ENGINEERING DESIGN REPORT

ROVERX

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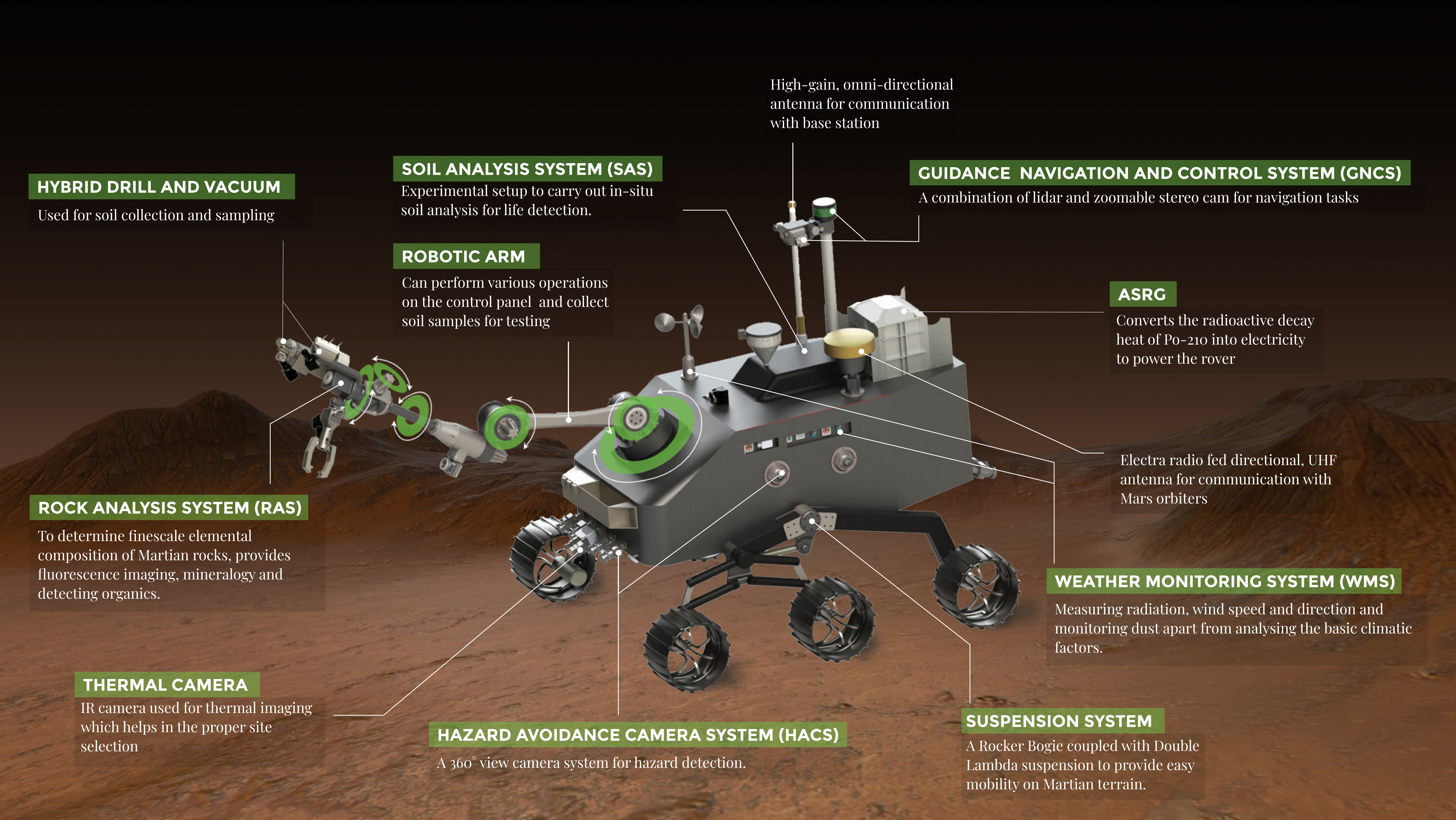
ORTHOGRAPHIC IMAGE



CHASSIS

The chassis is a combination of ladder and cruciform structure for better resistance to bending and torsional loads. This structure allows for uniform distribution of load throughout the base structure of the chassis. It is a double layer space frame of length 1634.00 mm, breadth 804.00 mm and maximum height 544.00 mm.

The structure is made from Grade 5 Titanium due to its excellent corrosion resistance, good formability, and weldability. It is covered with sheet metal made from Grade 6061-T6 Aluminium which is a heat-treated structural aluminium alloy and is used here as it is weldable and extremely corrosion resistant [1,2,3]. The purpose of the sheet metal is to protect the electronics and the science mechanism from the dust storms which are very frequent on the Martian surface.

It is rounded in the front part to give better impact resistance. Due to the high strength, stiffness, and toughness of Grade 4 Titanium the chassis can withstand the harsh Martian conditions.

