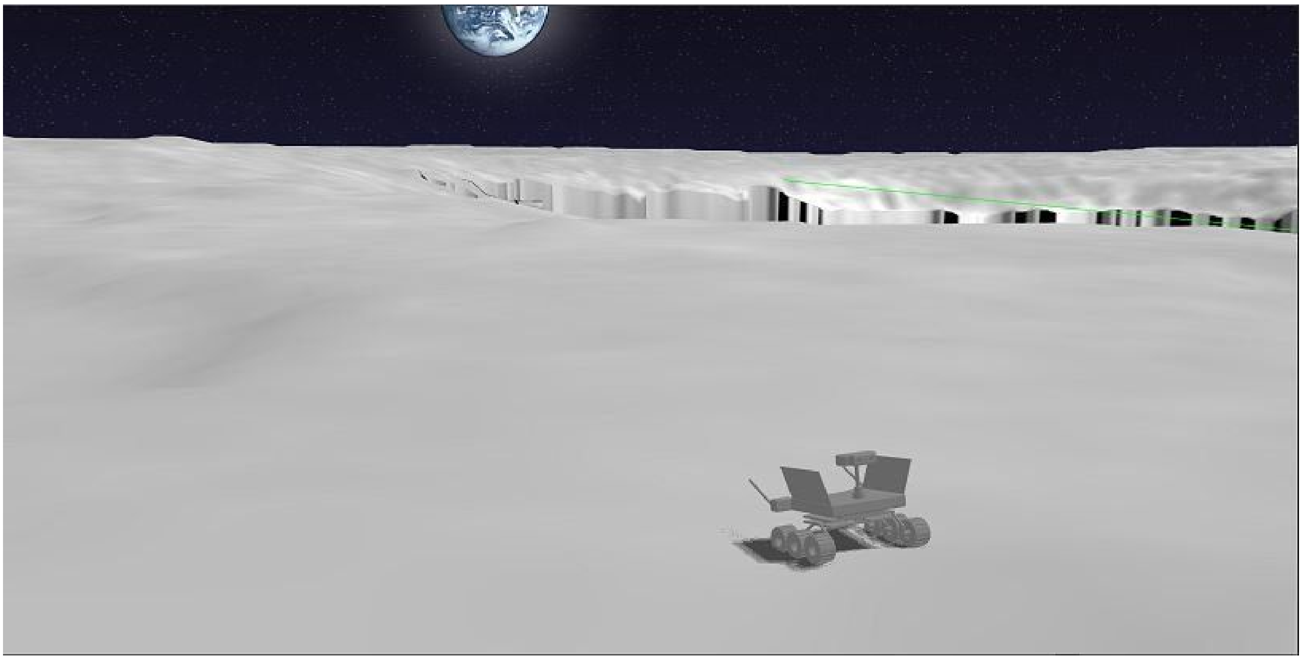
SINGAPORE SPACE CHALLENGE
2021

Team Hitchhikers

ROVER R-42

MISSION REPORT



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Mission Statement

“Design a rover model capable of carrying out excavation and/or In-Situ Resource Utilisation (ISRU) missions on the moon”

-SSC 2021 problem statement

After a thorough literature survey and talking to our mentors and industry experts, we came to understand that engineering in Space is unlike engineering on the Earth. With extreme temperatures, unknown surroundings and unfriendly environments, Space is where the true spirit of engineering is put to test. We rewired our thinking process to look at trade-offs and points of failure for every aspect of the design - to go one step beyond .

We ranked all of our ideas on the basis of four parameters:

1. Cognizance with the problem statement
2. The necessity of a rover to meet the objectives
3. Practical implications and findings
4. Value addition to upcoming lunar missions

We needed solid reasons to back our creative ideas. When we were confused we asked ourselves a few key questions:

1. Does this help in achieving our mission’s objective?
2. Is this absolutely necessary?
3. What happens if this fails?
4. Will this affect integration with other subsystems?

This process has helped in rationally developing a mission concept that is also feasible. It also helped us understand the key implications and requirements of our mission which will be discussed in the appropriate sections of the report. We then proceeded to define our own mission statement-

“To design a lunar rover capable of exploring lunar lava tubes around possible skylights using a ground penetrating radar”

1. INTRODUCTION

The goal of the mission is to detect and map the subsurface structures of a possible Lunar Lava Tube in Mare Tranquillitatis using a Ground Penetrating Radar (GPR) mounted on the rover (TARS R42).

1.1. BACKGROUND AND MOTIVATION

Why Lunar Lava Tubes?

Lunar lava tubes (LLT's) are tunnel-like subsurface structures present on the moon. They are said to have formed in the basaltic plains of the Mare regions due to the flow of lava. They are identified by small openings on the surface of the moon called as Skylights (Figure 1.1). Skylights essentially serve as openings for the LLT's. These lava tubes are important from various science perspectives and provide potential sites for future lunar base construction. Since the insides of lava tubes are shielded from meteorite bombtive, they are assumed to be in pristine condition. Moreover, the thick walls of the lava tube effectively shield space radiation and help maintain stable temperature conditions inside the tunnel. Since most of the regions inside the tunnel are permanently shadowed, there is a very high possibility of the presence of ice-deposits, making them excellent sites for lunar settlements. Furthermore, lunar lava tubes could facilitate easy access to:

1. Elevated regions for communication and solar power
2. Basaltic plains for landing sites
3. Underground mineral resources

The GPR depth-time data obtained can be used to effectively determine the dielectric properties of the regolith and the ejecta buried. Besides, this data could also be used to generate a tomographic image of the subsurface, thereby helping us visualise the structural profile of the LLT. Moreover, a radargram view can also be obtained (tomographic inversion principles) which could help us visualize the density variations in subsurface.

Collecting useful topographical data about the LLT's could greatly aid future missions like NASA's AXEL and Spacebit's ASAGUMO that plan to explore the Sky Lights in Lacus Mortis and Mare Tranquillitatis. Especially since some LLT's could have blocks next to the skylight entrance, in-depth information about this region will be very useful.

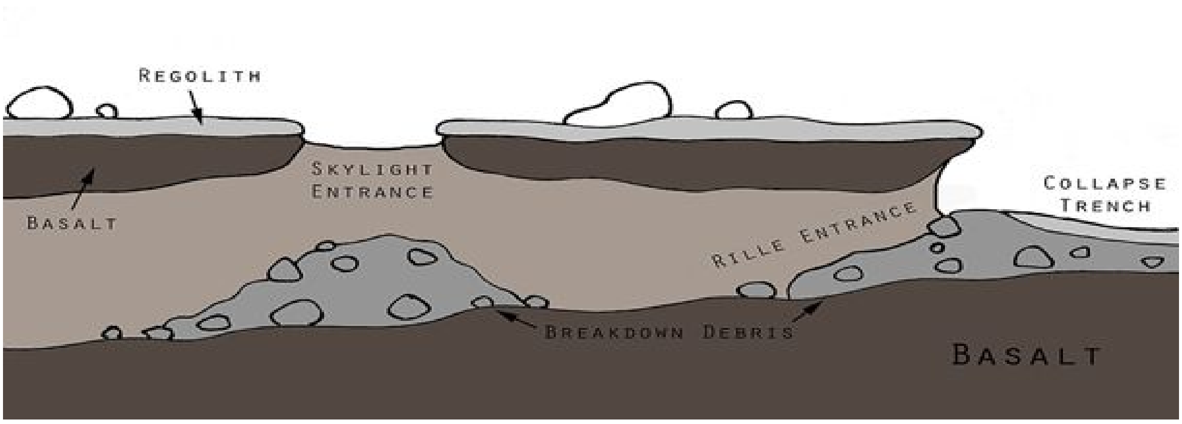


Figure 1.1: Topographic view of the LLT subsurface

1.2. MARE TRANQUILLITATIS - THE LANDING SITE

We chose to explore the skylight (possibly an entrance to an LLT) present in Mare Tranquillitatis primarily because of its size and location. The diameter of the rim is around 120 m which makes it possible for a rover to traverse a significant distance along the circumference of the skylight to collect data. Besides, existing data from LROC and other moon mapping missions also suggest a high possibility of the skylight being an actual LLT. The location of the skylight is also in close proximity to the Apollo 11 landing site which is indicative of the traversability (Maria are flat lava plains) of a rover in the landing site.

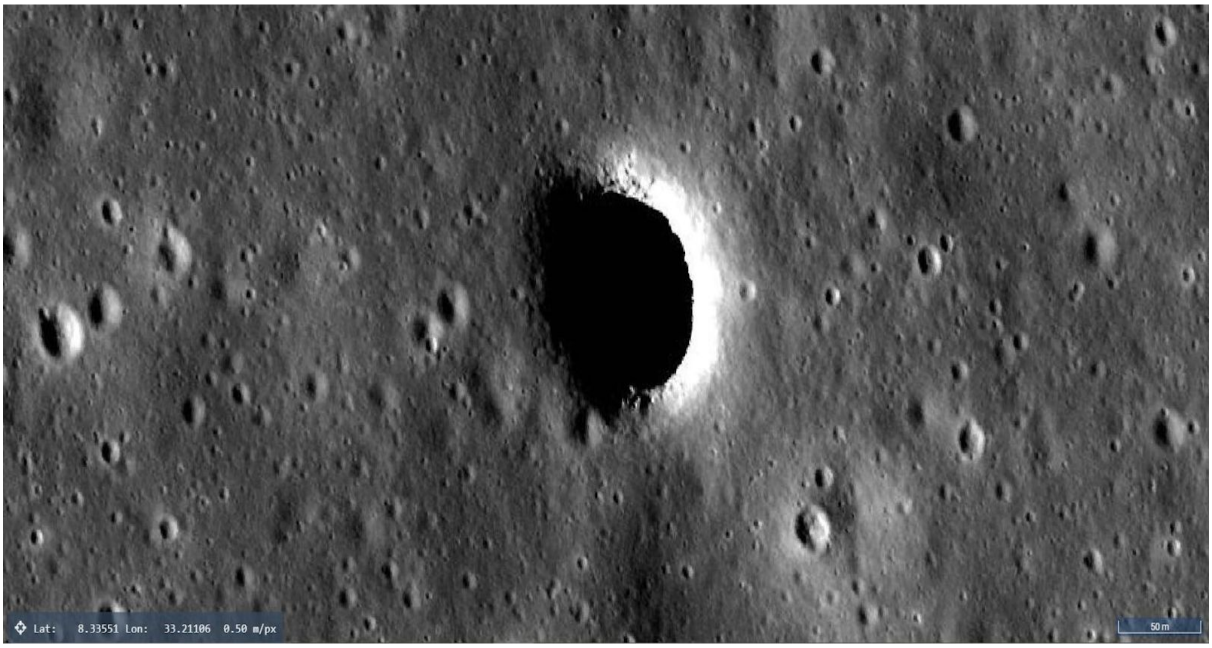


Figure 1.2: Skylight in Mare tranquillitatis

Table 1.2.1 gives some details about the landing site:

Location Coordinates	33.2 °E, 8.3 °N
Depth of the Rim (North-South)	120 m
Depth of the Rim (East-West)	180 m
Diameter of the Rim (North-South)	120 m
Diameter of the Rim (East-West)	110 m
Temperature Range (Interior of the LLT considering Albedo at 10%)	(0 to 20) Degree Celsius
Distance from Apollo 11 site	350 Km
Average Local inclination	7 to 12 degrees

Table 1.1: Landing Site details

1.3. KEY OBJECTIVES AND OUTCOMES

Listed below are the key objectives and outcomes of the mission:

1. Obtain the structural profile of the LLT- Depth, Shape, Size (Tomographic imaging using GPR)
2. Check for blockages inside the LLT
3. Determine the ejecta (debris) nature (size, shape) in the surroundings of the skylight
4. Provide necessary scientific data for the location of a future Moon base
5. Categorize the debris with respect to previous Mission data
6. Determine the nature of the host media (Regolith)- Dielectric, Density etc.,
7. Create a 3D map of the Mare Tranquillitatis terrain in proximity of the pit
8. Provide a scientific basis for a detailed study of the formation and evolution of the Moon

1.4. MISSION REQUIREMENTS

1.4.1. The rover shall weight no more than 60 Kg (Mission Constraint)
1.4.2. The rover dimensions shall not exceed 1 m x 1m x 1m (Mission Constraint)
1.4.3. The rover shall have a GPR to obtain subsurface topographic data of LLT's
1.4.4. The rover chassis shall be hermetically sealed
1.4.5. The rover structure shall remain equipotential

1.5 SUBSYSTEM REQUIREMENTS

1.5.1 PAYLOAD - GPR

1. The rover shall have a Ground Penetrating Radar (GPR) that images the subsurface to more than 40 m with vertical resolution better than 40 cm

2. The GPR shall be controlled by a separate computing element that is connected to the rover's primary on-board computer (OBC).
3. The GPR shall collect data during its operation time and store it on its on-board memory
4. The GPR shall send its collected data only when requested by the rover's primary OBC.

1.5.2 COMMUNICATION REQUIREMENTS

1. The rover shall communicate with the Lander wirelessly.
2. The rover shall send mission critical telemetry (velocity, position) at regular intervals
    a. During Teleoperation, the rover shall send a streaming video of real time movement
3. The rover shall send housekeeping messages to the Lander at regular intervals to confirm that all sub-systems are functioning properly.

