounding environment, maintain the rovers balance, and manipulate a variety of objects
- Utilize a modular robotic hand system to enable many different use cases for the robotic arms
- Safely traverse lunar terrain without tipping over
- Have some cargo space to transport items such as tools, scientific instruments, etc.

Environmental conditions on the lunar surface will also create constraints for the rover. The rover must:

- Withstand the thermal cycling between lunar day and night ($-173°C - 127°C$) for the mission duration
- Withstand cosmic radiation throughout the mission duration
- Withstand the impacts of lunar dust over the mission duration

There would also be a weight limitation as a result of the payload capacity of a lunar lander. The Griffin lander from Astrobotic was used as a benchmark for the expected payload capacity of current & future lunar landers. The rover must:

- Have a mass of no more than 625 kg[5].

2d. Robotic Arm

The robotic arm has 5 degrees of freedom: 2 shoulder joints that allow it to rotate about the base and move the arm vertically. There is also an elbow joint and 2 wrist joints that give the arm more freedom to move around and flexibility for the gripper on the end to reach different angles. The arm is 2 meters in length when fully extended, but when folded, it takes up a space of 32 by 131 by 25 centimeters (length by width by height).

The base of the robotic arm has an actuator that allows it to rotate about the rover's body, called the shoulder pan joint (Figure 1). There is a second actuator connected to the shoulder pan joint that lifts the rest of the robotic arm, called the shoulder lift joint (Figure 2). The end of the shoulder lift joint connects to the forearm section of the robotic arm by the elbow joint (Figure 3). The end of the arm has two wrist joints: the wrist flex joint controls the pitch (Figure 4), and the wrist roll joint controls the roll (Figure 5). Each actuator on the robotic arm would have a seal and cover to prevent lunar dust from degrading it over time[6]. Depicted below are models of each segment of the robotic arm designed in Fusion 360.

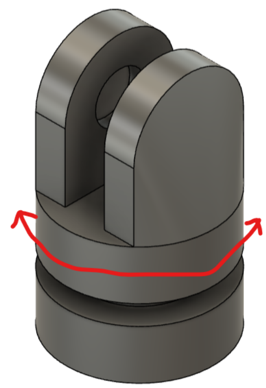

Fig. 1 The shoulder pan joint allows the entire robotic arm to pan left and right. The bottom section of this joint is mounted onto the rover body, while the top is connected to the rest of the rover arm. This joint has a 360-degree range of rotation. Own source modeled in Fusion 360.

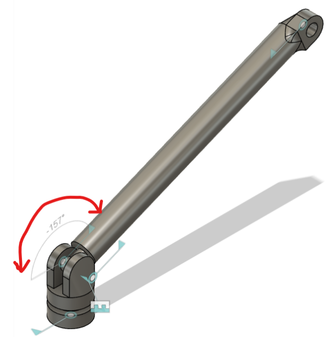

Fig. 2 The shoulder lift joint allows the robotic arm to lift vertically. This joint connects to the first section of the arm. This joint has a 180-degree range of rotation. Own source modeled in Fusion 360.

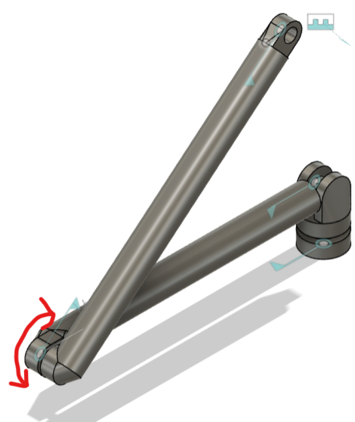

Fig. 3 The elbow joint allows the second half of the robotic arm, or the forearm, to rotate about the first portion of the arm. The forearm connects to the wrist section where the end effector is mounted. This joint has a 360-degree range of rotation. Own source modeled in Fusion 360.

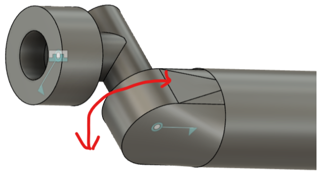

Fig. 4 The wrist flex joint allows the end effector to rotate about the rest of the robotic arm. This joint has a 360-degree range of rotation. Own source modeled in Fusion 360.

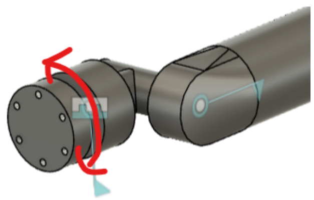

Fig. 5 The wrist roll joint allows the end effector to rotate about the wrist. This joint is especially useful for drills, screwdrivers, and other use cases that require rotation. This joint has a 360-degree range of rotation. Own source modeled in Fusion 360.

The 5 sections and joints form the full robotic arm (Figure 6).

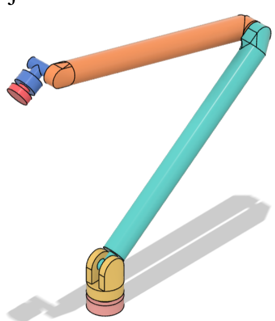

Fig. 6 The full robotic arm is colored by component. The shoulder section is pictured in yellow, the upper arm in teal, the forearm in orange, and the wrist in blue. Own source modeled in Fusion 360.

The elbow and shoulder joint motors weigh about 4kg each. The shoulder joint will have 2000 Nm of torque. This can be used to calculate the maximum weight the robotic arm can carry, as well as the torque requirement for the elbow joint.

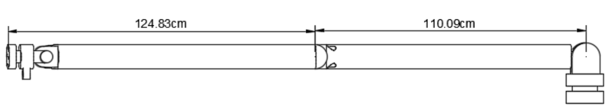

Fig. 7 A horizontal view of the arm stretched out, including basic dimensions in centimeters. Own source created in Fusion 360.