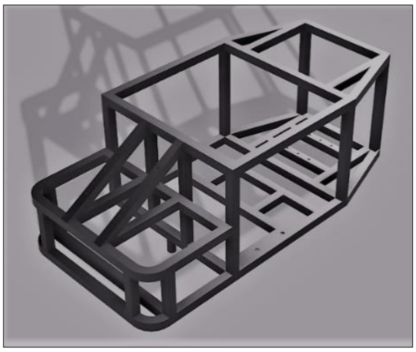


Figure 1.1 - Chassis Structure

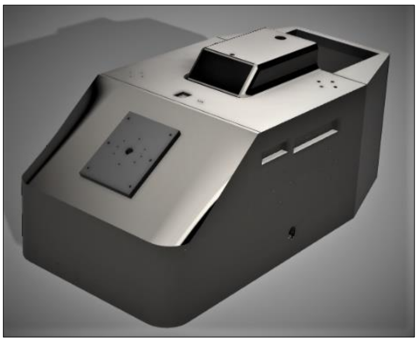


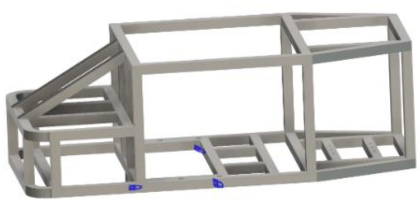
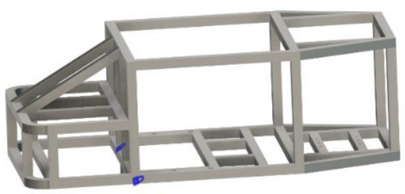
Figure 1.2 - Chassis with sheet metal

Density	4.43E-06 kg mm^{-3}
Young's Modulus	113763 MPa
Poisson's Ratio	0.35
Yield Strength	882.5 MPa
Ultimate Tensile Strength	1034 MPa

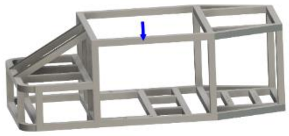
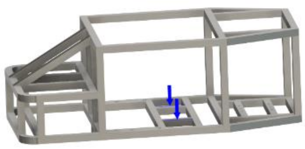
Table 1 – Properties of Titanium 6AI-4V

Chassis Simulation Studies

Constraints:

S.No	Location of Constraint	Reason
1.		Constrained due to the location of Bar Differential of Suspension
2.		Constrained due to the location of Bearing for Suspension

Loads:

S.No.	Point of application of force	Force Magnitude
1.		Magnitude of Force Applied due to weight of chassis = 450N
2.		Magnitude of Force Applied due to weight of Arm = 500N
3.		Magnitude of Force Applied due to weight of Advanced Stirling Radioisotope Generator (ASRG) = 400N
4.		Magnitude of Force Applied due to weight of Soil Analysis System (SAS) = 200N

Simulation Results

The below simulation shows the stress distribution within the chassis with the maximum stress coming out to be 21.02 MPa and the maximum displacement in the chassis after applying the appropriate loads is coming out to be 0.7393 mm.

STRESS

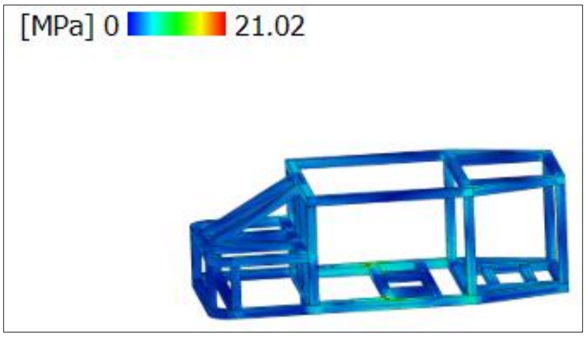


Figure 1.3 - Stress Distribution for Static Loads

DISPLACEMENT

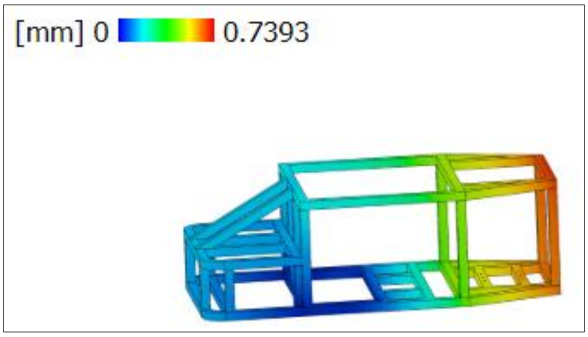


Figure 1.4 - Displacement for Static Loads

Conclusion

The support given to the Robotic Arm, ASRG and the Science subsystem in the ladder arrangement is working well as the displacement in the chassis after applying the appropriate loads and the material is coming out to be minimal.

SUSPENSION SYSTEM

A Rocker Bogie with a double-lambda mechanism has been selected. Rocker-bogie mechanism is advantageous while distributing load on the wheels nearly equally, but it has an overturn problem that creates a moment due to the obstacle reaction force. To overcome this, a double lambda mechanism can be combined with a rocker-bogie design [4]. Small angular displacement of the rocker can be neglected.

Material	Titanium 6AI-4V
Ground Clearance	500mm
Max angle without toppling	70 degrees
Max height of obstacle (Individual rocker)	1.2m
Max Ravine depth and width	1.2m x 1m

Table 2 - Suspension specifications

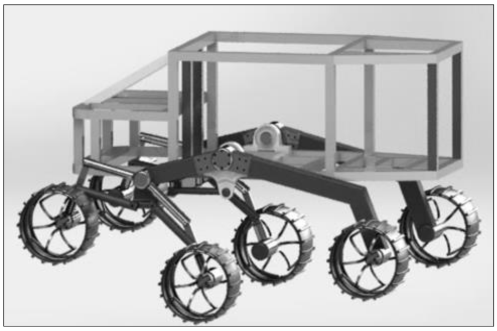


Figure 2.1 - Suspension Mounted on Chassis

Figure 2.2 - Bar Differential

The suspension is made completely out of Titanium 6AI-4V which provides ideal chemical resistance along with superior strength capabilities for Martian terrain in comparison to other titanium alloys.