1.5.3 NAVIGATIONAL REQUIREMENTS

1. The rover shall have two operational modes (Teleoperation, Autonomous) and will switch between them as required
2. The rover shall use several onboard sensors to navigate the lunar terrain in each operational mode.
3. The rover shall have several pairs of stereo cameras to achieve specific functions that will allow it to satisfy criterion 2.
    a. One pair of navigation cameras (NAVCAMS) for mapping, path estimation, localization and navigation.
    b. One pair of hazard avoidance cameras (HAZCAMS) to identify and avoid obstacles.
    c. One Inertial Measurement Unit (IMU) to aid navigation and localization.
4. The rover shall maintain its commanded velocity using a feedback control loop.

1.5.4 POWER AND OPERATIONS

1. The rover will have a solar array with a solar-battery charging circuit as its primary source and the rechargeable battery as its secondary source of power.
2. The rover shall have a watchdog processor that monitors the primary OBC, the payload processor and all sensors.
3. The rover shall contain several temperature sensors to monitor temperature levels on its body.

2. MISSION PLANNING AND OPERATIONS

The chosen landing site is depicted by L in Fig 2.1. This image has been sourced from LROC QuickMap. The coordinates are given in Table 2.1.
The path and the way points were chosen from LROC data based on the terrain conditions and local inclination (Easiest possible path for the rover to traverse - under the best illumination conditions, with minimum slope and elevation). Here,

- L to G1 : 485m
- G1 to G17 : 600m
- Total path length (L to G17) : 1085m

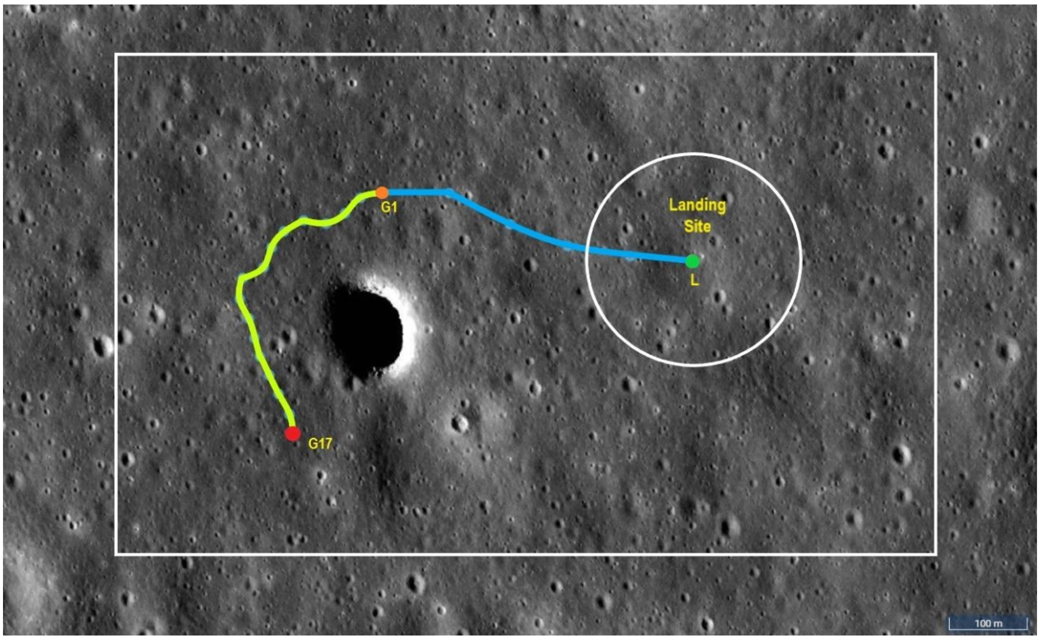


Fig 2.1: Mission path

POINT	LATITUDE	LONGITUDE
G1	8.34098	33.22273
G2	8.34075	33.22159
G3	8.34009	33.22073
G4	8.33966	33.21972
G5	8.33978	33.21855
G6	8.33931	33.21750
G7	8.33859	33.21678
G8	8.33775	33.21631
G9	8.33729	33.21520
G10	8.33637	33.21492
G11	8.33554	33.21535
G12	8.33471	33.21552
G13	8.33391	33.21575
G14	8.33310	33.21615
G15	8.33229	33.21654
G16	8.33143	33.21703
G17	8.33053	33.21716
L	8.33800	33.23841

Table 2.1 LROC coordinates of landing site and GPR exploration points

The mission will be carried out in phases as in Fig 2.2:

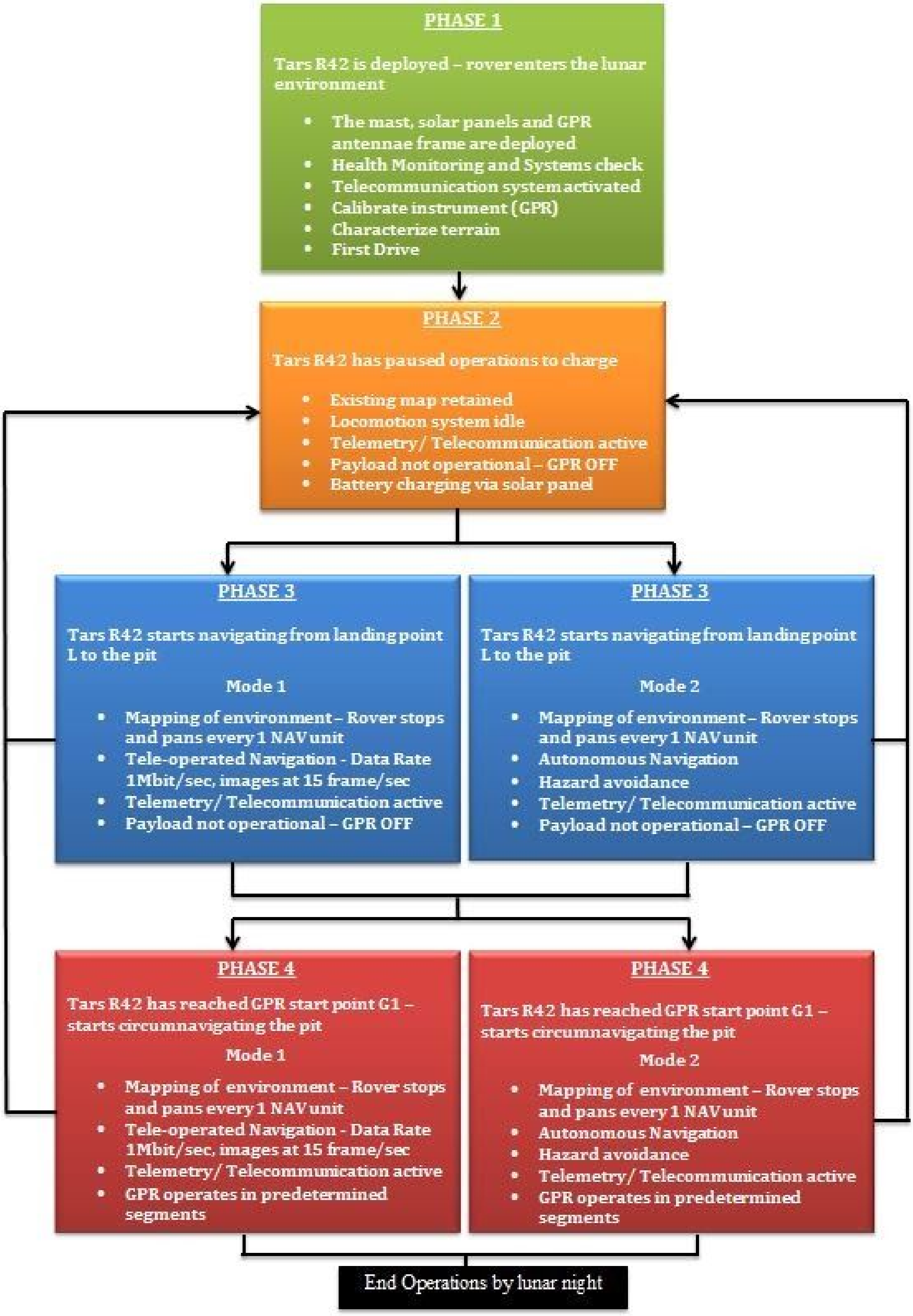


Fig 2.2: Mission operation

- **PHASE 1**

  Once the spacecraft has completed entry, descent and landing (during lunar day), the process of rover egress begins. The mast containing the NAVCAMS, Low-gain antenna is deployed. The solar panels are also deployed. and the rover begins to charge its batteries. The frame containing the GPR’s first channel antennae is also deployed. All instruments are calibrated and checked for proper functioning. The rover begins communicating with the Earth, using the Lander as a bidirectional relay point. A visual survey is performed by the rover’s multiple stereo cameras to image the surrounding terrain and run a test drive from the landing site.

- **PHASE 2**

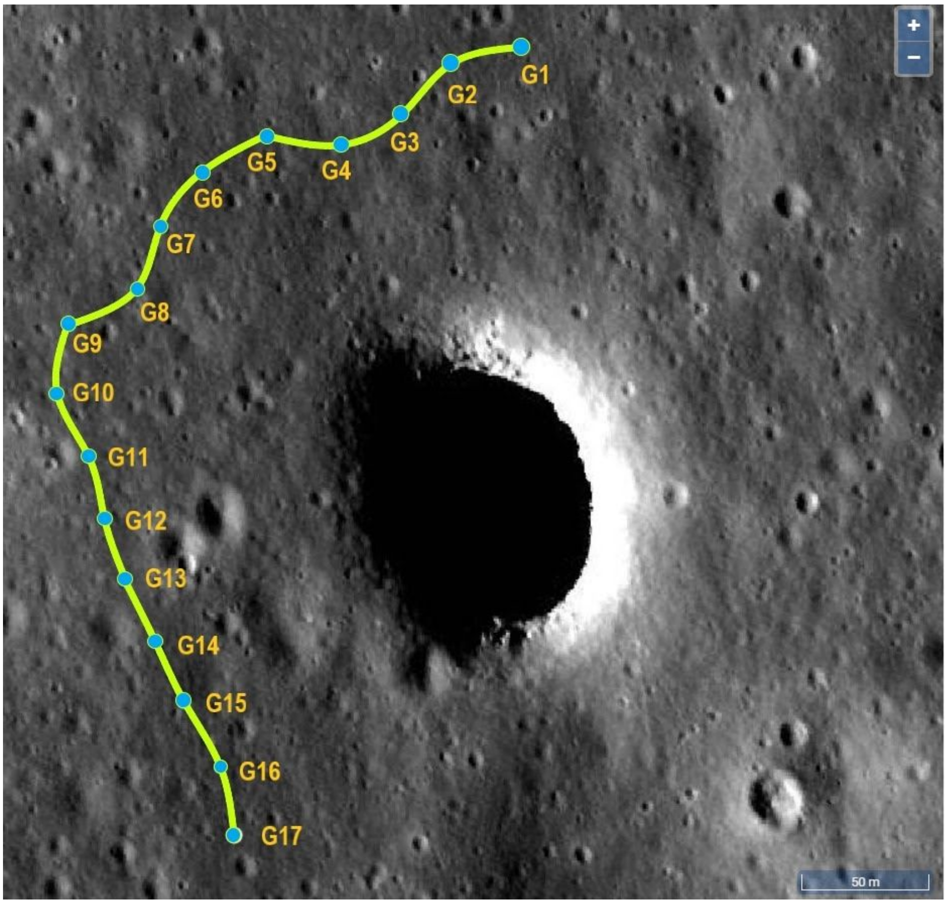
  The rover pauses all operations to charge its batteries using the solar panel. The batteries shall be used to provide power under peak load. When the level of charge reduces below the amount of power that the rover needs to operate in its current phase, the rover will stop to charge its batteries. This phase will be repeated as required.

- **PHASE 3**

  The rover begins navigating towards the Mare Tranquillitatis pit either autonomously or via teleoperation. The rover stops every 6m (1 NAV unit) and pans the NAVCAMS on the mast to survey the environment. It uses this map to traverse the terrain through predetermined waypoints. During autonomous navigation, hazard avoidance is facilitated by the pair of HAZCAMS situated at the bottom of the rover. The rover receives commands and sends telemetry as required.

- **PHASE 4**

  The rover is in proximity to the Mare Tranquillitatis pit. It begins operating its GPR during pre-determined segments. The GPR exploration points are shown in Fig 2.3 and the operational segments are shown in Fig 2.4. Here one segment Gi to Gi+1 is 36m. The data is stored on the payload processor’s on-board memory and sent on request. Mapping is carried out as in Phase 3. The rover navigates through teleoperation or autonomously, if the rover’s LOS (Line-of-Sight) is blocked by large rocks and the communication link is weak. The rover receives commands and sends telemetry as required.



GPR OPERATIONAL SEGMENTS
G1 – G4
G5 – G8
G9 – G12
G13 – G16

Fig 2.4: GPR exploration points

- **RECOVERY**
  If the communication link is severed, the rover will use its map to traverse back the last point of contact and try to re-establish the link. If a scenario exists where the rover is unable to function and has to cease operation, the rover will switch to critical mode and transmit all of the data collected by the GPR and the map data.

Depicted below in Table 2.2, are the phases the rovers will operate in, calling out which specific subsystems are active and how much average power the phase consumes.