Assuming a worst-case scenario, where the arm is stretched horizontally outwards. The torque experienced by the shoulder joint in Newton-meters will be equivalent to the sum of the weight of the payload, forearm section, and shoulder section multiplied by the length of the whole arm and the gravity on the moon.

$$\tau_{\text{arm}} = (m_{\text{payload+forearm}} + m_{\text{shoulder}}) \cdot g_{\text{moon}} \cdot L_{\text{arm}}$$

$$2000\,\text{Nm} = (m_{\text{payload+forearm}} + 4\,\text{kg}) \cdot 1.62\,\text{m/s}^2 \cdot 2.3492\,\text{m}$$

Solving for the payload + forearm mass:

$$m_{\text{payload+forearm}} = \frac{2000\,\text{Nm}}{1.62\,\text{m/s}^2 \cdot 2.3492\,\text{m}} - 4\,\text{kg} = 521.53\,\text{kg}$$

So, the arm can hold 521.53kg of mass on the moon. This can be used to calculate the torque requirement for the elbow joint.

$$\tau_{\text{elbow}} = (m_{\text{payload}} + m_{\text{forearm}}) \cdot g_{\text{moon}} \cdot L_{\text{forearm}}$$

$$\tau_{\text{elbow}} = 521.53 \cdot 1.62 \cdot 1.2483 = 1054.66\,\text{Nm}$$

To sum up these calculations: The elbow joint would require a torque of 1055Nm, the shoulder would require a torque of 2000Nm, and 1 arm can hold up to 521kg safely. This means 2 arms together would be capable of lifting around 1000kg.

2e. End Effectors

The robotic arms require end effectors to be used around the lunar base. An end effector is a mechanism on the end of a robotic arm that allows it to perform a task. For most robotics applications, one end effector is chosen based on the activity being performed by the system. However, this rover will have many different use cases around the lunar base. It will support the astronauts in routine inspections, cleaning, maintenance, clearing out new areas for construction, supporting the construction of new segments, and any other necessary task the rover can feasibly do. While having many different use cases is beneficial, each use case will require a unique end effector. Some potential end effectors for the rover include:

- Connector
- Scoop (Figure 8)
- Drill
- Spectrometer
- Gripper (Figure 9)
- Electromagnet
- Cleaning tool

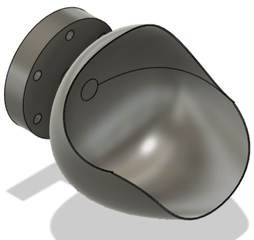

Fig. 8 An example of a scooping end effector. Own source modeled in Fusion 360.

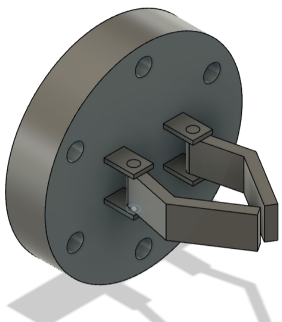

Fig. 9 An example of a gripping end effector Own source modeled in Fusion 360.

Rather than only picking one or two of these potential end effectors, this design opts for a modular design. Essentially, the end effectors could be removed and replaced with a different one depending on the astronauts' task. The end effectors would most probably be switched in and out by the astronauts, though it could potentially be automated with robotics at a rover substation.

Each end effector would have a base diameter of 10 cm. The robotic arms wrist joint has a flat 10 cm diameter plate where end effectors could be fitted using the 6 threaded holes on the plate and bolts. A testing framework has been outlined to make it clear what constraints the end effectors will have.
Testing Framework:

- Docking test: Connect and disconnect the end effector in a vacuum chamber 100 times.
- Functionality test: Test the use of the end effector 100 times.
  Ex. A gripper would pick up an object.
- Durability test: Simulate the thermal cycling of the lunar surface, as well as the effects of lunar dust on the end effector.

2f. Communications

The mission requires low-latency data transfer between the lunar base and the rover. A review on lunar communications and antennas suggested that a low-frequency UHF-band antenna is best suited for lunar rovers and surface operations, as the frequency range can penetrate lunar soil easily. Therefore, a low-gain dipole antenna will be used for this rover.

Table 1 Antenna Specifications

Specification	Dipole Antenna
Gain (dBi)	2 dBi[7]
Bandwidth (MHz)	401 MHz[8]
Power Draw (W)	6 W[8]

Total Latency = Propagation delay + Transmission delay + Queueing delay + Processing delay.

- Propagation delay is the time it takes the signal to travel.
- Transmission delay is the time it takes the data to be uploaded into the transmission medium (in this case, radio waves)
- Queuing delay is the time it takes for the data packet to pass through the queue. This value is dynamic and varies based on network load.
- Processing delay is the time it takes data to be processed by the system. This varies from system to system.

For this work, the antennas' latency will be quantified with the transmission and propagation delays. Queueing delay is a variable value that will change based on mission circumstances, while processing delay varies from system to system. Therefore, neither will be accurate for comparison. When calculating transmission delay, a packet size of 1 kilobyte will be used as a control value to ensure calculations are equally represented. Similarly, the speed of light (299792458 m/s) will be used to calculate propagation delay because that is the speed at which radio waves travel. The dipole antenna is meant to function at a range of around 1 kilometer, so that distance will also be used to calculate propagation delay.