The link lengths and pipe dimensions have been optimised using Kinematic motion simulation for constant relative velocity based movements. This distributes the impact to the whole link rather than a single point, thus reducing the chances of failure.

Chassis Simulation Studies

Figure 2.3 – Constraint locations

Type	Force
Magnitude	500 N
X- angle	45 deg

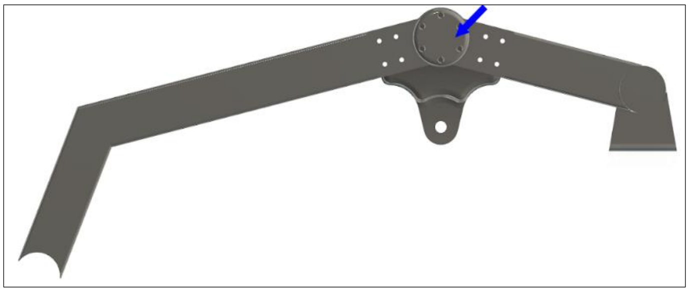


Figure 2.4 - Load due to inclination of Chassis

Type	Force
Magnitude	1500 N
Z –value	-1500N

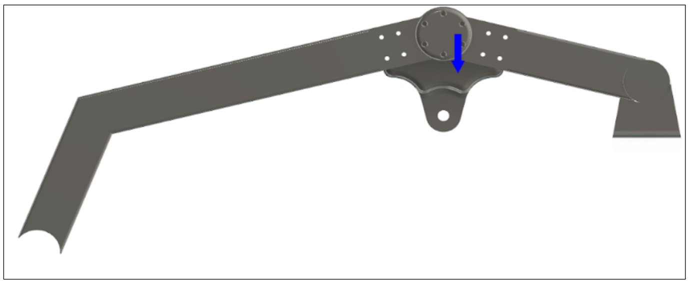


Figure 2.5 –Load due to chassis on Suspension at Pivot Road

Type	Force
Magnitude	500N
X-value	500N

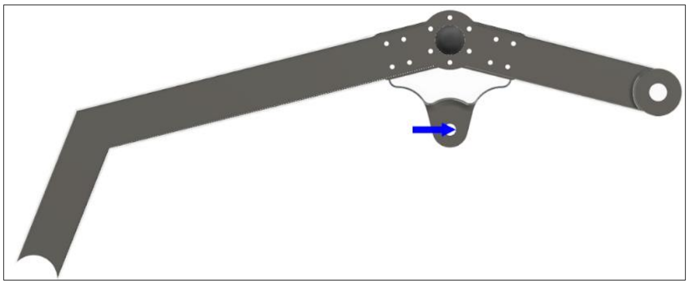


Figure 2.6 – Load Due to Bar Differential on Suspension

STRESS

Figure 2.7 - Static Load Stress Distributions

DISPLACEMENT

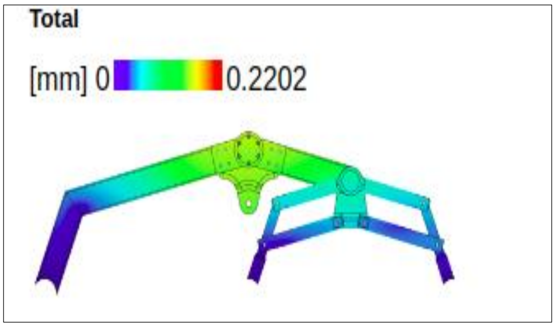


Figure 2.8 - Static Load Displacements

Results:

A max displacement of 0.2202mm and max stress of 63.19 MPa clearly indicates the sturdy nature of the suspension and build material.

WHEELS

The rover has six wheels, each with its own individual motor. Each wheel has an aggressive tread composed of 20-grousers (or cleats), machined into its surface. The grousers give the rover excellent traction when driving in both soft sand and on hard rocks. The rover has a top speed of $34cms^{-1}$ on flat hard ground.

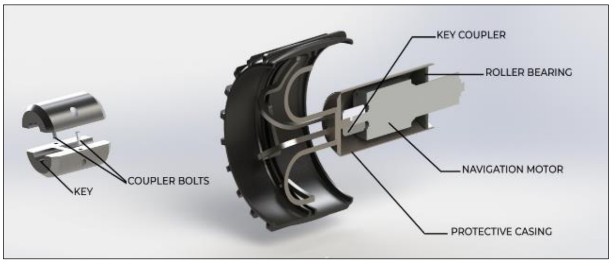
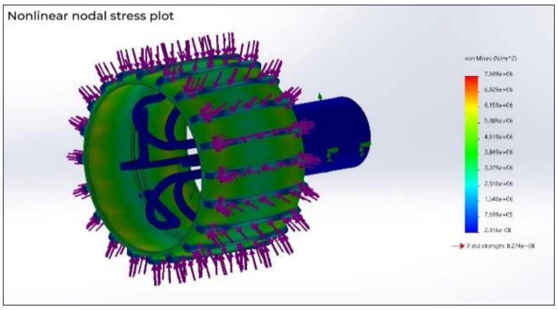
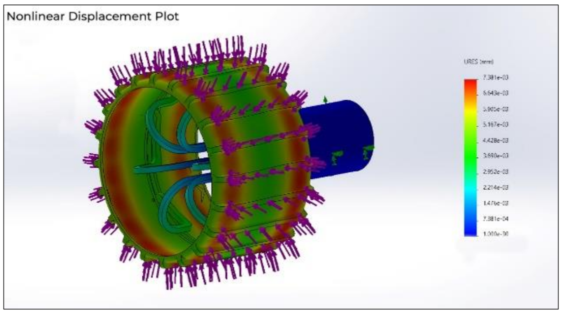
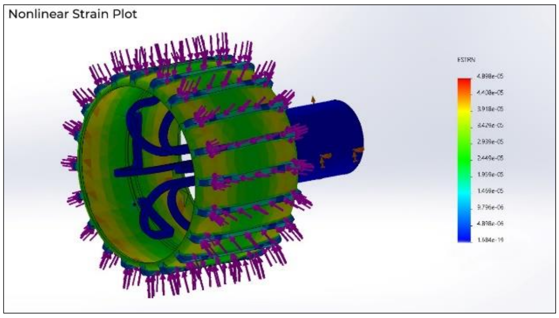