INSTRUMENT/ SUBSYSTEM	PHASE 1	PHASE 2	PHASE 3		PHASE 4	
			MODE 1	MODE 2	MODE 1	MODE 2
IMU	ACTIVE	IDLE	ACTIVE	ACTIVE	ACTIVE	ACTIVE
NAVCAMS	ACTIVE	IDLE	ACTIVE	ACTIVE	ACTIVE	ACTIVE
HAZCAMS	ACTIVE	IDLE	IDLE	ACTIVE	IDLE	ACTIVE
LOCOMOTION	IDLE	IDLE	ACTIVE	ACTIVE	ACTIVE	ACTIVE
GPR	IDLE	IDLE	IDLE	IDLE	ACTIVE	ACTIVE
TEMP. SENSOR	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE
COMMUNICATION	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE
BATTERY	DISCHARGING	CHARGING	DISCHARGING	DISCHARGING	DISCHARGING	DISCHARGING
POWER CONSUMPTION	66.6W	9W	81.6W	83.6W	91.4W	93.4W

Table 2.2: Operations table with power requirements

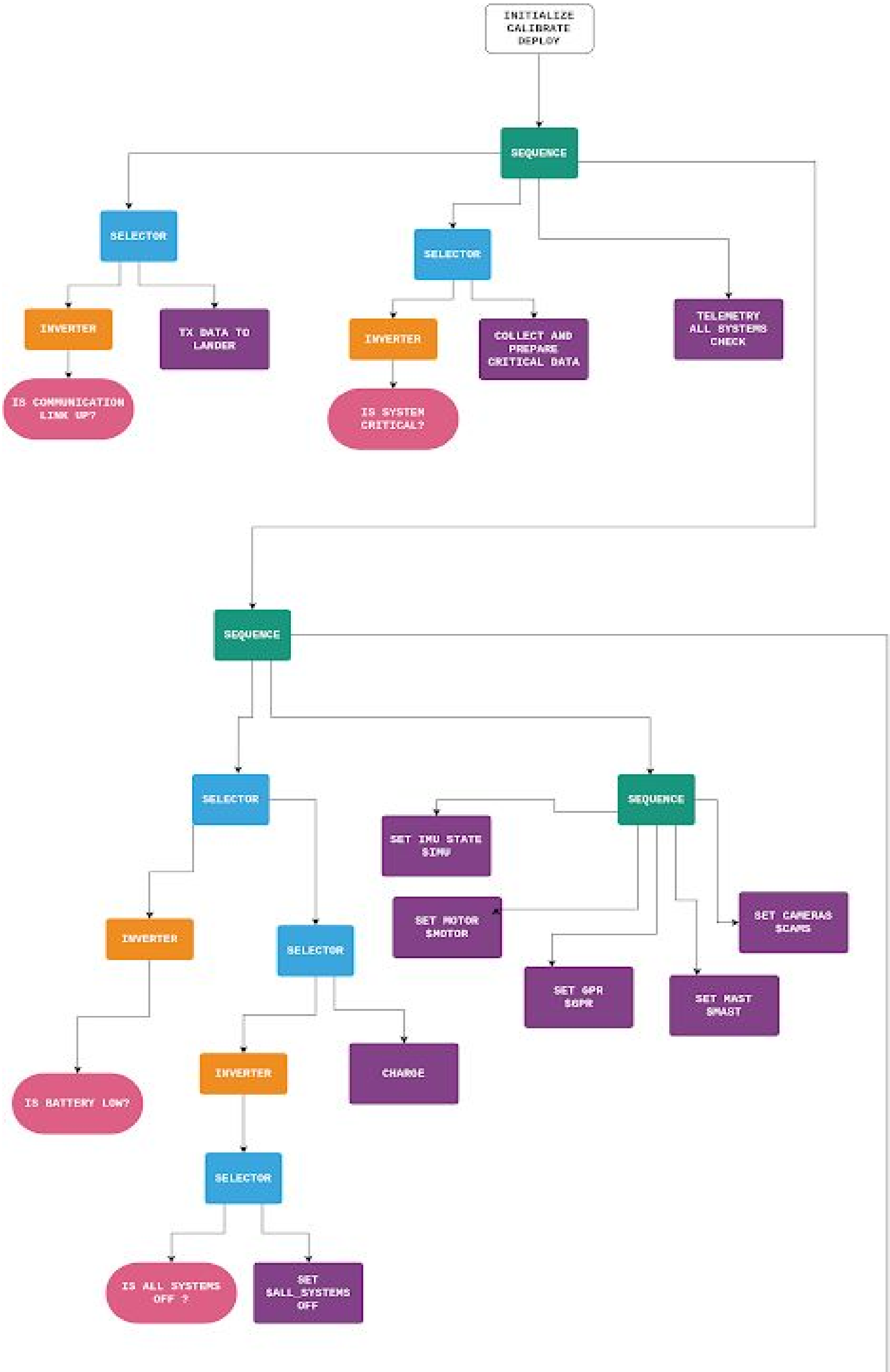
Phase 4 (Mode 2) consumes the most power. The power system is designed accordingly and is presented in Section 7. Additional operating mechanisms include:

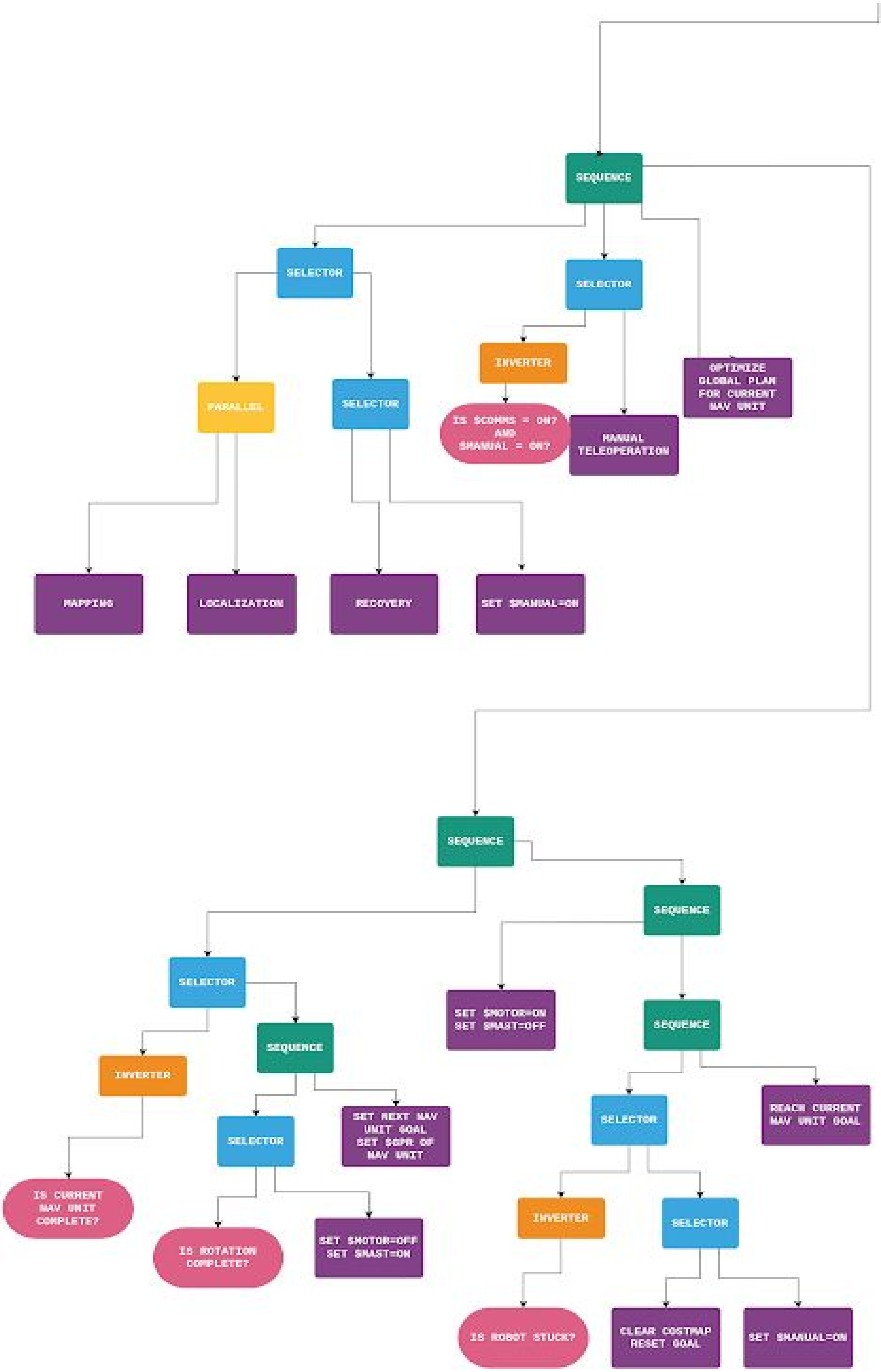
- Deployment mechanisms (Solar panel, Mast, GPR antenna frame)
- Mast rotation (To pan the NAVCAM every NAV unit)

2.1 BEHAVIOR TREE

A behavior tree is a way to structure the switching between different tasks in an autonomous agent. Behaviour trees are very efficient in creating complex structures that are both modular and reactive. Properties such as safety, robustness and efficiency, which are extremely important for a lunar rover, can be effectively designed with the help of behavior trees. This section illustrates a behavior tree describing the various operations of Tars R42 during the course of the mission.

(Clear picture available in the appendix)


INITIALIZE CALIBRATE DEPLOY
SEQUENCE
SELECTOR
INVERTER
IS COMMUNICATION LINK UP?
TX DATA TO LANDER
SELECTOR
INVERTER
IS SYSTEM CRITICAL?
COLLECT AND PREPARE CRITICAL DATA
TELEMETRY ALL SYSTEMS CHECK
SEQUENCE
SELECTOR
INVERTER
IS BATTERY LOW?
SELECTOR
INVERTER
CHARGE
SELECTOR
IS ALL SYSTEMS OFF ?
SET $ALL_SYSTEMS OFF
SEQUENCE
SET IMU STATE $IMU
SET MOTOR $MOTOR
SET GPR $GPR
SET MAST $MAST
SET CAMERAS $CAMS


SEQUENCE
SELECTOR
SELECTOR
INVERTER
OPTIMIZE GLOBAL PLAN FOR CURRENT NAV UNIT
PARALLEL
SELECTOR
IS $COMMS = ON? AND $MANUAL = ON?
MANUAL TELEOPERATION
MAPPING
LOCALIZATION
RECOVERY
SET $MANUAL=ON
SEQUENCE
SEQUENCE
SELECTOR
SET $MOTOR=ON SET $MAST=OFF
SEQUENCE
SEQUENCE
INVERTER
SELECTOR
REACH CURRENT NAV UNIT GOAL
SELECTOR
SET NEXT NAV UNIT GOAL SET $OPR OF NAV UNIT
IS CURRENT NAV UNIT COMPLETE?
IS ROTATION COMPLETE?
SET $MOTOR=OFF SET $MAST=ON
INVERTER
SELECTOR
IS ROBOT STUCK?
CLEAR COSTMAP RESET GOAL
SET $MANUAL=ON

3. MECHANICAL SUBSYSTEM

3.1 OVERVIEW

We went through a rigorous iterative design process after weighing every design decision on a trade-off scale. The model was designed using SOLIDWORKS. The choice of material was **Al T6-6061** because of its high young's modulus (69 GPa), density (2.7 g/cc) and lightweight nature. Standard M3 and M4 Titanium bolts were used throughout the rover. The extended-side rails on the chassis are designed in such a way to provide sufficient isolation between the Tx and Rx antennae of the GPR. The Rover also has a differential steering mechanism to minimize turn radius as much as possible-because of the high debris density/obstacles near the rim of the LLT.

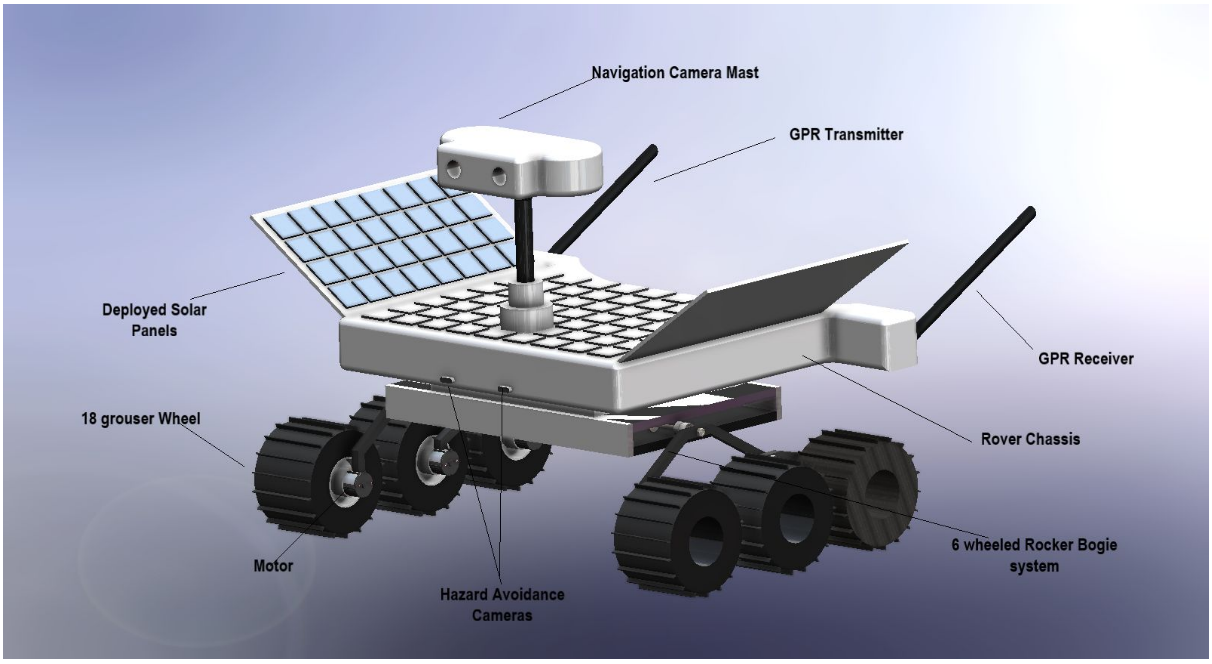


Figure 3.1. 3-D view of R42 Rover

3.2 LOCOMOTION

We chose a 6 wheeled rocker bogie suspension as opposed to a 4 wheeled rocker system in order to maintain maximum stability and wheel contact in the regions close to the rim of the skylight where the ejecta density is relatively high and the terrain too rough. Also, a 6 wheeled design would also imply a greater net torque which makes traversing through 20-degree inclines easier.