For the dipole antenna:

$$\text{Transmission delay} = \frac{\text{Packet Size (bytes)}}{\text{Bandwidth (bytes/second)}}$$

$$\text{Bandwidth} = 401\,\text{MHz} = 401,000,000\,\text{Hz}$$

$$1\,\text{Hz} = 1\,\text{bit/second}$$

$$401,000,000\,\text{bits/second} = \frac{401,000,000}{8} = 50,125,000$$

bytes/second

$$1\,\text{kb} = 1000\,\text{bytes}$$

$$\text{Transmission delay} = \frac{1000\,\text{bytes}}{50,125,000\,\text{bytes/second}}$$

$$= 19.9501247\,\mu s$$

$$\text{Propagation delay} = \frac{\text{Distance (m)}}{\text{Speed of transmission (m/s)}}$$

$$= \frac{1000}{299,792,458} = 3.33564095\,\mu s$$

$$\text{Total delay at 1 km} = 19.9501247 + 3.33564095 = 23.29\,\mu s$$

$$\text{Propagation delay at 10 km} = \frac{10,000}{299,792,458} = 33.3564095\,\mu s$$

$$\text{Total delay at 10 km} = 19.9501247 + 33.3564095 = 39.20\,\mu s$$

Transmission delay + Propagation delay = 39.20 microseconds

The difference in transmission speed between a distance of 1 kilometer and 10 kilometers is a matter of around 16 microseconds, which is not a noticeable difference. The rover could hypothetically travel tens of kilometers without a significant latency drop. However, the rover is limited by the line of sight to the base at longer ranges. Too many objects in the path of the signal could block the signal. So, while the range of the rover cannot be calculated, it will be limited by the environment.

2g. Power System

The rover requires a stable power supply to function properly. The lunar day-night cycle is 14 days, and the lunar poles experience less sunlight than other parts of the moon. A lunar base is most likely to be placed around the south pole due to the abundance of ice, which would be a valuable resource to mine. With this in mind, solar panels are not a likely candidate for a power supply. The rover would not generate any power during the 14-day night, which would call for large batteries. These solar panels could also succumb to lunar dust collecting on them, which would reduce the efficiency and over time could lead to the rover becoming inoperable if not regularly cleaned by astronauts.

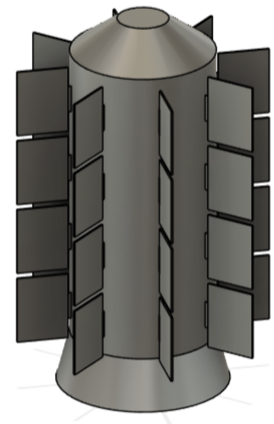

Fig. 10 A model of a potential General Purpose Heat Source Radioisotope Thermal Generator for the rover. Own source modeled in Fusion 360.

An effective solution would be a radioisotope thermal generator (RTG). A nuclear power source would not require any sunlight, nor does it need to be cleaned. Another benefit of using an RTG is that it could be used for thermal control of the rover. A rover powered by solar panels would require a separate heating unit to keep the rover within operable temperatures. However, RTGs generate their own heat, which could be leveraged to heat the rover directly. Therefore, they could be a simpler and more reliable method of managing the temperature of the rover (Figure 10).

Specifically, a General Purpose Heat Source Radioisotope Thermal Generator (GPHS-RTG) would be used on the rover. General Electric developed the GPHS-RTG for NASA and has been used on the Galileo and Ulysses spacecraft. The RTG would harness the alpha decay of Plutonium-238 to generate heat, which is converted to electricity by thermocouples. Plutonium-238 has a half-life of 88 years and a specific power of 0.568 watts per gram[9]. The high specific power and long half-life ensure the power system of the rover would function well past the mission requirements. The decay of plutonium-238 passively generates heat, which is converted into electricity. Therefore, the RTG will constantly generate power because the decay of plutonium cannot be actively controlled.

The rover will operate around a crewed lunar base, so the power system must not expose astronauts to unsafe radiation levels. The primary material for the RTG will be aluminum, much like the rest of the rover. As mentioned earlier, the RTG utilizes alpha decay of Plutonium-238. Alpha particles have the weakest piercing power of the three types of nuclear radiation (alpha, beta, gamma). Alpha particles are too large to pass through a

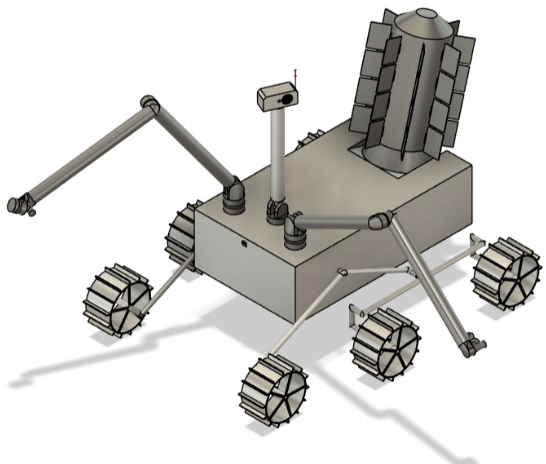

Fig. 11 A model of the GPHS-RTG mounted onto the back of the rover. Own source modeled in Fusion 360.

sheet of paper, therefore, no alpha particles will exit the body of the RTG [10]. This would ensure the safety of astronauts, even while they are close to the rover. Figure 11 depicts the RTG integrated with the rover.

The GPHS-RTG would have a diameter of 0.422m, a length of 1.14m, and a weight of 55.9 kg [11]. The RTG would provide 250 W of power [11]. The GPHS-RTG would be used to power thermal systems, such as heaters, the onboard computer and electronics, the 6 wheels of the rover, and the actuators for the 2 robotic arms. The GPHS-RTG could also be directly utilized for heating purposes, as the heat inside can be distributed to other sections of the rover, however, this would reduce power output.