Figure 3.1 - The Hub

Materials	The inner wheel suspension is made Titanium and the exterior shell and spokes are with cleats for traction and curved titanium spokes for springy support. The key coupler, bearings and the bolts are made of Aluminium 7075 alloy. The Titanium Grade 5 – Titanium 6Al-4V offers its high strength at a light weight useful formability and high corrosion resistance making it the most suitable material to withstand the corrosive atmosphere of mars during night.
Size	33.3 centimetres (13.11024-inches) in diameter.
Other	One full turn of the wheels with no slippage drives the rover 1.046 meters (41.188-inches).The maximum displacement that occurs in full stress is 0.0161m.
Simulation	The following simulation results were obtained when subjected to a constrain of 1000N of force per wheel uniformly distributed along its grousers.   

ROBOTIC ARM

The robotic arm on the rover is designed according to task specifications. It has an end-effector which can perform multiple tasks, from picking up rocks to helping the astronauts in equipment servicing.

Figure 4.1 - The Robotic Arm

The arm uses harmonic drives (which use encoder motors with high resolution feedback) with a reduction ratio of 200:1. Harmonic drives were chosen instead of normal reduction methods and backlash prevention methods like worm gears, spur gears etc as they provide higher precision and higher reduction ratios of about 100:1 to 200:1. Also the arm has 8 DOF instead of standard 5 DOF to attain maximum manoeuvrability of the tools present on the end-effector.

End-Effector

Material	Titanium 6AI-4V
Reach	1.8m from the rover
Weight	70kgs on Earth (27kgs on Mars)
Degrees of Freedom	8(6 arm + 2 gripper)
Tools	Spectrometer, Science Camera, ,Drill, Moisture sensor, Gripper, Vacuum.

Table 3 – Robotic arm specifications

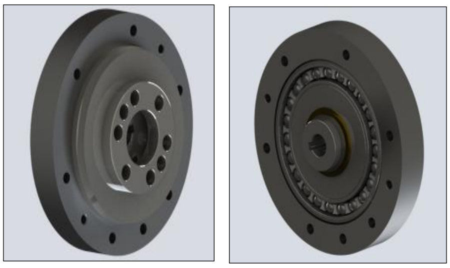


Figure 4.2 - Harmonic Drives

To refrain from using complex mechanisms for swapping out modules, a T-Joint is used to connect the arm to all the components on the end- effector. We have three instruments at our disposal the whole time. The T-Joint is rotated about the point of attachment to the arm so that the instruments required can be employed wherever required. A scientific camera (functionality under science) has been mounted onto this joint.

Gripper

The gripper that is used in our rover is designed keeping in mind the varying atmospheric conditions in mars. A layer of silicone rubber is added to the end of the gripper for providing traction and better grip while holding the tools to be used for equipment servicing.

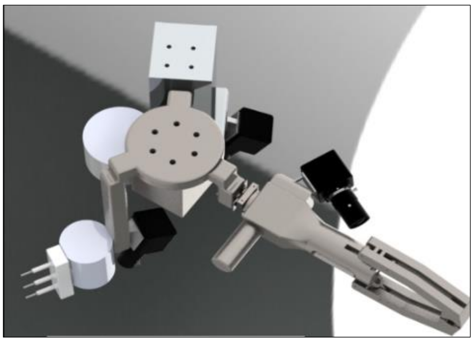


Figure 4.3 - T-joint after mounting of components

Mechanism: Gripper has two degrees of freedom namely roll motion and the opening and closing of the fingers. The opening and closing of the gripper is performed with the usage of an 8mm diameter lead screw which has a high mechanical advantage in a compact envelope. The movements are monitored which enables the accurate motion of the lead screw. These mechanisms offer stiffness along with precision of motion.[7]

The length of the lead screw is 50mm and it is well constrained to move only in the required direction making it less susceptible to the small vibrations that it experiences during the motion of the lead screw nut. The grippers close and open with increased accuracy.
The fingers of the gripper can hold objects having dimensions ranging from 10mm to 80mm and lift a maximum load of 10kgs. For the roll motion of the gripper a set of bevel gears are used with a reduction of 1:2 keeping in mind the torque required for the roll motion. Bevel gear was used because of its increased efficiency (approx. 95%). The Gripper weighs 4.5 Kgs on earth (around 1.73 Kg on Mars).