3.2.1 WHEEL DESIGN AND SUSPENSION

The wheel has 18 grousers that are each 1.5 cm high to provide enough traction and draw bar pull to traverse through. Our calculations for the regolith parameters and wheel design is listed in the table 3.1 below.

Figure 3.2: Wheel Design

Wheel diameter	15 cm
No of grousers	18
Grouser Height	1.5 cm
Angle between grousers	18 degrees
Width	15 cm
Draw bar pull calculated	3.7 N (Incline of 20 degrees)
Sinkage Exponent	1

Subsequent Sinkage	0.5 mm

Table 3.1: Wheel Design parameters calculated

The grousers are designed in such a way that at any given time, no more than 1 grouser shall remain in contact with the level ground. Figure 3.3 shows the rocker bogie suspension system and the wheel drive.

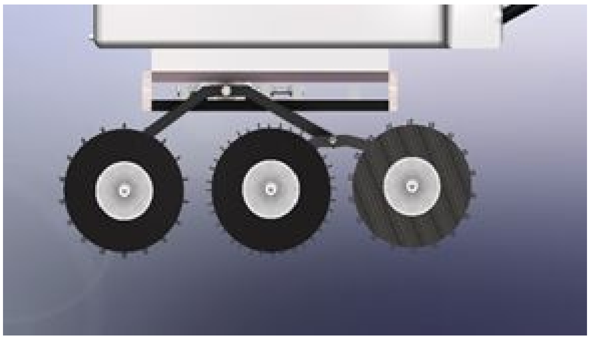


Figure 3.3: Rocker Bogie Suspension System

Figure 3.4 shows the interlocking differential gears that control the suspension movement angle and restrict it up to 60 degrees.

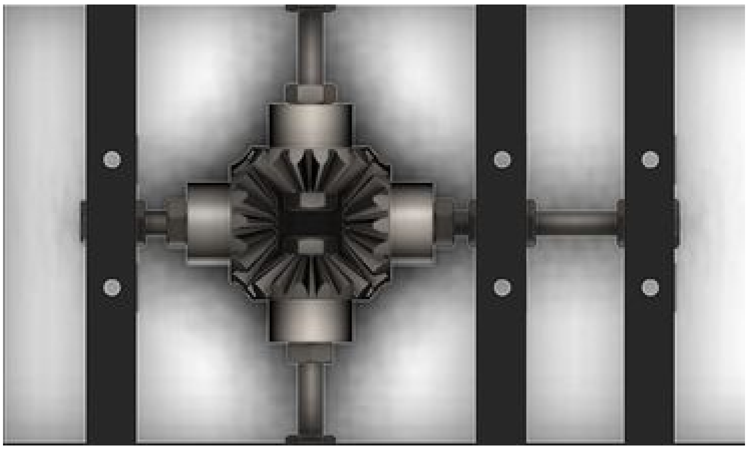


Figure 3.4: Rocker arm interlocking differential

3.2.2 MOTORS

All six wheels of the rover are independently powered by custom designed BLDC motors.

Power required-level terrain (per wheel)	Power required total for all wheels (level terrain)	Power required per wheel at an incline of 20 degrees	Total power required for all wheels at an incline of 20 degrees

0.0125 W	1.5 W	0.05 W	15 W

Table 3.2: Power requirements for custom motor

Torque (per wheel) on level terrain	0.108 Nm
Torque (per wheel) on 20-degree incline	0.450 Nm

Table 3.3: Torque requirements for the custom motor

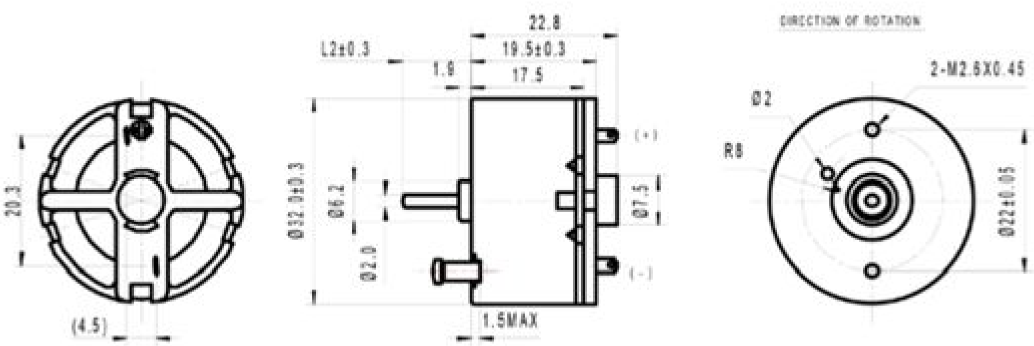


Figure 3.4: Custom BLDC motor design

Tables 3.2 summarize the power requirements for locomotion, Table 3.3 details the torque values and Fig 3.4 shows the design of the BLDC motors.

3.2.3. CAMERA MAST

The rover's camera mast is a 0.25 m long boom that has a 120-degree rotation capability to scan the surroundings. The mast is made of Aluminium alloy and is placed at the centre of the rover chassis panel. The mast is placed at a distance of 10 cm away from the front edge of the rover in order to ensure that the field of view of the navigation camera (50-degrees) is not hindered by the rover structure. 2 Maxon motors with a torque output of 20 mNm is used to rotate the mast. Figure 3.5 depicts the front view of the camera mast.

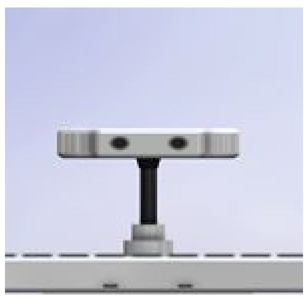


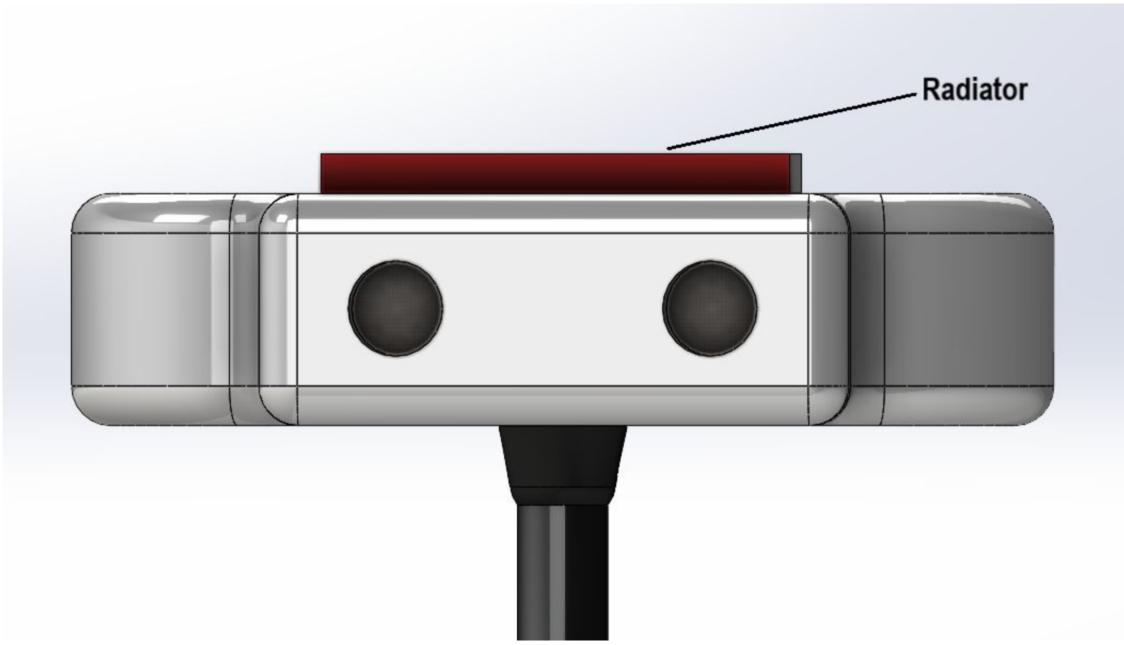
Figure 3.5. Camera Mast front view

3.3 THERMALS:

Similar to a human body, the Lunar Exploration Rover cannot function well under excessively hot or cold temperatures. In order to survive during all of the various mission phases, the rover's vital components must not exceed extreme temperatures of -40° Celsius to +40° Celsius (-40° Fahrenheit to 104° Fahrenheit). The rover's essentials, such as the batteries, electronics, and computer, which are basically the rover's heart and brains, stay safe inside a Warm Electronics Box (WEB), or the rover body. Both active and passive methods can be adapted to keep the rover at optimum temperature during various phases of the mission.

We have adapted passive thermal control methods to protect the rover from the hostile thermal environment of the moon. The devices we have integrated into the rover for the necessary thermal control are mentioned below:

1) **Radiators**: To reject the heat loads during lunar surface operation coming from the internal equipment, radiators are placed on the upper panels of the rover which will also aid in reducing the heat losses between the electronic components and the radiator itself.



2) **Multi layer Insulation:** The rover body which is highly sensitive to the external environment is protected by a multi layer insulation of Mylar material by insulating the body from any thermal exchange with the lunar surface.

3) Temperature sensors, thermostats and heaters are equipped within the modules of the rover in the warm electronics box (WEB) to readily switch on and make sure that the rover is not too hot or too cold.

3.4 MASS BUDGET:

COMPONENT	WEIGHT (KG)	QUANTITY	TOTAL WEIGHT (kg)
Mechanical Structure	11.5	1	11.5
Wheels	0.35	6	2.1
Fasteners	0.5	-	0.5
On Board Computer	7	2 (1 redundant)	14
Bus	3	1	3
IMU	0.5	1	0.5
Camera system	0.25	4	1

Antenna	0.5	2 (1 redundant pair)	1
Transceiver	0.5	2 (1 redundant)	1
Camera System	0.25	4	1
Solar panels	2	-	2
GPR	5.5	1	5.5
Motors -Wheel	0.15	6	0.9
Motors - Mast	0.13	2	0.26
Batteries	5	-	5
Miscellaneous wiring	1.5	-	1.5
Total weight			50.76
Total Lunar weight			8.46

4. TELECOMMUNICATION SYSTEM

The Telecommunications system is responsible for telecommand and telemetry. As mentioned in the requirements, the rover will have to send healthkeeping data, mission critical data and GPR data to the ground station. The rover will also receive commands and data from the ground station in return. Therefore this system also plays a key role in monitoring and controlling mission operations. The communication antennas are located in the mast of the rover.

4.1 DESIGN DRIVERS

- The overall mass and power limitations for the rover will play a major role in the design of the communications system
  - The mass of Tars R42 is around 25-26kg.
  - Larger, heavier antennas are most likely not suitable for the mission concept for Tars R42. The surface area of the antennas on the rover ought to be minimized so as to make the rover lighter and easier to store.
  - Additionally, the power requirement of different types of antennas will impact the design, as a rover of this size has a limited power budget.

- The communications from the rover to the lander, earth, and/or orbiter are limited to the maximum data transfer rate of which the rover's technology is capable.
  - GNC for Tars R42 operates in two modes: Autonomous and Teleoperated mode. The teleoperated navigation mode requires a real-time streaming video. This requires a data rate of at least 210 kbps.

- The final design requirement is that the system should not have a single point of failure - individual failures must not cause the entire communications system to cease proper operation. There must be back up designs for transmitting and receiving data, should one of the antennas malfunction.

4.2 DESIGN CONFIGURATION

Based on these drivers and the telecommunication module of Team Italia's AMALIA rover (Google XPRIZE candidate from Italy), the following configurations were considered

- Use of X-Band links to communicate with the Lander and also directly with Earth
- Use of L-Band link to communicate with the Lander and X-Band link to communicate directly with Earth.
- **Use of a redundant L-Band communication link to communicate only with the Lander, with no direct communication with Earth.**

After analysis, the third configuration has been selected. In this configuration, the rover will not be able to communicate with the Earth directly. The telecommunications architecture uses the lander as bidirectional data relay with the Earth, both for low rate (TM/TC) and high throughput data (images). The data rate is chosen as 1Mbit/sec.

The L-Band has been chosen because it requires a limited amount of electrical power with respect to other communication bands, because of the short distance between the Rover and the Lander. Nominally, the maximum distance between the rover and the lander on the lunar surface is around 500 m. At this distance the L-Band is more efficient than others. This configuration also has the least mass and is less power demanding than the others.

Fig 4.1 shows the telecommunication system configuration for Tars R42.

The module has a redundant transmission/ reception L-Band unit with a redundant transponder, which will be activated in case the main unit fails. The transmitter and receiver are connected to an RF diplexer, which will allow them to share a single communication channel via an omnidirectional low-gain antenna. The transmitter and receiver will need to be isolated properly to ensure minimum direct power transfer from the transmitter to receiver.