Inside the rover would be a lithium-ion battery pack capable of storing 3 kilowatt-hours of power. This battery pack would be comprised of LG 18650 MJI cells combined into 120V DC packs. A dissertation by Alexander Bendoyro explains a linear relationship between the mass of this specific type of battery pack and amp-hours required [12]:

$$M = 0.6376A - 0.0469$$

Where M is the mass in kg, and A is the battery's amp-hours. The rover could draw 451 watts of power at any given point in time. At the most, the rover needs to store at least 2688 watt-hours. This value was rounded up to 3 kilowatt-hours for redundancy. 3 kWh translates to about 25 Ah at 120 V. Using 25 Ah as the battery amperage, the mass of the battery will end up being 15.89 kg.

Table 2 Power Systems Weight Breakdown

Power Subsystem	Weight (kg)
GPHS-RTG	55.9
18650 Lithium-ion Battery Cells	15.89
Miscellaneous Wiring & Hardware (cables, voltage regulators, etc)	~ 1
Total	72.79

2h. Power Requirements Analysis

To calculate the power draw of the wheel, the rolling resistance of the lunar soil on the rover will be calculated.

$$F_r = \text{Rolling resistance}$$

$$\mu_r = \text{Rolling resistance coefficient} \approx 0.42$$

$$N = \text{Normal force} = mg, \quad g = 1.62\,\text{m/s}^2, \quad m \in [291, 314]\,\text{kg}$$

$$F_r = \mu_r \cdot N$$

$$F_{r,\text{min}} = 0.42 \cdot 291 \cdot 1.62 = 198.00\,\text{N}$$

$$F_{r,\text{max}} = 0.42 \cdot 314 \cdot 1.62 = 213.65\,\text{N}$$

$$F_r \in [198.00, 213.65]\,\text{N}$$

$$v \in [0.28, 0.83]\,\text{m/s}$$

$$P = F_r \cdot v$$

$$P_{\text{min}} = 198.00 \cdot 0.28 = 55.44\,\text{W}$$

$$P_{\text{max}} = 213.65 \cdot 0.83 = 177.33\,\text{W}$$

$$P \in [55.44, 177.33]\,\text{W}$$

$$P_{\text{motors}} = \frac{P}{\text{Efficiency}}$$

$$P_{\text{motors,min}} = \frac{55.44}{0.90} = 61.60\,\text{W}$$

$$P_{\text{motors,max}} = \frac{177.33}{0.80} = 221.66\,\text{W}$$

$$P_{\text{motors}} \in [61.60, 221.66]\,\text{W}$$

$$P_{\text{total,min}} = 61.60 \cdot 1.5 = 92.4\,\text{W}$$

$$P_{\text{total,max}} = 221.66 \cdot 1.5 = 332.49\,\text{W}$$

$$P_{\text{total}} \in [92.4, 332.49]\,\text{W}$$

$$P_{\text{total}} \approx \frac{92.4 + 332.49}{2} \pm \frac{332.49 - 92.4}{2}\,\text{W}$$

$$P_{\text{total}} \approx 212.45 \pm 120.05\,\text{W}$$

Therefore, the rovers wheels will require a minimum of 92.4 W at 0.28 m/s (1 kph), and a maximum of 332.49 W at 0.83 m/s (3 kph), with a median value of 212.45 W (about 2 kph).

Estimations of the power requirements by component were made based on similar rovers designed by NASA[13]. The system would cycle between 4 different modes: Full Operation, Rough Terrain, Heavy Lifting, and Idle. Full operation optimizes for all systems, rough terrain directs more power to the mobility systems to maximize torque, heavy lifting directs power to the robotic arms, and idle mode conserves power by minimizing the power draw of each component.

Table 3 Power draw during different operation modes by component.

Component	Full Operation Mode	Rough Terrain Mode	Heavy Lifting Mode	Idle Mode
Onboard Computer	10	10	10	5
Thermal Management	5	5	5	5
Cameras and sensors	30	30	30	10
Mobility Systems	200	300	100	0
Robotic Arms	200	100	300	0
Communications Systems	6	6	6	6
Total	451	451	451	26

An example schedule for the rover:

- 8:00 PM 8:00 AM: Idle Mode
- 8:00 AM 10:00 AM: Full Operation Mode
- 10:00 AM 1:00 PM: Heavy Lifting Mode
- 1:00 PM 3:00 PM: Full Operation Mode
- 3:00 PM 6:00 PM: Rough Terrain Mode
- 6:00 PM 8:00 PM: Full Operation Mode
- 8:00 PM 12:00 AM: Idle Mode

Table 4 Power consumption, generation, and battery charge throughout a day of operation

Power Mode	Power (W)	Time (hrs)	Cumulative Energy Generated (Wh)	Cumulative Energy Consumption (Wh)	Battery Charge (Wh)
Idle	26	12	3000	312	2688
Full Operation	451	6	4500	3018	1482
Heavy Lifting	451	3	5250	4371	879
Rough Terrain	451	3	6000	5724	276
Total		24	6000	5724	276 kWh surplus

2i. Camera Mast

The camera for the rover is mounted atop a mast that can lift up the camera from the resting position (Figure 12). The camera can rotate 360 degrees about the camera mast, allowing it to view in all directions (Figure 13). The camera itself consists of an HD color camera, the larger lens, and a LiDAR camera, the smaller lens (Figure 14). The lens of the camera would be coated using lotus-coating technology. Inspired by the water-repellant leaves of a lotus, the technique involves a nanotexture made of silica, zinc oxide, and their oxides. Above the nanotexture, a hydrophobic coating is applied to create a very hydrophobic surface that lunar dust will not stick to. Connected to the camera is the low-gain communications antenna. The antenna is positioned on the camera for two reasons. It is the highest point on the rover excluding the robotic arms, allowing the signal to travel slightly farther than if it were on the base of the rover. Second, the latency between the information from the camera to the antenna would be extremely low, giving astronauts at the base real-time video of the rover with only milliseconds of latency. This is important for astronauts actively controlling the rover, as they must know the situation of the rover at all times to make the best decisions during any scenario.