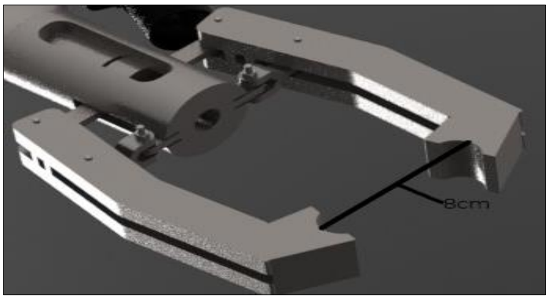


Figure 4.4 - Max. separation between fingers is 8cm

Figure 4.5 - Gripper with fingers closed

Hybrid Drill

Considering the drilling requirements and challenges posed by the Martian conditions we decided to use a Hybrid Drill with a lead screw drill feed mechanism to perform efficient drilling and penetrate a variety of formations. This technology combines Roller cones and PDC (Polycrystalline Diamond Compact) fixed cutters into a single, patented design [8].

Materials	Tungsten Carbide, TC Matrix, Polycrystalline Diamond, Steel

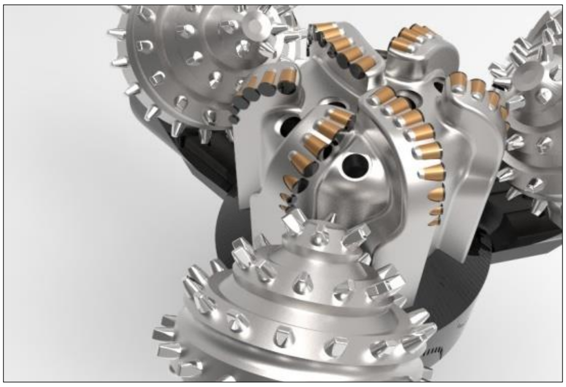


Figure 4.6 - Hybrid drill

Mechanism:
As the drill rotates, the cones roll along the bottom of the hole, the individual hard teeth (Tungsten Carbide Inserts) will induce compressive failure in the formation. Similarly, the fixed head bit (PDC) rotates about the axis of penetration cutting through the formation with its continuous shearing action. It is designed to penetrate a depth of 15cms.
For penetration through ice-bound soil the roller is designed with a positive rake angle with respect to direction of cut [9]. The usage of a lead screw mechanism eliminates the complexities of a percussive drilling mechanism such as solenoid braking or vibrational interference caused to the other components of the rover [10].With an increased bore diameter (8 cms) and optimised drilling dynamics the required WOB (Weight on Bit)

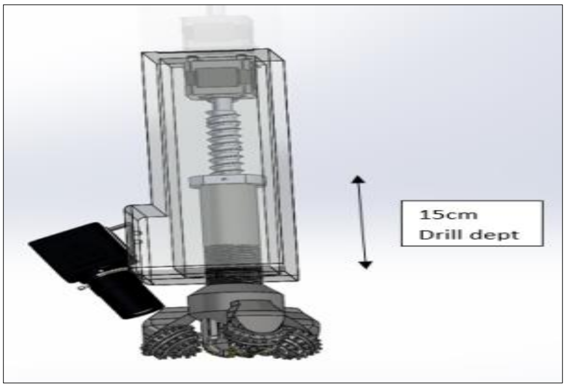


Figure 4.7 – 15 cm drill depth for soil sampling

is reduced. Also the torsional (stick-slip), vertical (bit bounce) and lateral (whirl) is significantly reduced.

Vacuum pump

A miniaturized vacuum pump with a moisture sensor (functionality under science) is used. After the hybrid drill loosens the Martian soil, the end effector will position the vacuum above the loose soil. This needs to be taken for soil analysis. Sufficient inlet pressure is provided by the pump so that the soil is sucked into the vacuum tube leaving a partial vacuum in it. The arm will then rotate by 180^{o} and position the vacuum pump on top of the funnel.

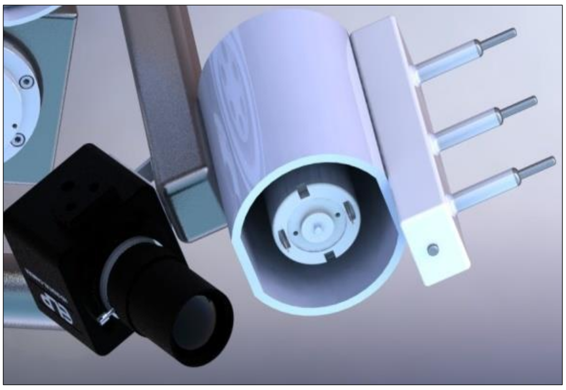


Figure 4.8 - Vacuum

With the help of the partial vacuum the pressure created throws out the soil out of the vacuum tube. The sand then falls in the funnel after which it is filtered and taken for further analysis (under science). This phenomenon of partial vacuum is also used to remove dust from the rocks. It will first throw out air under pressure and remove the layer of dust from the rocks. The atmospheric pressure will then push air into the pump to compensate for partial vacuum. [6,7]

POWER SOURCE

Currently there are two practical long-term Power source solutions for Space- Exploration: Using Solar Energy or using a RPS (Radioisotope Power System).Some previous missions on Mars have used Solar panels to generate electricity but with the insubstantial solar flux on Mars, the dynamics of dust storms and the limited power output, going with a Radioisotope Power source seemed to be the only viable option. We have chosen to use an Advanced Stirling Radioisotope Generator with Po-210 as the fuel to power our Rover.

Advanced Stirling Radioisotope Generator (ASRG)

The ASRG is a radioisotope power system that uses a Stirling power conversion technology to convert radioactive- decay heat into electricity.