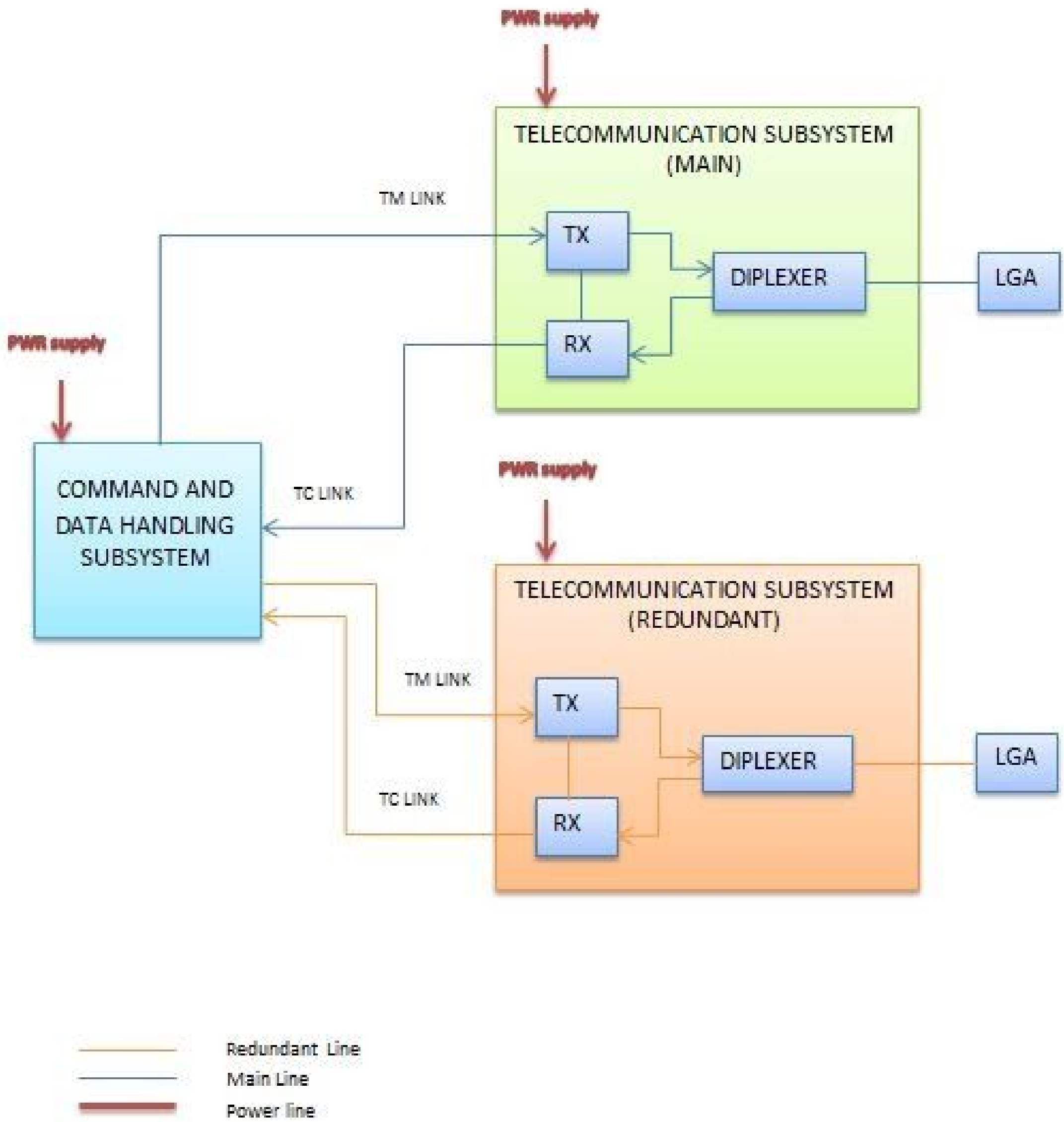


Fig 4.1 Telecommunication Subsystem

5. COMMAND AND DATA HANDLING SYSTEM

The command and data handling (CDH) subsystem is responsible for executing all the computation functionalities, coordinating/controlling the activities required for the operations of the Rover, and also realizing the necessary redundancy that allows the correct functioning even in case one of its boards fails. It also provides the interfaces with all the other subsystems (Fig 5.1), allowing to manage both the housekeeping data to be provided to the telecommunications subsystem and the tele-commands received from the ground station. The CDH of Tars R42 is also modelled after the AMALIA rover's system.

In cases where the CDH does not directly perform the operation, the CDH manages housekeeping data, the commands issue, monitoring, supervision and interfaces functions. For example: The Navigation subsystem requires dedicated electronics for video acquisition, processing and 3D reconstruction. Similarly the locomotion system also requires separate electronics to convert CDH commands to motor commands.

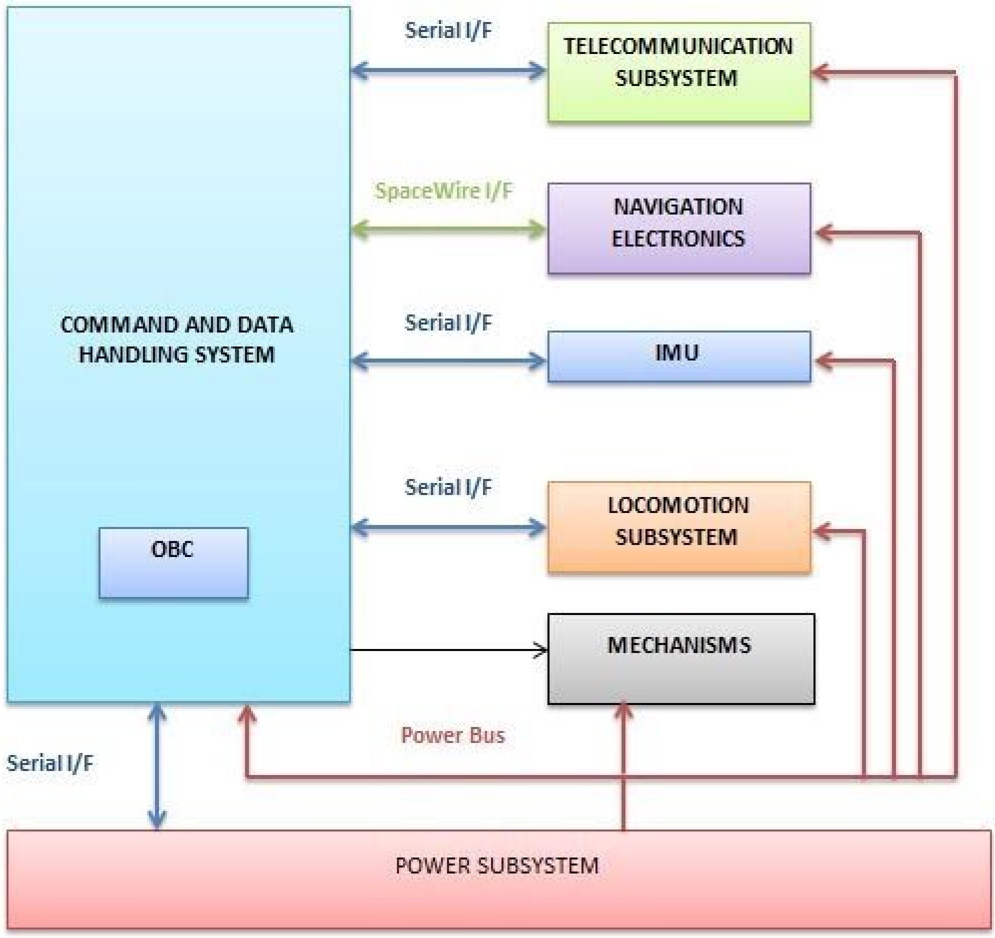


Fig 5.1 CDH and its interfaces

5.1 COMPONENTS

The components of the CDH system and their functionalities are described below:

- **Two On-Board Computers (OBC's) - (1 main, 1 redundant)**
  - To control/ monitor the operation of the Rover subsystems and anomalies detection.
  - To implement GNC algorithms according to the operational mode.
  - Sample processor: BAERAD750
- **Two Interface boards - (1 main, 1 redundant)**
  - To provide SpaceWire and RS422 interfaces with all other subsystems - Navigation, IMU (Honeywell), Locomotion, Power system, Motion control etc.
- **Two DC-DC converters - (1 main, 1 redundant)**
  - To supply CDH components.
- **Two TM/TC interface boards - (1 main, 1 redundant)**
  - To manage the serial interface with the telecommunications system.

    - To provide watchdog functionality.
- **Two motion control boards**
    - To enable the deployment and rotation mechanisms listed in Section 2.

6. NAVIGATION SYSTEM

6.1 DESIGN

Tars R42 is required to travel the pre planned path, while measuring the tomography of the subsurface with the GPR. The primary challenges faced in the lunar environment include:

- Harsh lighting conditions
- Uneven terrain
- Debris and rocks near the skylight of the lunar lava tube

The navigation system is designed to overcome these challenges and provide a safe path for the rover to traverse in the lunar environment.

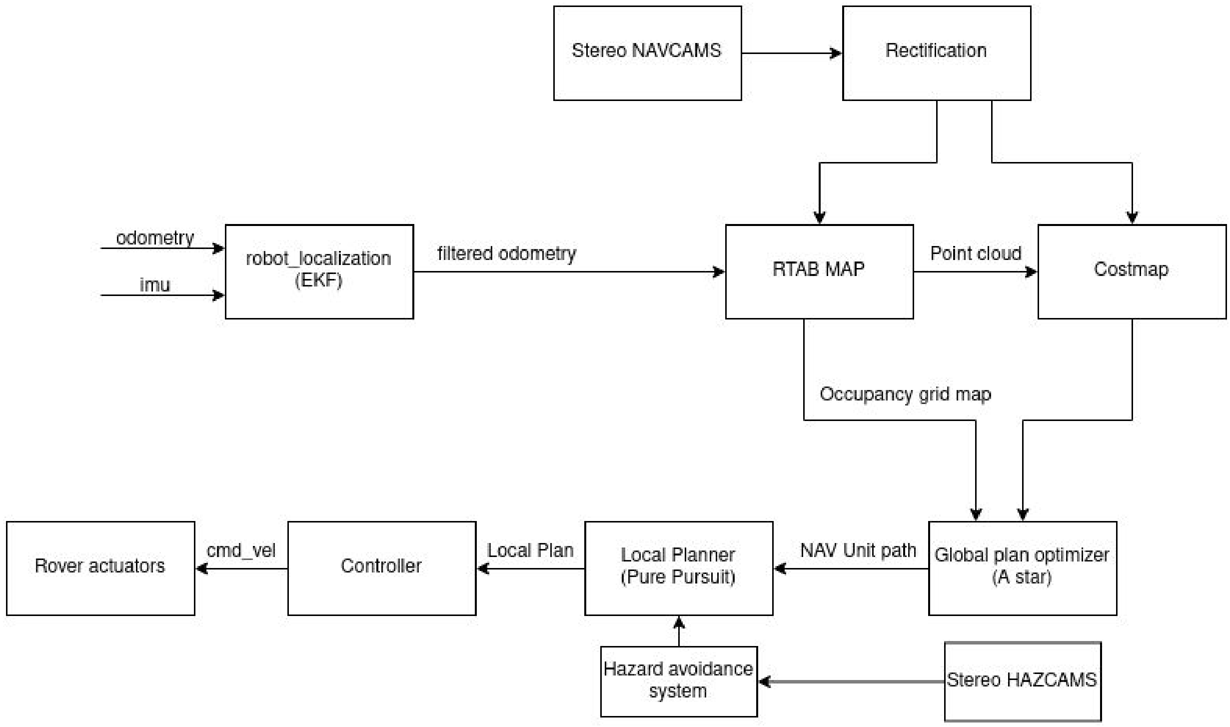


Fig 6.1: Block diagram of navigation system

6.2 IMAGE ACQUISITION AND PROCESSING

Two sets of stereo cameras are mounted on the rover - NAVCAMS and HAZCAMS (parameters in Table 6.1). These stereo cameras are used to perceive depth information from the environment and generate 3D point clouds, which is used in mapping and navigation.

As the name suggests, the NAVCAMS are used for performing mapping and navigation in the lunar environment. The NAVCAM stereo pair is mounted on the mast of the rover, at a height of 42 cm above the lunar surface. The cameras are separated by a distance of 8 cm. The HAZCAMS are used to perform hazard avoidance of unmapped obstacles. They are mounted on the chassis of the rover, with a spacing of 10.8 cm between each of the cameras.

The stereo images are synchronized and rectified. The images are projected onto a common image plane and their epipolar lines are made horizontal using the eight point algorithm.

Camera	Focal Length (mm)	Baseline (mm)	Field of view (degrees)	Image Size
NAVCAMS	15	270	40	1024 X 1024
HAZCAMS	7	100	120	1024 X 1024

Table 6.1: Camera parameters

6.3 MAPPING AND LOCALIZATION

The landing and operations site on the Mare Tranquillitatis has a maximum slope of 12 degrees, as obtained from the Digital Terrain Map/ Digital Elevation map. (Source: LROC). In order to navigate through uneven terrain effectively, the rover constructs a 3D map while navigating through the lunar environment, using a Visual SLAM technique called RTAB-Map (Fig 6.2 shows the block diagram for this framework).