2j. Wheels and Suspension

The rocker-bogie mechanism is a type of suspension commonly used in planetary rovers (Figure 15). NASA has used this mechanism on the Spirit, Opportunity, Curiosity, and Perseverance rovers. The rocker-bogie allows the rover to tilt 45 degrees without falling[14]. This makes it a good candidate for this rover, as it will likely traverse rocky or uneven terrain during its mission. A rocker-bogie mechanism consists of two pieces that can rotate independently, the rocker and the bogie. The bogie is attached to the rocker, while the rocker is attached to the main body of the rover. A rocker bogie mechanism must also be attached to the opposite end of the rover. This is either through an averaging

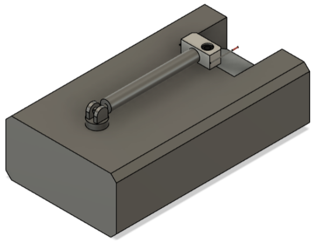

Fig. 12 The camera mast is positioned in resting position. Own source modeled in Fusion 360.

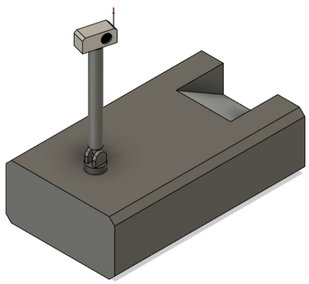

Fig. 13 The camera mast is upright, with the camera partially rotated counterclockwise. Own source modeled in Fusion 360.

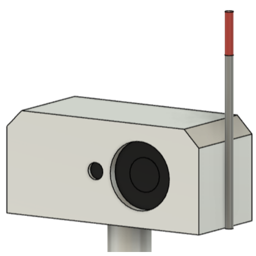

Fig. 14 Close-up of the camera and antenna. Own source modeled in Fusion 360.

gearbox inside or a differential mechanism on the rover body. The point of the gearbox or differential is to allow for each side of the mechanism to turn in opposite directions. For example, if one side of the rover moves up because it is going over a rock, you need the opposite end of the rover to push down to keep each wheel on the ground.

My rover will opt for a rocker-bogie mechanism (Figures 16, 17). Additionally, it will use a gearbox on the inside of the rover (Figure 18). This is primarily due to space limitations on the body of the rover. A differential mechanism could get in the way of the camera mast, the robotic arms, or the scientific instruments. The axle of the gearbox would have a maximum angle of rotation of 45 degrees clockwise and counterclockwise. However, this scenario is very rare as that would imply the rover is tilted a full 45 degrees, which is dangerous and would likely never be attempted under normal circumstances. Each motor of each wheel, as well as the bearings for the rocker-bogie mechanism will require a seal and a cover for the final design. The seal prevents lunar dust from damaging the bearing, and the cover would be a redundant measure to ensure the seal does not

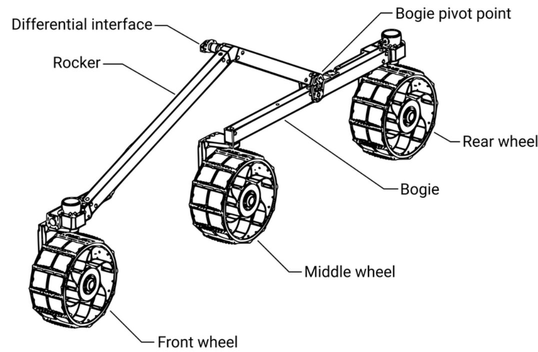

Fig. 15 A diagram of a rocker-bogie mechanism. The rear and middle wheels on the bogie rotate about the bogie pivot point, while the front wheel on the rocker rotates about the differential interface [15].

degrade over time [6].

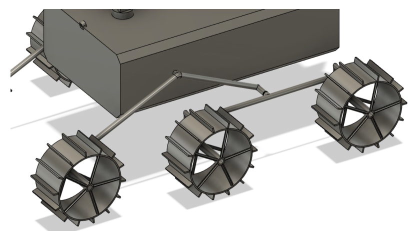

Fig. 16 The rovers rocker bogie mechanism. Own source modeled in Fusion 360.

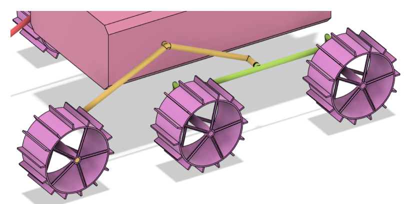

Fig. 17 The rovers rocker bogie mechanism colored by component. Own source modeled in Fusion 360.

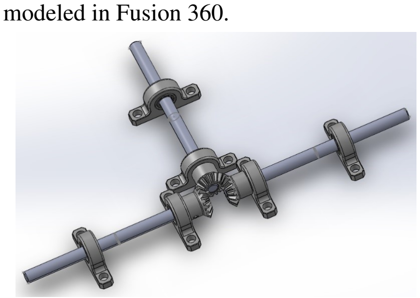

Fig. 18 An example of a gearbox that could be in the rover. The axles on the left and right lead to the left and right rockers. The middle axle and bevel gear simply convert the rotational motion between both rockers. This keeps the rover stable when it goes over a bump or rock [10].