The Nuclear Fuel is contained within several layers of rugged and heat resistant Carbon-Carbon material, Graphite and iridium metal altogether known as GPHS (General Purpose Heat Source). This heat from the GPHS is used to oscillate a small magnetic piston through a coil and hence generate a flow of electrical power. The piston is accompanied by a displacer and the assembly is suspended in Helium Gas. The displacer forces alternating expansion and contraction of the Helium gas driving the magnetic piston through the coil and producing alternating current.

The external housing of the ASRG is made up of Aluminium-6061, the housing integrates radiator-fins for efficient heat dissipation.

The most common Radio-isotope fuel for any RPS is Plutonium-238 with a half-life of about 88 years, however the specific power density is low (0.54 W/g).To suffice for the Power requirement of our Rover we plan to use Polonium-210 (140 W/g) as the Radio-isotope fuel in the ASRG. Due to the low Melting Point of pure Po-210 metal (256 C) we alloy it with Gadolinium. This Po-Gd alloy has a specific power of 82 W/g. The half-life of Po-210 (138 days) is also adequate for the mission duration of our Rover. [11,12,13]

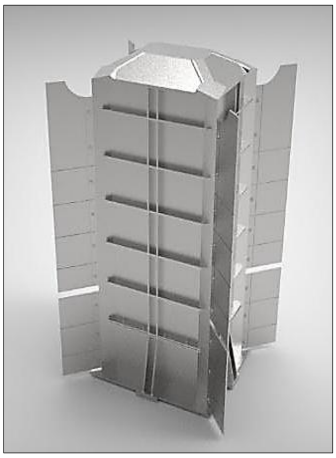


Figure 5.1 ASRG on the rover

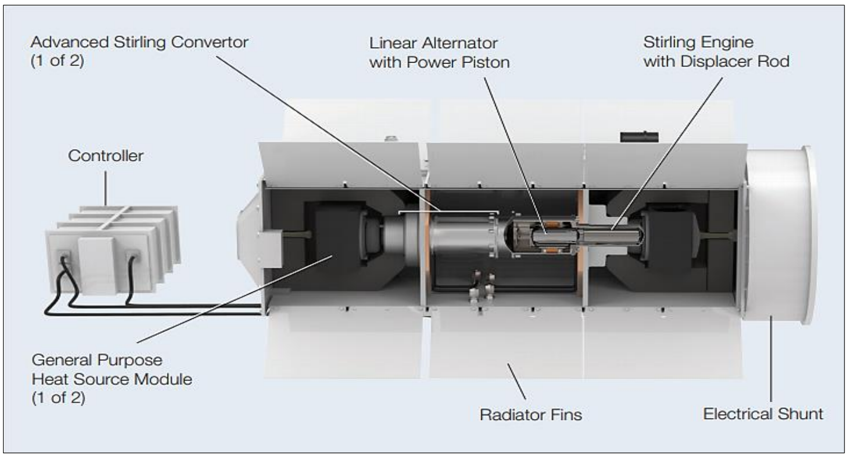


Figure 5.2 Cross section of the ASRG

The ASRG can provide steady power independent of distance and orientation with respect to the Sun. Its operation is not hindered by the atmospheric and extreme environmental conditions, radiations or temperatures on Mars. Its compactness offers ease of transport and installation. It is mounted on the aft end of the Rover Chassis in a vertical configuration as the gravity assisted (vertical) orientation of the ASRG optimizes the power output.

AC to DC Conversion

A controller connected by electrical cables to the ASRG synchronize the two pistons, provides data about the status of the ASRG to the Rover carrying it, and transforms the alternating current (AC power) produced by the generator into direct current (DC power) at a voltage that the Rover can use.

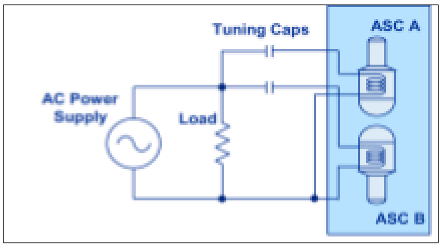


Figure 5.3 - Bus controller configuration for ASRG

Advantages of ASRG Over RTG

- ASRG uses 2-4 times less amount of Pu-238, in spite of that their efficiency is almost 4 times greater than past and present RTGs.
- The system efficiency of ASRG is approximately 26% while that of MMRTG is 6.3%.
- Total system weight of ASRG is 20 kg and that of MMRTG is 44.2kg.
- Number of GPHS (General Purpose Heat Source Module) in MMRTG are 8 and in ASRG are 2.

Storage of Energy

- We will be using Li-ion batteries for storage of energy which have many desirable characteristics such as high efficiency, a long cycle life, high energy density, and high-power density.
- Li-ion batteries offer good energy storage for their size. They don't self-discharge and hence can be used to store charge in it for a long time.
- Due to these factors Li-ion batteries are used for storing the electrical energy and smoothing the output power.
- Li-ion batteries help in significant enhancement in the mission with 4x improvement in mass and 8x enhancement in volume compared Ni-Cd and Ni-H_2.
- Operating at temperature as low as - 40 ^oC.
- Tolerance to high intensity radiations (up to 16 MRad.)