RTAB-Map (Real-Time Appearance-Based Mapping) is a Graph-Based SLAM approach based on an incremental appearance-based loop closure detector. The loop closure detector uses a bag-of-words approach to determine how likely a new image comes from a previous location or a new location. When a loop closure hypothesis is accepted, a new constraint is added to the map's graph, then a graph optimizer minimizes the errors in the map.

Salient features of RTAB-Map that make it suitable for lunar navigation are explained in brief:

- **Flexibility**:
  The RTAB map employs the BVoW technique for visual mapping. The bag-of-visual-words model is an image classification technique, treating images as documents and image features as words. Existing lunar images can be fed to the BVoW model, thereby increasing the efficiency of the image classification model and rendering more accurate maps.
- **Robust localization:**
  The RTAB-Map is able to recognize when it is revisiting past locations (for loop closure detection) to correct the map. Illumination changes on the moon, geometry changes or even repetitive environments can lead to incorrect localization or failure to localize. The RTAB-Map approach is robust to such false positives.
- **Low-drift odometry:**
  While loop closure detection can correct most of the odometry drift, in certain locations on the lunar surface, the rover cannot properly localize itself on the map, either because it is exploring new areas or that there is a lack of discriminative features in the environment. During that time, odometry drift is minimized by taking inputs from wheel odometry and the IMU.
- **Multi-session mapping and map merging:**
  multi-session mapping allows the SLAM approach to initialize a new map with its own referential on startup, and when a previously visited location is encountered, a transformation between the two maps can be computed.
- **Memory management:**
  A memory management approach is used to limit the number of locations used for loop closure detection and graph optimization, so that real-time hardware constraints of the rover and constraints on large lunar environments are always respected.

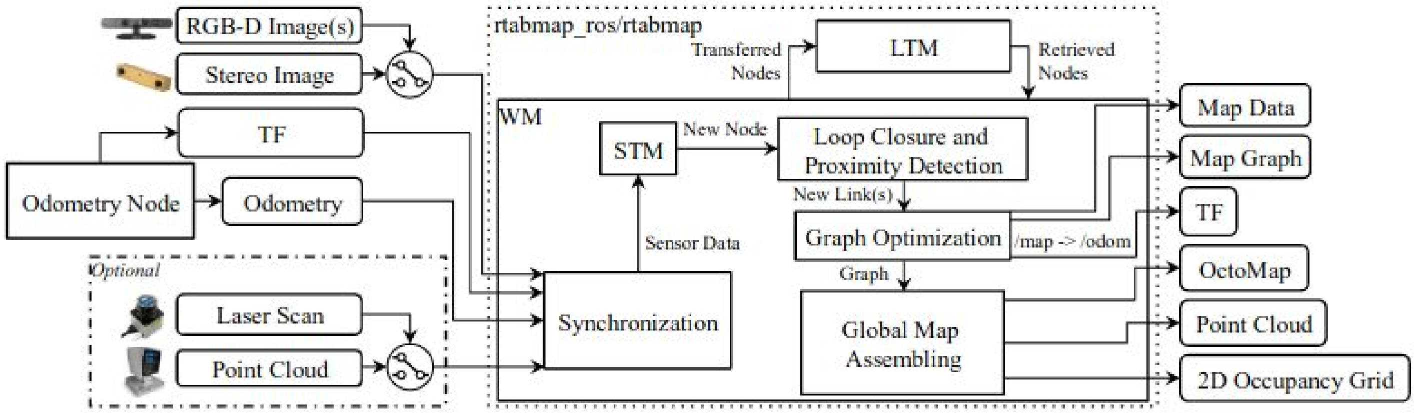


Figure 6.2: Block diagram of RTAB-Map in the ROS framework

6.3.1 INITIAL POSE ESTIMATE

After the rover is deployed and the cameras are calibrated, the exact coordinates of the lander in the Lunar Reconnaissance Orbiter Camera (LROC) map are calculated. With the lander as the origin of the map in the rover frame, the coordinate frame transformation between the LROC map frame and the rover frame is obtained.

6.3.2 IMPLEMENTATION

The NAVCAMS are a stereo pair of cameras, mounted on the mast of the rover. As explained in section 1.2, the rover travels for 1 NAV unit and stops. The mast is rotated from -60 degrees to +60 degrees and back to center, to maximize the field of view . The images obtained from these cameras are rectified (Section 6.1) and fed to the mapping algorithm.

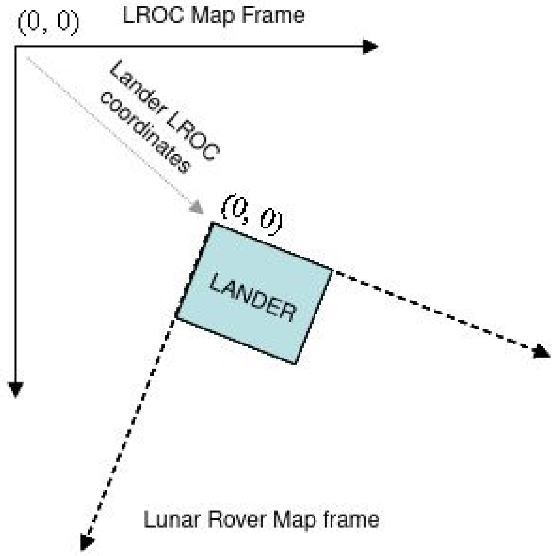


Figure 6.3: Initial pose estimate of the lunar rover

The data from the wheel encoders (Odometry) and the IMU are fused with the help of a Kalman Filter to yield a filtered odometry output with a low covariance matrix. This filtered odometry is then fed to the mapping algorithm.

The localization and mapping run on parallel threads so that the rover can navigate while simultaneously exploring the environment and building the map.

6.4 PLANNING

The mapping technique described in the previous step generates a 2D Occupancy Grid Map The occupancy grid is a discretization of space into fixed-sized cells, each of which contains a probability that it is occupied. From the occupancy grid map, and the sensor inputs, a 2D costmap is generated.

A costmap represents the cost (difficulty) of traversing different areas of the map and is used to guide a route planning algorithm to find efficient and safe routes across the ground. The roughness index (explained in section 6.5.1) is fused with the costmap such that the cost has lower values where the terrain is flat and higher values where the terrain is rough/sloping. The costmap is continuously updated to enable optimal path planning. Table 6.2 provides the parameters for the occupancy grid map.

Resolution	**Free space Threshold**	**Occupied space threshold**
0.05 m	0.65	0.196

Table 6.2: Occupancy map parameters

6.5 GLOBAL PLANNING

A global plan of length 1085m is computed, before the mission, using the data obtained from the LROC map. This path is planned by the mission team taking into account factors such as slope and possible debris while maintaining a safe distance of 70-90 metres from the skylight.

The LROC coordinates are projected to the lunar rover map frame, and a global plan is obtained. Since the LROC map has a resolution of 50m, the global plan may not be completely optimized. To overcome this problem, with the help of the costmap, the global plan is optimized using an A* algorithm for every NAV UNIT such that the cost of the plan is kept minimum.

6.6 LOCAL PLANNING

A pure pursuit algorithm is used to generate the local plan of the rover. Pure pursuit is a path tracking algorithm which computes the angular velocity command that moves the rover from its current position to reach a lookahead goal in front of the robot. The algorithm then updates the look-ahead point on the global path based on the current position of the robot until the last point of the path. It can be thought of as the rover constantly chasing a moving point on the global path.

The lookahead distance is kept at a low value of 10 cm to ensure that the rover follows the global path as closely as possible. Every NAV UNIT is regarded as a separate global path such that the lookahead goal treats the end of the NAV UNIT as the final pose, until it is updated with the next NAV UNIT.

6.6.1 VELOCITY PROFILE

From the 3D point clouds generated while mapping, the Roughness Index(RI) of the terrain is calculated using the height of the pointcloud generated from the mapping algorithm and the ground clearance of the lunar rover.

A sinusoidal base elevation model (SBEM) is used to generate the linear velocity of the rover. The SBEM velocity profile (Figure 6.3) is the safest while traversing rough terrain.

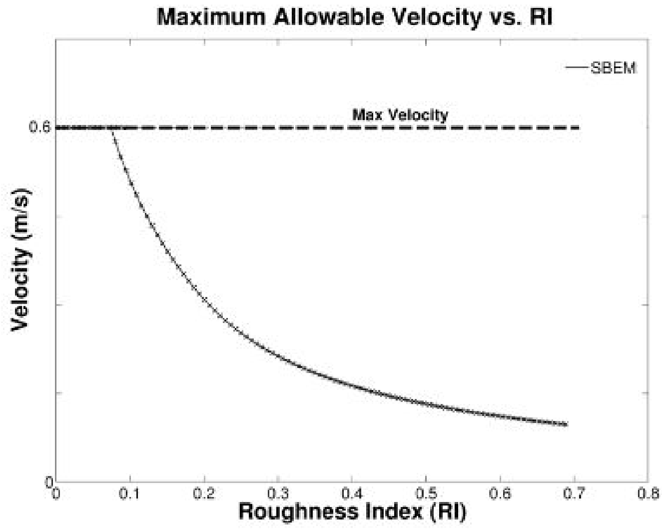


Fig 6.3: SBEM Velocity profile

6.7 OBSTACLE AVOIDANCE

The stereo pair of HAZCAM performs image segmentation using Deep Learning to identify obstacles when the robot is too close to them. The detected obstacles are generated as a point cloud and added to the local costmap. If the HAZAMS detect obstacles that are too close (< 50 cm): the rover will either stop, reverse or switch to teleoperation mode.

We have used the Artificial Lunar Landscape Dataset - Photorealistic images of the Moon's ace with ground truth rock segmentation which contains 9,766 realistic renders of rocky lunar landscapes, and their segmented equivalents (the 3 classes are the sky, smaller rocks, and larger rocks). The software used for creating the images and their ground truth is Planetside Software's Terragen. The authors used NASA's LRO LOLA Elevation Model as a source of large-scale terrain data. Fig 6.4 shows the render on the RHS with segmented ground truth on the LHS

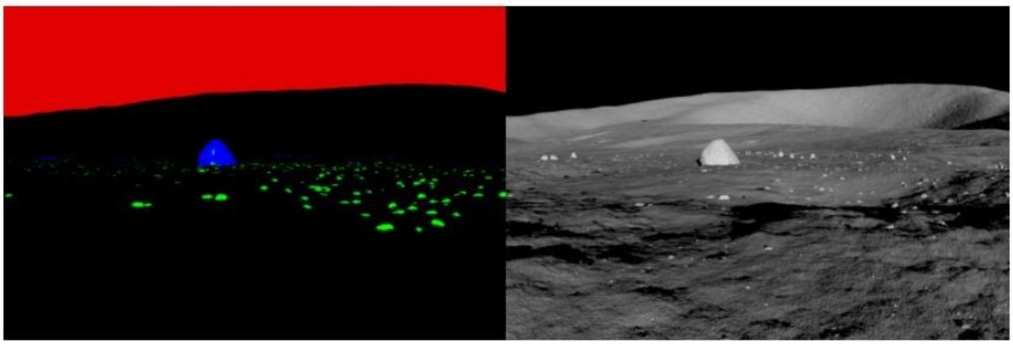


Fig 6.4: Segmented ground truth with its appropriate render image

6.7.1 TRAINING

The concept of Transfer learning and UNet are combined to create an image segmentation model that could segment out the rocks and boulders from images of the surface of the moon. The UNet architecture is used with a pretrained ResNet-34 (ResNet-34 was trained on the Imagenet dataset) as the backbone network.

The training was performed in 3 stages to improve the segmentation accuracy in each stage. Stage 1 uses 4 epochs, followed by two epochs in other stages. The latent vector obtained is of dimension (23x15) with 1024 channels. Table 6.3 shows segmentation accuracy and loss function in each stage.

epoch	train_loss	valid_loss	seg_accuracy	time
0	0.124503	0.210709	0.927335	12:14
1	0.131647	0.159141	0.949325	12:18
2	0.115805	0.243996	0.926383	12:21
3	0.068949	0.175921	0.942547	12:14

Table 6.3: Segmentation accuracy in each stage

Overall segmentation accuracy is **0.9635**

6.7.2 TESTING

We applied the modified UNet architecture on the Artificial Lunar Landscape dataset and used the trained result on real moon images, taken by Yutu's PCAM and TCAM on the Chang'e 3 mission

As shown in Fig 6.5 and Fig 6.6, the left hand images show the image taken by the rover and the right hand images represent the segmented output. Table 6.4 helps with the interpretation.