A study from the Israel Institute of Technology ran dynamic simulations of rocker bogie vehicles to understand the stability of the rocker-bogie mechanism in different scenarios[16]. Overall, the study found that the rocker-bogie mechanism is a very stable configuration for wheels. A key insight from the research is that when traveling up steps or inclined slopes, the wheels' speed must be regulated. If the wheel spins too fast, there will be slippage. The rover discussed in this paper has large grooves to improve traction on the lunar dust, and the average speed of this rover is around 2 kilometers per hour. Therefore, it will likely not face significant slippage, based on the factors described in the simulation study.

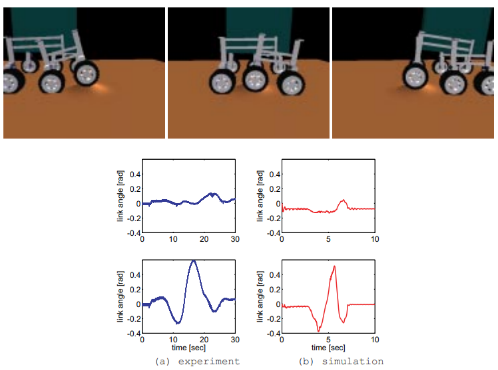

Fig. 19 A simulated rover with a rocker-bogie mechanism traveling over a bump[16]

2k. Structural Analysis

A study on the structural stability of a Mars rover performed a finite element analysis on an example Mars rover[17]. The rover in the study shares multiple key traits with the rover discussed in this work. Notably, a main central chassis, 6 wheels, a robotic arm mounted on top, and a rocker bogie mechanism. The length-to-width ratio of the chassis is also similar to the length-to-width ratio of the chassis in this work. Thus, the structural analysis done in this study can be used as a validation of the structural design of this rover. The study found that the design had minimal displacement, with the most being 0.153 mm at the edge of where the load was applied. They found that steel was the best at minimizing displacement, aluminum was good for minimizing weight while maintaining structural stability, and titanium was good for reinforcing joints. With this in mind, aluminum was chosen as the primary material for this rover design.

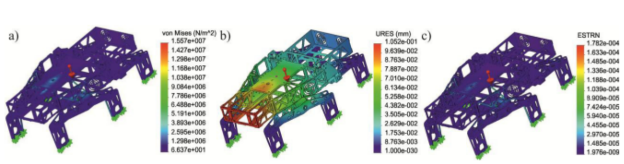

Fig. 20 A finite element analysis of a rover with a similar structure to the rover discussed in this paper (ie, a main chassis, a rocker-bogie mechanism, 6 wheels)[17].

2l Mass Estimate

The volume and material of each subsystem will be used to estimate the rovers mass. While this estimation is not the exact mass of the rover, it can be compared to the mass requirements of Artemis missions to determine if the rover is within the payload capacity of future lunar missions.

Results

The final rover design consists of six wheels, two robotic arms, a camera atop a mast, and an GPHS-RTG to provide power. The total size of the rover comes out to be 2.93 x 2.08 x 1.65 m. The total mass of the rover will be within 291-314 kg, well within the 625 kg requirement set by the Griffin Lander from Astrobotic.

Within the rover body is the rovers onboard computer, battery, thermal control, and averaging gearbox. The rocker-bogie mechanism allows the rover to tilt in any direction by 45 degrees without tipping over, making it very stable. This rover concept could be controlled remotely by astronauts to perform a multitude of tasks around a lunar base, such as clearing areas of rocks, modifying or repairing sections of the base, handling scientific equipment, and inspecting sections of the base, to name a few. The rover body has plenty of extra room to incorporate scientific instruments or new features, such as a storage unit for collected samples, lights, extra cameras, telemetry instruments, or any other useful addition. Overall, the rover fulfills all the chosen criteria for the design (Figures 21-22).

Discussion

The rover designed during this research is for a future manned lunar mission, so it has a very different mission profile than most current rovers sent to the moon. The primary commonality between this rover and others is the wheels. As an example, the Yutu 2 rover on the moon also utilizes 6 wheels (Figure 23). However, the two rovers share little similarity other than that. The Pragyan rover also utilizes 6 wheels, as well as a rocker-bogie mechanism similar to this rover design (Figure 24).

This rover does not share many similarities with current or previous lunar rovers. The Yutu 2 rovers size is 1.5 x 1.0 x 1.1 m, while Pragyan is 0.9 x 0.75 x 0.85 m[20,21]. This papers rover design is larger than Yutu and Pragyan, lacks solar panels, and has entirely different instruments than the example rovers. This

Table 5 Rover mass breakdown by component. Items marked with an asterisk (*) are estimates based on the type of system, its size, and corresponding weights in other rovers. Low and high values are included for each of these estimates. Cells shaded blue are used in the total weight calculation

System	Volume (cm^3)	Material	Material Density (g/cm3)	Mass (kg)
Main Chassis	30887.33	Aluminium 7075	2.81	86.7926
Bogie	1408.26	90% Aluminium 7075 10% Titanium 6Al-4V	2.81 (Al) 4.43 (Ti)	4.1853
Rocker	2351.18	90% Aluminium 7075 10% Titanium 6Al-4V	2.81 (Al) 4.43 (Ti)	6.9877
Rocker-Bogie Suspension				11.173
1 Wheels	3546.54	Aluminium 7075	2.81	9.96577
2 Suspension Systems + 6 Wheels Total Weight				82.14062
1 Robotic Arm	3268.725	85% Aluminium 7075 15% Titanium 6Al-4V	2.81 (Al) 4.43 (Ti)	9.97636442
Electronics + Actuators for 1 Robotic Arm*				7 - 12
2 Robotic Arms Total Weight				33.95 43.95
Camera Mast	1406.84	Aluminium 7075	2.81	3.95322
Camera*				3 - 6
Power Systems				72.79
Thermal Management Systems (Heat pipes, heaters, insulation, etc)*				1 - 2
Communications Systems*				2 - 6
Onboard Computer + Electronics*				2 - 3
Navigational Instruments (Lidar, IMUs, sensors, etc)*				2 - 5
Misc. (Connectors, wiring, joints, fasteners, etc)*				2 - 3
Total estimated weight of rover				291 - 314