Power Requirements

Calculations made by considering all modes of operation and factors like stall current and stall torque.
Navigation motors = 1616 W
Arm motors = 710.28 W
Science motors = 62.5W
Sensors = 3.56 W
Vision system and Computing = 734.5 W

Navigation (Navigation motors + Sensors + Vision system and Computing)	2,354.06W
Science operations (Vision system & Computing +Science motors+ Sensors)	800W
Arm Operation (Vision system and Computing + Arm motors)	1444.78W

Table 5 - Power consumption during various modes of operation

Amount of Fuel Required

Efficiency of the system = 26%
Specific Power of Po-Gd alloy = 82 W/g
Specific Power of the System:26%×82 = 21.32W/g
Required Power Output = 2500 W
Amount of Fuel= 2500/21.32 = **117.26 g of Po-Gd alloy**

ELECTRICAL SUBSYSTEM

The electrical subsystem has 5 custom designed circuit boards, powering various components of the rover. These include the arm, navigation, sensors, science tasks and a separate board for distributing the power.

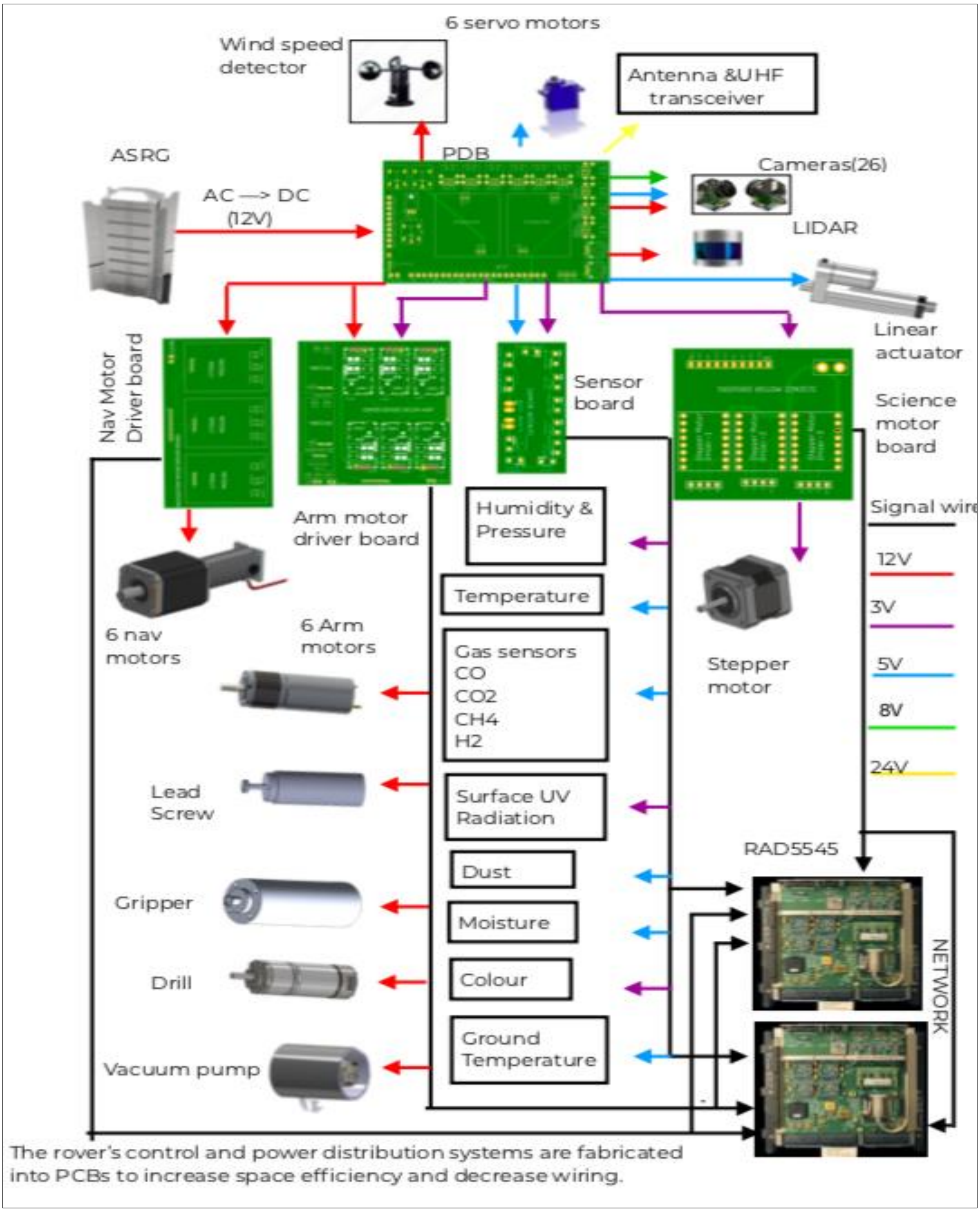


Figure 6.1 - Electrical subsystem architecture diagram

Printed Circuit Boards

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<tr><th>PCB used in the rover</th><th>Functionality</th></tr>
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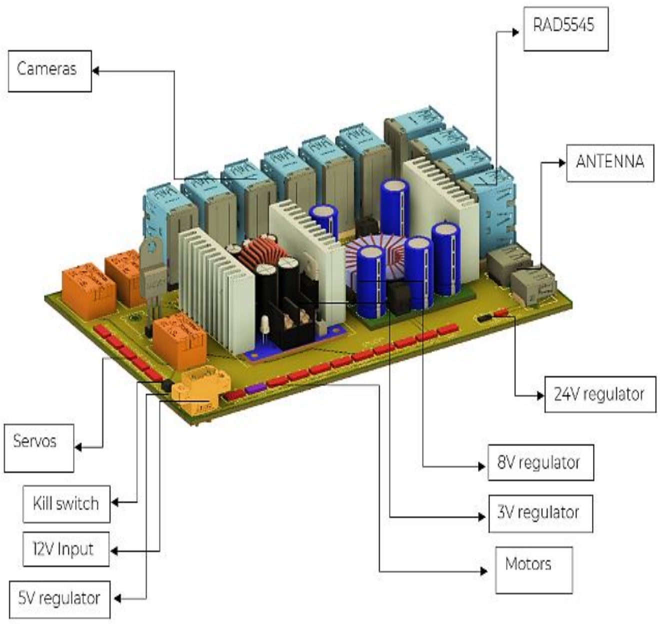