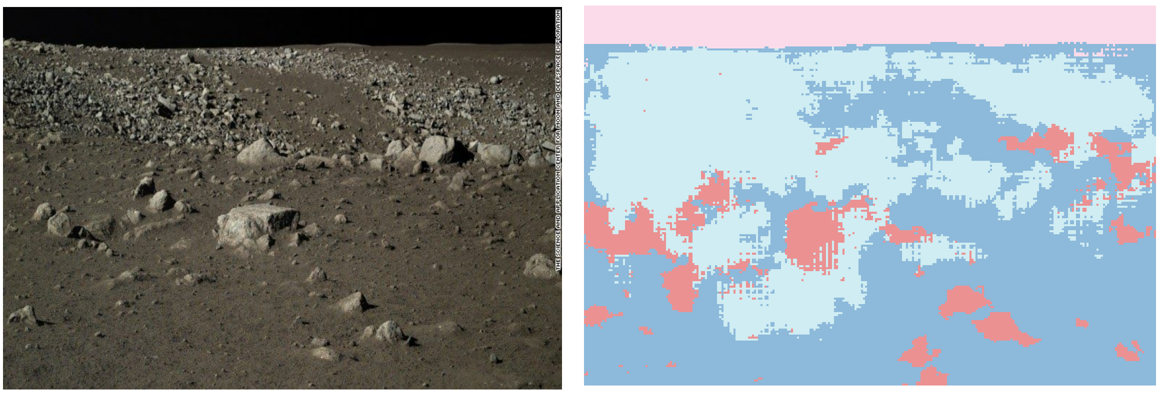


Fig 6.5: Real moon pictures (LHS) with its segmented outputs (RHS)

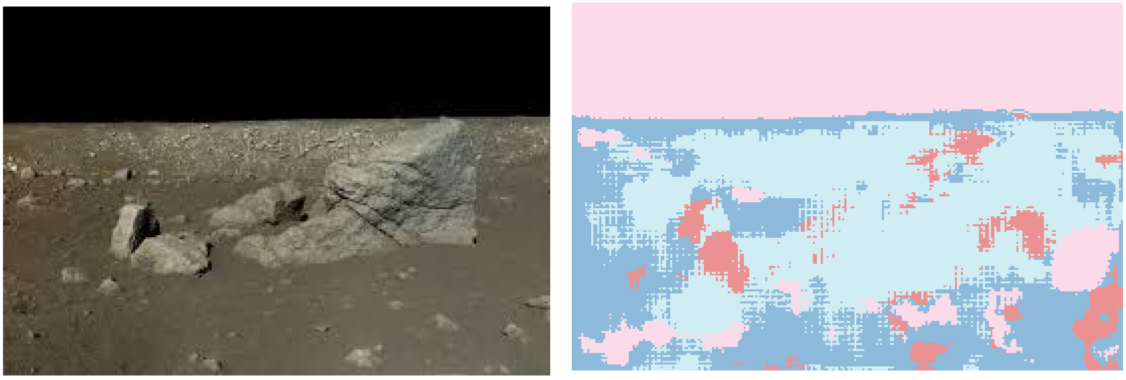


Fig 6.6: Real moon pictures (LHS) with its segmented outputs (RHS)

COLOR	INTERPRETATION
Baby pink	Sky
Light blue	Small rocks
Red-pink/ Dark pink	Big rocks
Dark blue	Terrain

Table 6.4: Interpreting the segmented outputs

The sky is represented in baby pink, light blue represents the small rocks and dark pink, the red rocks. The remaining part in dark blue, is the terrain that the robot will try to navigate in. The rocks that have been detected are classified as obstacles, and the depth is estimated by the rover's stereo HAZCAMS. This information is integrated with the local costmap.

6.8 TELEOPERATION

As explained in the previous section, if the rover is too close to an obstacle, as detected by the HAZCAMS, the rover exits the autonomous mode and switches to man-in-the loop or teleoperated mode. The images from the NAVCAMS and the HAZCAMS are transmitted back to the ground station via the lander, and velocity commands are issued from the ground station.

6.9 RECOVERY

The following challenges may arise when the rover is traversing lunar environment:

- Robot localization is lost:

The rover stops and the mast is rotated by 360 degrees to relocalize. If this attempt fails, the rover retraces its path by a maximum of 1m, while trying to relocalize.
If the communication link is available, the rover switches to the manual teleoperated mode and the rover is driven in the man-in-the loop mode until it is able to relocalize.

- Rover is stuck:

The costmap is cleared and populated with the updated sensor values and the lookahead goal is reset. If this attempt fails, the rover switches to manual teleoperated mode.

7. POWER SYSTEM

The Electrical Power System (EPS) includes a **Solar Array (SA)** as a primary energy source, an 8S Li-Ion battery as a secondary energy source, a Power Converting Unit (PCU) comprising 4 autonomous Array Power Regulators (APR) and a Power Distribution Unit (PDU) generating payload buses at 28V, 12V and 5V. Additional voltage conversion units (3.3V) are provided as required.

During the lunar night the Rover is allowed to freeze and no device for temperature control or Radioisotope Heating Unit is provided. Wear out failures or degradation by radiation dose are not considered as an issue due to the short mission duration.

7.1 SYSTEM OUTLINE

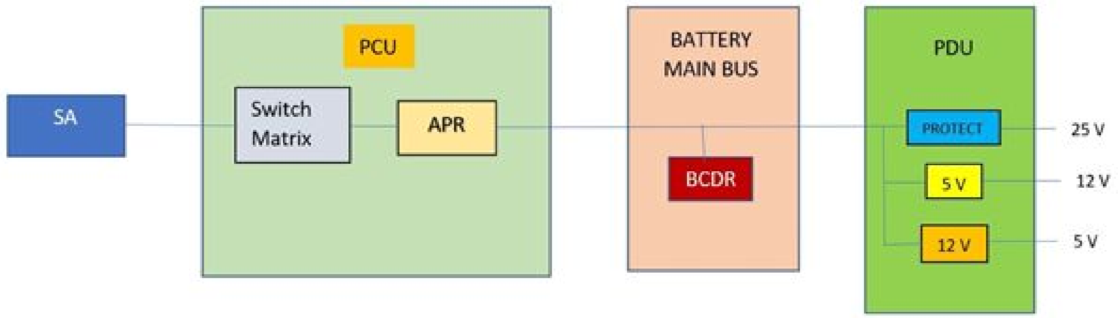


Fig 7.1 Power system

7.2 DESIGN

The Power system is represented in Fig 7.1 (The figure only shows the outline of the system and not the exact quantity of each unit). It consists of four solar arrays (SA) connected to the Power Converting Unit (PCU). The PCU consists of a Switch Matrix and 4 Array Power Regulators (APR) each connected to a single string of the SA. Every string of the solar array has a buck dc-dc converter - so the operating voltages of different sections are set independently based on the number of illuminated solar cells and of their temperature. The array power regulators (APR) will be provided with maximum power point tracking (MPPT) capability, in order to minimize the battery depth of discharge (DOD) and charging time. This is based on the design of the power system in the AMALIA rover.

The Battery S/S (8S array of Li-Ion cells) comprises three units in redundancy 2/3. It is mainly intended to support primary generation during load peaks. The Power Distribution Unit (PDU) generates voltage buses of 28V, 12V and 5V - with one redundant line for each. The Main Bus (MB) is kept at a 28V nominal voltage. It is distributed to several payloads and subsystems by a switch board. The Battery Charge Discharge Regulator (BCDR) supplies a regulated 28V from an 8S array of Li-Ion cells and also provides bus voltage regulation for the payload interfaces.

Throughout the design process, we have strived to adhere to the rule of avoiding single-point failures - Switch Matrix, which addresses this issue as shown in Fig 7.2.

- In the presence of one failed APR the current generated from the corresponding SA string is readdressed by means of a network of switches, which are automatically managed on board or can be commanded by Earth

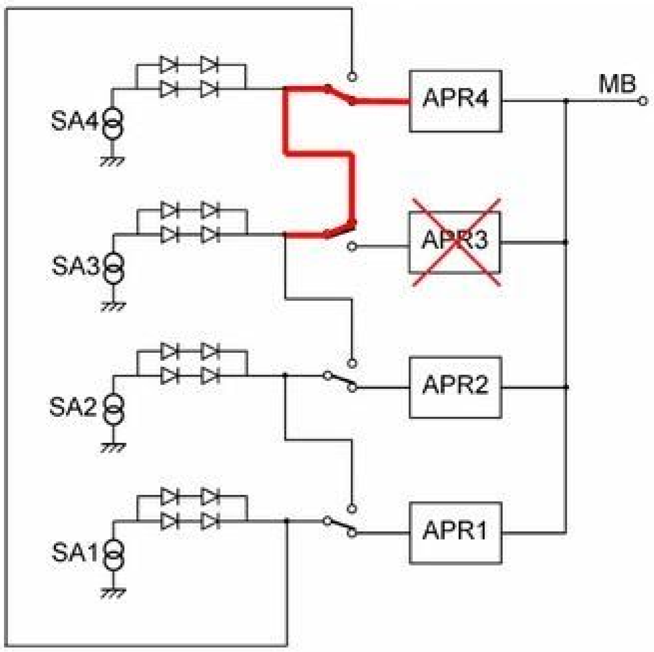


Fig 7.2: Switch matrix operation when APR3 fails, the array is redirected to APR4. Figure sourced from AMALIA power system report.

It is also to be noted here that this PCU design has been flown previously in Low-Earth-Orbit microsatellites.

7.3 OPERATION

The main design driver was peak power. Tars R42 is required to traverse around 1085, where it may have to operate under full load in several sections. To understand the power requirements for our mission, we analyzed the power consumption by various subsystems in different operating modes, throughout the duration of the mission. This has been presented in Tables 2.1, under Section 2.1 Mission Planning and operations.

The peak power under full-load operation is when Tars operates in Phase 4 - Mode 2, consuming approximately 94W of power. The Li-ion battery has a typical power density of 120Whr/kg. Thus the battery is capable of providing around 100W of power to the bus in full autonomy for 1 hour under full load conditions, which exceeds the operation requirement.

8. PAYLOAD - GROUND PENETRATING RADAR

8.1 WORKING PRINCIPLE

Ground-penetrating radar (GPR) is a non-intrusive, geophysical method that uses radar pulses to image the subsurface. A GPR transmitter emits pulses of electromagnetic energy in the microwave band of the radio spectrum (UHF/ VHF frequencies) into the probed surface. When discontinuities in the sub-surface are encountered, some of the electromagnetic energy is reflected back to the surface. The discontinuity could be a boundary or interface between materials with different dielectrics or it could be a subsurface object. The reflected pulses are detected by a receiving antenna and the variations are recorded. The information can then be displayed on a radargram. Fig 9.1 shows this process.

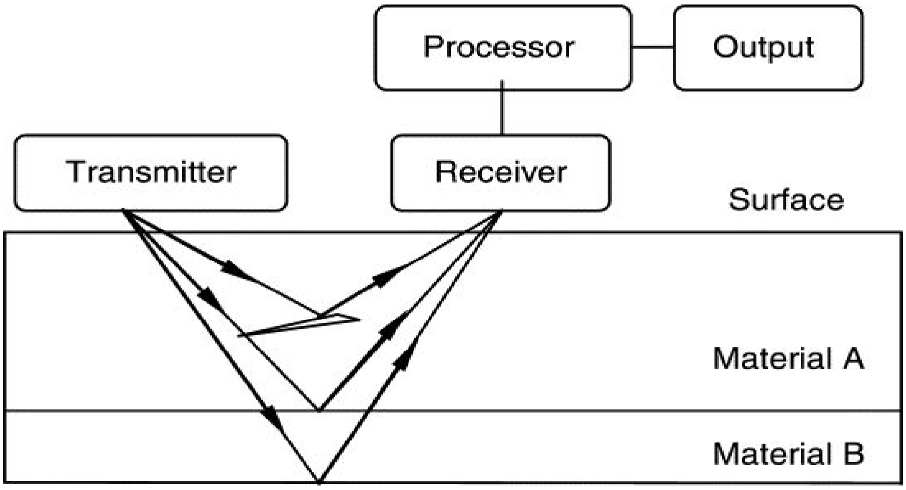


Fig 8.1 GPR working diagram

8.2 INSPIRATION

- **Study of the lunar subsurface**

The subsurface geological structure is of great importance for studying the **origin and evolution of lunar crust**. At present, the Moon's interior geological structure and the distribution of regolith thickness on the Moon are poorly understood. There is no overall understanding of the origin and formation process of the Moon. Due to geological structures on the Moon being related to its evolution history, if the geological conditions beneath the Moon's surface can be explored, the origin and evolution of the Moon can be better understood. This study is also critical for **quantifying potential resources** for future lunar exploration and engineering constraints for human outposts.

- **Heritage of radar usage in space missions**

In the past 20 years, space-borne/rover-deployed (GPR) has progressively become the most suitable geophysical techniques to investigate planetary subsurface stratigraphy.

  - GPR on-board a lunar rover

    The first attempt to survey the Moon's subsurface using a **GPR onboard a rover**, was made by the Yutu rover on the Chang'E-3 mission in Mare Imbrium. The rover was equipped with low- (60MHz) and high-frequency (500MHz) antennas. The Chang'E-4 mission also equipped its Yutu-2 rover with a similar dual-frequency GPR to study the eastern floor of Von Kármán crater.

  - Orbiting Radar used to survey Lunar Lava Tubes

    Prior to this, **two orbiting radars** were hosted on NASA's Apollo 17 and Japan Aerospace Exploration Agency's Kaguya missions, the Apollo Lunar Sounder Experiment (ALSE) and Kaguya Lunar Radar Sounder (LRS), which were able to survey the subsurface structure down to a depth of 1 to 2 km. The LRS aboard the Kaguya (SELENE) orbiter had an operation frequency of 4-6MHz (around 60m wavelength) and a transmission power of 800 W.

    The LRS on-board SELENE was used to investigate underground intact lava tubes at depths of a few tens to a few hundreds of metres in the Marius Hill Hole (MHH - 13.00–15.00°N, 301.85–304.01°E) region. The findings reported a characteristic feature in LRS data indicating a large second echo peak after a precipitous decrease in echo close to the MHH, a possible skylight of an underground lava tube. Since there are no possible features on the surface which could cause a second echo peak, it was concluded that these locations are candidate sites for the presence of underground lava tubes or cavernous voids. It was also estimated that the cave lies at least 75m below the surface.

Thus radars are a viable instrument for In-Situ Resource Utilization on the lunar surface. Tars R42 will have a GPR onboard as its only science payload, to survey the regions around the skylight in Mare Tranquillitatis. The key objectives have been covered under Section 1.3. The following sections will describe the design and operation of the GPR on-board Tars R42.