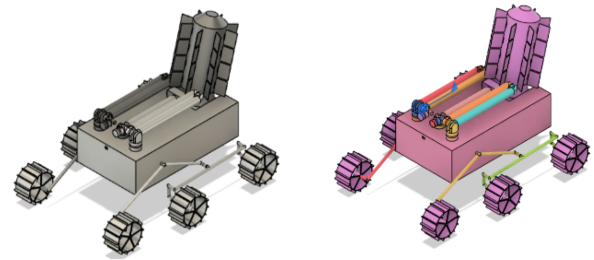

Fig. 21 Isometric view of the full rover with all components in resting position. The left view is colored with default colors. The right view is colored by component. Own source modeled in Fusion 360.

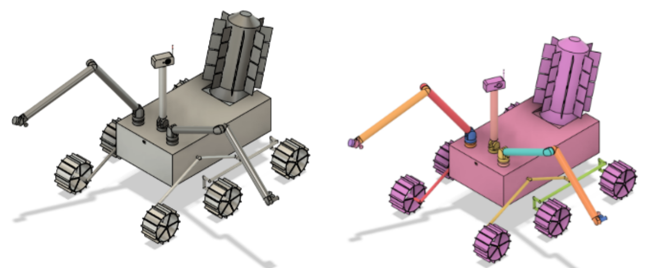

Fig. 22 Isometric view of the full rover with all components deployed. The left view is colored with default colors. The right view is colored by component. Own source modeled in Fusion 360.

is, again, due to the significantly different mission profiles of the rovers. However, the similarity in the number of wheels and the repeated use of rocker bogie mechanisms is an interesting coincidence. This is likely due to 6 wheels being very stable for rovers and optimal for most designs if the size permits it. While this rover is not very similar to lunar rovers, it may share more similarities to Martian rovers.

When comparing the rover to the perseverance rover, for example, there are quite a few similarities that can be observed. For one, both rovers opt for an RTG as a power source, though the lunar rover in this paper utilizes a General Purpose Heat Source (GPHS) RTG, while Perseverance opts for a Multi Mission RTG (MMRTG). The GPHS-RTG has better power output than the MMRTG, which is why it was chosen for this rover design. While the design choices were made with different contexts in mind, the overall issue it solves is the same. The rovers will not receive sunlight continuously and must withstand long periods with little to no sunlight. Both rovers also use 6 wheels and a rocker-bogie mechanism. They also both have a camera atop a mast and a robotic arm to perform work (Figure 25). This rover design is ideal for supporting astronauts on the lunar surface because of its subsystems that are designed to aid astronauts, such as the robotic arms which will be actively controlled by astronauts, an RTG which will make the rover more reliable, a stable rover body, and finally LiDAR and HD

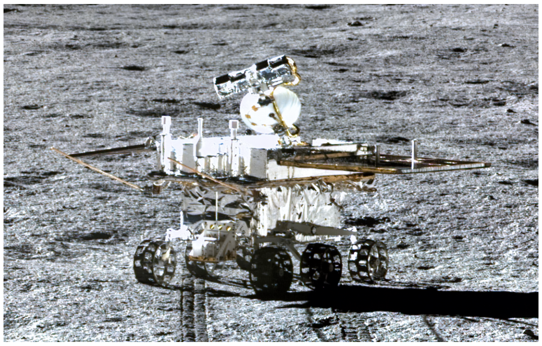

Fig. 23 Picture of the Yutu 2 rover operating on the lunar surface [18]

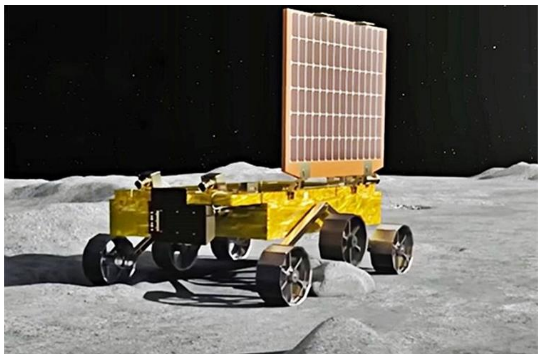

Fig. 24 Artist rendition of the Pragyan rover operating on the lunar surface [19].

Table 6 Comparison of this papers rover, Yutu 2, Pragyan, and Perseverance in key characteristics.

Characteristics	**This Rover**	**Yutu 2** [20]	**Pragyan** [21]	**Perseverance** [4]
Lunar Rover	Yes	Yes	Yes	No
Size (LxWxH) (m)	2.93 x 2.08 x 1.65	1.5 x 1.0 x 1.1	0.9 x 0.75 x 0.85	2.9 m 2.7 m 2.2
Power Source	GPHS-RTG	Solar	Solar	MMRTG
# of Wheels	6	4	6	6
# of Robotic Arms	2	0	0	1
Robotic arm length	2.42 m	N/A	N/A	2.1 m

camera information for the astronauts.

The differences between the rovers are that the Perseverance rover contains many more scientific instruments than this design, and it only has one robotic arm without a modular end effector. This design intentionally lacks instruments so that it can be modified in the future to incorporate instruments if necessary. It will also be close enough to human beings to be actively modified during its mission time, unlike Perseverance, which cannot be modified physically.

Fig. 25 A picture of the perseverance rover on the Martian surface [22].