8.3 DESIGN

This section describes the design, working process and properties of the GPR on Tars R42.

8.3.1 SYSTEM DIAGRAM

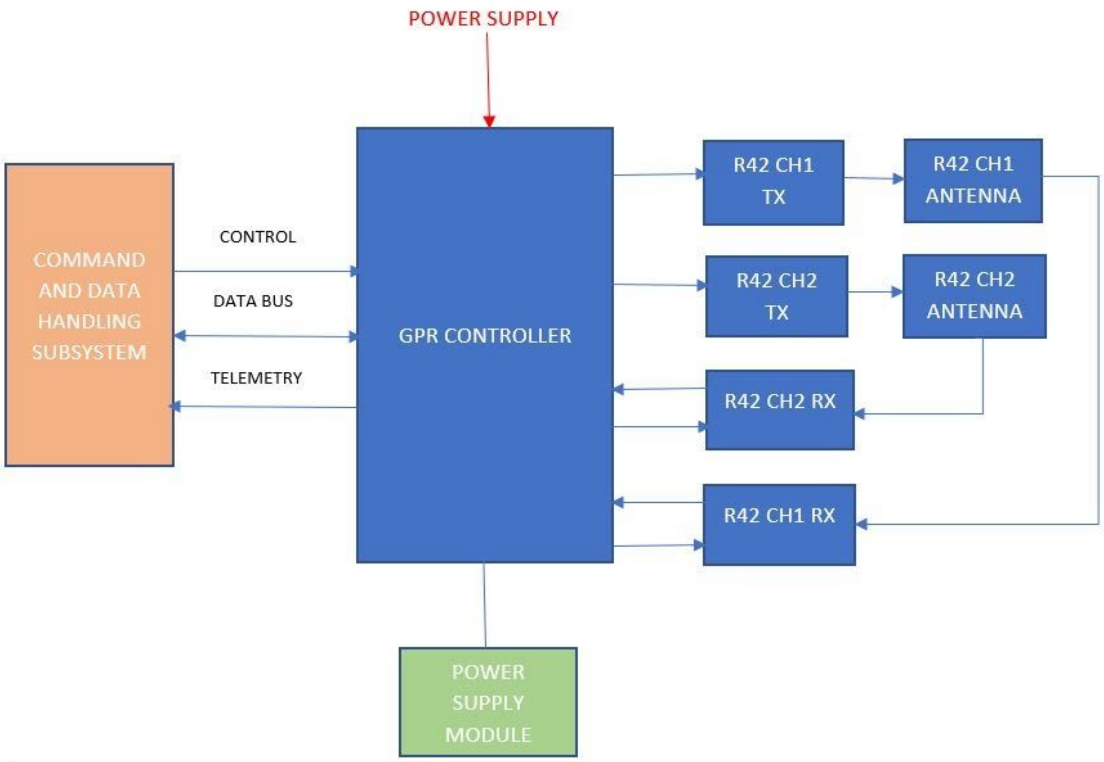


Fig 8.2 GPR payload subsystem

The subsystem is represented as in Fig 8.2.

8.3.2 HARDWARE

The sampling controller mainly consists of a FPGA (XQR2V3000) three 8-bit digital-to-analog converters (DACs) and three single-to-differential transformers. Nearly all functions are implemented in the FPGA, which is the heart of the sampling controller. The functions include digital sampling tasks, gain control tasks, data storage tasks, logic control tasks, and communication tasks.

8.3.3 WORKING PROCESS

- The Channel pulse transmitter is triggered by a clock signal from the LPR controller to generate a reliable pulse signal, and then the pulse is fed to the CH1 transmitting antenna and is transmitted into the lunar subsurface.
- The echo signal from the underground target is received by the receiving antenna and sent to the pulse receiver.
- The echo signal is amplified in the receiver which is controlled by the LPR controller, and then the amplified signal is sent to the controller for digitizing.

This principle for both R42-CH1 and R42-CH2 channels. All the data from both channels are processed by the LPR Controller and are packed and sent to the integrated electronic system through the data bus.

8.3.4 PROPERTIES

The GPR on Tars R42 is designed after the GPR on the Chang-e Yutu and Yutu-2 rovers. The radar uses the Ultra Wide Band (UWB) impulse technique, and transmits UWB signals when the rover moves along its designated route. Echoes will be produced when the signals encounter interfaces in the medium under the surface of the Moon, and are received and identified by the LPR, which can be used for the detection of subsurface structure

The GPR will have a dual detection channel -

- The first channel (R42-CH1) works in the frequency band 40–80 MHz and the depth resolution is about several meters. This channel is used to detect the structure of the shallow lunar crust along the path of the rover.
- The second channel (R42-CH2) operates in the frequency band 250–750 MHz and the depth resolution is less than 30 cm. This channel is used to detect the thickness and structure of lunar regolith along the path of the rover.

The following table details the technical parameters of the GPR:

PARAMETER	**First Channel Value**	**Second Channel Value**
Center Frequency	60 MHz	500 MHz
Frequency Band	40 - 80 MHz	250–750 MHz
Antenna type	Dipole	Bowtie
VSWR	≤ 3	≤ 1.8
Transmitter Pulse Amplitude (V)	1000 (with 5% bias)	400 (with 5% bias)

Transmitter Pulse Repetition Frequency (kHz)	0.5, 1,2	5,10,20
Transmitter Pulse Rising Time (ns)	≤ 2	≤ 2
Receiver Band (MHz)	10.193	10.1359
Receiver Sample Rate (MHz)	400	3200
Receiver Dynamic Range (dB)	103.3	96.7
System Gain (dB)	152	133.33

Table 8.1: GPR properties

8.4 OPERATION DURING THE MISSION

The operation of the GPR is in congruence with the requirements mentioned in Section 3. The GPR exploration points (G1-G17) are shown in Figure 9.3. Gi and Gi+1 are separated by 36m.

(Figure in next page)

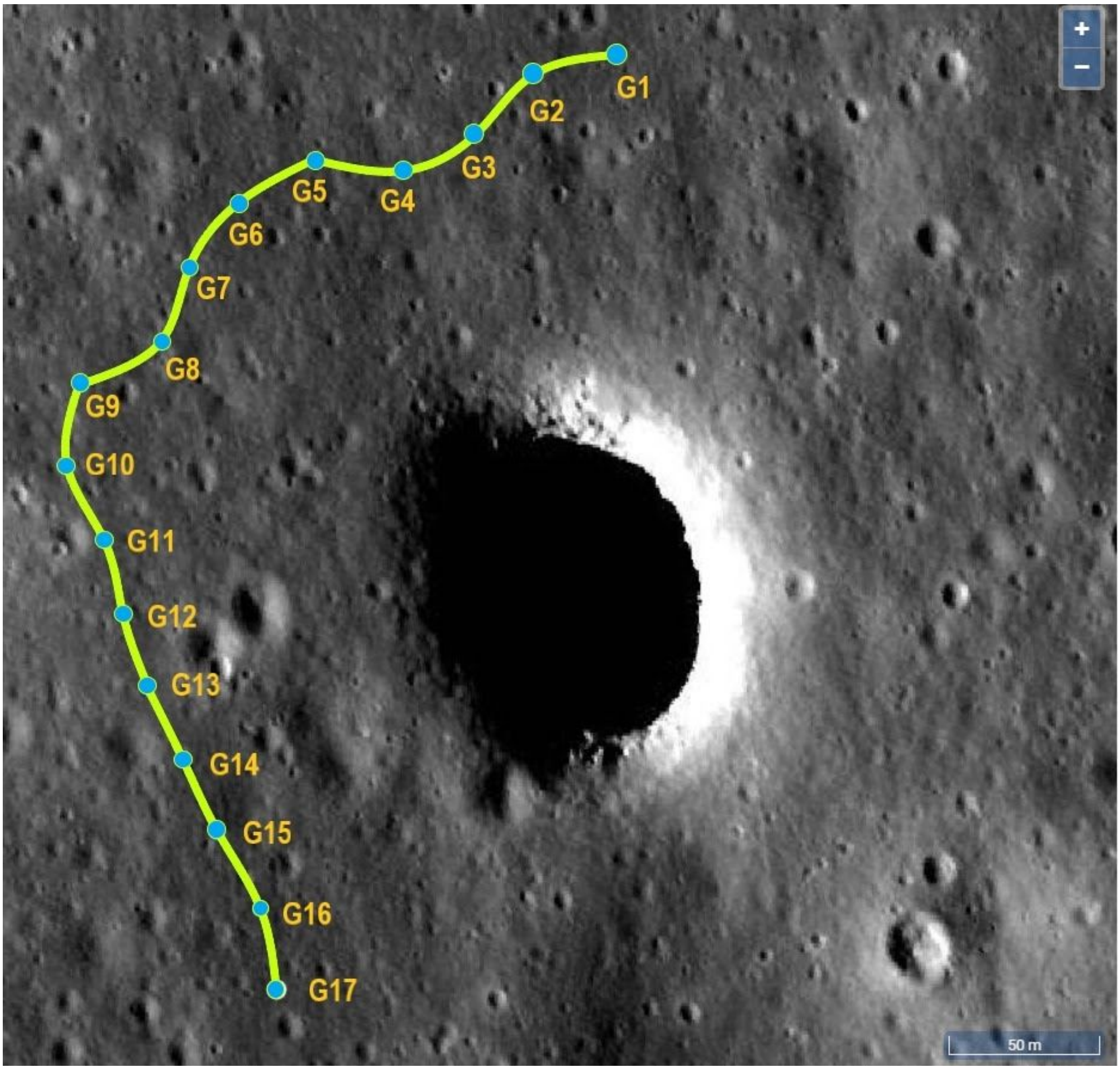


Fig 9.3 GPR Exploration points and segments

The GPR will begin operating from exploration point G1 and will remain operational in the following segments:

GPR OPERATIONAL SEGMENTS
G1 – G4
G5 – G8
G9 – G12
G13 – G16

Table 9.2: GPR operational segments

These segments have been designed according to the power requirement of the rover during this face and the power that can be provided by the battery. The following table details the calculations that follow operation during these segments:

PARAMETER	VALUE
Speed of rover Tars R42	6 cm/s
1 Navigation unit	6 m
1 GPR segment	36 m
Time taken to traverse 1 GPR segment	10 minutes
Time taken to traverse 3 GPR segments	30 minutes
Mode of operation during GPR usage	Phase 4 – Mode 1 or Mode 2
Peak power usage during this Phase	94 W

Table 8.3: Operational parameters

The peak power during the traversal of these segments is well under the capacity of the battery (100 W in 1 hour). The data collected by the GPR will be stored on the onboard memory of the payload controller and will be sent to the Rover's OBC on request from the same.

8.5 ISSUES AND SOLUTIONS:

There were two major issues faced by previous missions involving a ground penetrating radar. They are discussed here:

- Coupling with the rover's metallic body:
  The location of the low-frequency R42-CH1 antennas lead to coupling with the rover's metallic body. This was a problem that led to significant issues in the low frequency channel's data collection in the Change-3 mission. Later research revealed that having XX polarization or a parallel broadside configuration, is the preferred antenna configuration for both subsurface targeting and surface reflectivity surveys. This is the configuration that Tars R42 will adopt.

- Coupling between TX and RX antenna:
  Coupling between the TX and RX antenna occurs when they are placed too close to each other. Tars R42 has a deployable frame that will extend the separation to around 67cm, thus decreasing the possibility of TX-RX coupling.

In addition to this, there are many software applications (EkkoProject V.5, Sensors and Software Inc.) that can analyze radargrams and effectively remove or mitigate the artifacts.

9. COST BUDGETING

This section tabulates the estimated cost for the lunar mission.

SYSTEM/ INSTRUMENT	COMPONENTS	FUNCTION	COST ESTIMATE (USD)
Communications	Antenna Transceiver	TM/TC with Lander and Earth	135,000
Avionics	CPU, RAM IMU Processors Bus	Operation monitoring, GNC	180,000
GPR	Processing system Antenna	Payload instrument	60,000
Power	Solar array Battery Circuits and components	Power generation, conversion and distribution	150,000
Structures	Material fabrication, machining for the entire rover, Fasteners	Rover mechanical design	250,000
Locomotion (Motors for mechanisms)	Mast rotation and wheel drive	Locomotion and navigation	4500
Navigation (in both operational modes)	Processing unit	Teleoperation and Autonomous navigation	150,000
Human Resource-Development Cost	Development	Research and Development	75,000
Work Space	Development	Development	155,000

PHASE	FUNCTION	COST ESTIMATE (USD)
Individual Testing	Component analysis	25,000
Subsystem Testing	PCB Fabrication, Board qualification ,Testing	45,000
Assembly and Integration	Structural qualification Vibration test Assembly and Integration	15,000
Launch Cost	Launch-Rocket-Payload cost-Space X Falcon 9	279,766.6
Miscellaneous	Damages and Replacements, HR affairs etc.,	100,000
Total Mission Cost		**1,624,266.6**

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11. APPENDIX

- **LROC Quick Map reference link for path details:**

https://quickmap.lroc.asu.edu/query?extent=33.2066733,8.3296471,33.2373707,8.3416792&proj=10&layerListFilter=&selected=16&layers=NrBsFYBoAZIRnpEBmZcAsjYIHYFcAbAyAbwF8BdC0yioA

- **Diagram of Behavior Tree fooperationshttps://drive.google.com/file/d/1EnL2FvGqCY9Auqu2POOuTSiVjColoU6J/view?usp=sharing**

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