4a. Limitations

A limitation of this design is that it does not delve into the inner workings of the rover. The complexities of designing all the circuitry and inner components of the rover are out of the scope of this research. Instead, this research opts to provide a general concept of what a future lunar rover intended to assist a lunar base may look like. Future rover designs for this use case could build off of this design by designing specific types of end effectors for different uses on the moon, or developing the inner workings of the rover.

Conclusion

This research aimed to generate a lunar rover design capable of aiding astronauts working on a lunar base with tasks to be performed in the lunar environment. The final design is a remote-controlled lunar rover with two robotic arms that astronauts can control to interact with the environment. The astronauts can also attach different end effectors to the robotic arms when necessary to perform different tasks. While it does not share many similarities with current or previous lunar rovers, it does have many design similarities with current Martian rovers, such as perseverance. This design could potentially be used in the future as a starting point for a rover that would operate on the first manned lunar base. Ultimately, the future of manned lunar exploration will require rovers similar to the design presented in this paper to make progress towards sustainable lunar presence on the moon.

Acknowledgments

I would like to thank Dr. Michel Lacerda for his support and mentorship throughout the development of this paper.

References

1 T. Stubbs, R. Vondrak and W. Farrell, *Impact of Dust on Lunar Exploration*, https://adsabs.harvard.edu/full/2007ESASP.643..239S, 2005, [cited 2023 Oct 27].

2 K. Hayatsu, M. Hareyama, S. Kobayashi, N. Yamashita, M. Miyajim, K. Sakurai *et al.*, *Biological Sciences in Space*, 2008, **22**, 59–66.

3 D. Schauer and O. Linton, *Health Physics*, 2009, **97**, 1–5.

4 NASA, *Perseverance Rover Components*, https://science.nasa.gov/mission/mars-2020-perseverance/rover-components/, 2024.

5 *Lunar Landers — Astrobotic Technology*, https://www.astrobotic.com/lunar-delivery/landers/.

6 P. Abel, M. Anderson, E. Blom, C. Calle, P. Dunlap, P. Greenberg *et al.*, *Lunar Dust Mitigation: A Guide and Reference First Edition (2021)*, https://ntrs.nasa.gov/api/citations/20220018746/downloads/TP-20220018746.pdf, 2023.

7 J. Baik, T. Lee, S. Pyo, S. Han, J. Jeong and Y. Kim, *IEEE Transactions on Antennas and Propagation*, 2011, **59**, 80–88.

8 J. Taylor, A. Makovsky, A. Barbieri, R. Tung, P. Estabrook and A. Thomas, *Article 10 Mars Exploration Rover Telecommunications*, https://descanso.jpl.nasa.gov/DPSummary/MER_article_cmp20051028.pdf, 2005.

9 K. Stephenson and T. Blancquaert, *Nuclear Power Technologies for Deep Space and Planetary Missions*, http://cs.roboticbuilding.eu/images/1/13/NUCLEAR_POWER_TECHNOLOGIES_FOR_DEEP_SPACE_AND_PLANETARY.pdf.

10 DHS.gov, *AWR-923-W Course Materials*, https://cdp.dhs.gov/shared/se/courses/default/AWR-923-W%2005122021%201.2-20210512144644/groups/26.html, 2024.

11 G. Bennett, J. Lombardo, R. Hemler, G. Silverman, C. Whitmore, W. Amos *et al.*, *Mission of Daring: The General-Purpose Heat Source Radioisotope Thermoelectric Generator*, https://nuke.fas.org/space/gphs.pdf, 2006.

12 A. Bendoyro, *Nuclear fission rovers for Martian exploration*, https://louis.uah.edu/uah-dissertations/436?utm_source=louis.uah.edu%2Fuah-dissertations%2F436&utm_medium=PDF&utm_campaign=PDFCoverPages, 2024, [cited 2025 Apr 7].

13 P. Berkelman, M. Chen, J. Easudes, J. Hancock, M. Martin, A. Mor *et al.*, *Design of a Day/Night Lunar Rover 6. AUTHOR(S) CMU-RI-TR-95-24*, https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=0e8982b22206abdbb169fabacc2f0cb54a4a08a3, 1995.

14 D. S. C, S. S. G, R. N. P, R. M. S and P. S. M, *IARJSET*, 2017, **4**, 46–50.

15 D. Rodrguez-Martnez, K. Uno, K. Sawa, M. Uda, G. Kudo, G. H. Diaz *et al.*, *IEEE Robotics and Automation Letters*, 2024, **9**, 619–626.

16 M. Mann and Z. Shiller, Proceedings of the 2006 Conference, 2006, pp. 861–866.

17 P. Ptak, M. Pierzgalski, D. Cekus and K. Sok, *Procedia Engineering*, 2017, **177**, 175–181.

18 A. Jones, *Chinas Yutu 2 rover about to wake up on the far side of the moon*, https://www.space.com/china-yutu-2-moon-rover-chang-e-4-wake-up-may-202, 2021, Accessed 2024-09-16.

19 *Chandrayaan 3: Five fascinating facts about the Pragyan rover*, https://www.autocarpro.in/news/chandrayaan-3-things-to-know-about-pragyan-moon-rover-116507, 2024, Accessed 2024-09-16.

20 NASA, *NASA - NSSDCA - Spacecraft - Details*, https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2018-103A, 2018, Accessed 2024-09-16.

21 NASA, *NASA - NSSDCA - Spacecraft - Details*, https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2019-042A, 2019, Accessed 2024-09-16.

22 P. Ariel, *Roving the Red Planet IAAC BLOG*, https://blog.iaac.net/roving-the-red-planet/, 2023, Accessed 2024-09-16.