Figure 6.2 - Power Distribution Board
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- The power distribution board distributes the power from ASRG to all the components used in the rover. The input voltage is 12V.
- The components are rated at 12V, 24V, 8V, 5V and 3V and hence different voltage regulators are used keeping the current requirements in mind. The 5V and the 24V converters are placed outside the board.
- The board contains ports to the 26 cameras (FISHEYE, STEREOCAM, SCIENCE CAM, NORMAL CAM), the antennas, transceiver, motors, sensors, LIDAR, RAD5545, IMU, wind speed detector.
- A kill switch is connected to the Power Distribution board via a combination of relays. This switch is used to stop all the motors in the rover during emergencies.
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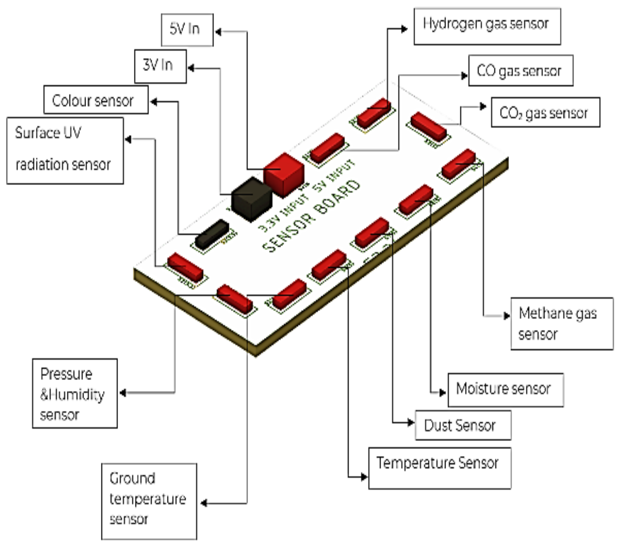

Figure 6.3 - Sensor board
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- The rover has several sensors to monitor the environment. As a part of the electrical subsystem, the sensors are chosen to meet the guidelines to the maximum.
- This board is designed to power all the sensors used in the Rover: UV radiation sensor, moisture sensor, temperature sensor, pressure and humidity sensors. This board connects to the sensors placed in different parts of the rover according to their functionalities.
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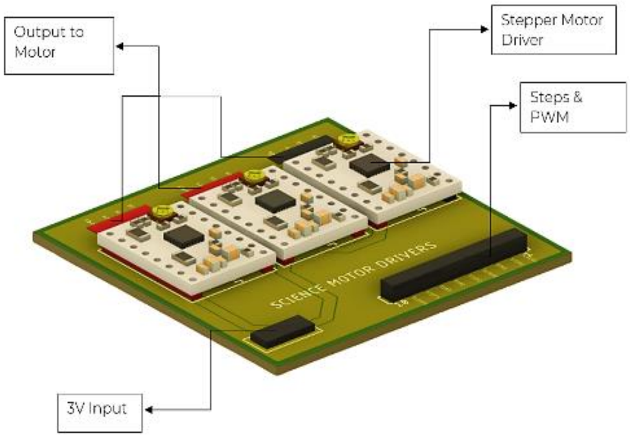

Figure 6.4 - Science board
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- Three NEMA 17 stepper motors are used in the science tasks. These are controlled using the Pololu DRV8834 low voltage stepper motor driver. Each stepper motor driver controls one motor.

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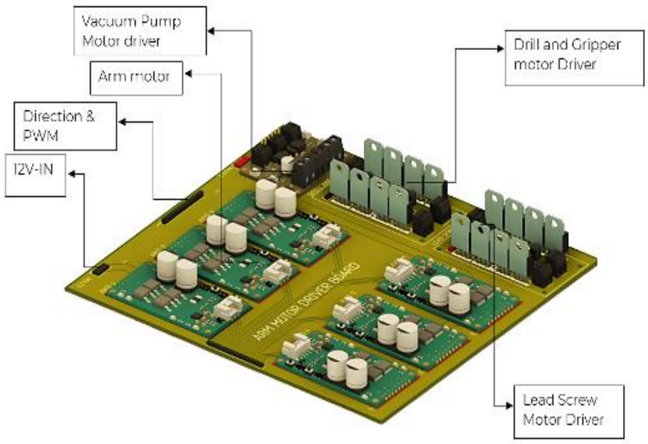

Figure 6.5 - Arm control board
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- The arm control board contains 9 motor drivers to control, 6 motors used on the Rover arm and the 3 used on the end effector.
- Each motor used in the arm is controlled by a Cytron MD13S motor driver with a peak current of 30A per channel.
- One cytron maker H bridge motor drive is used to control the micro vacuum pump on the end effector with a maximum of 1.5A for the motor. The Driller, gripper and the lead screw motors are controlled using 2 RKI1004 H-bridge motor drives (5A max).

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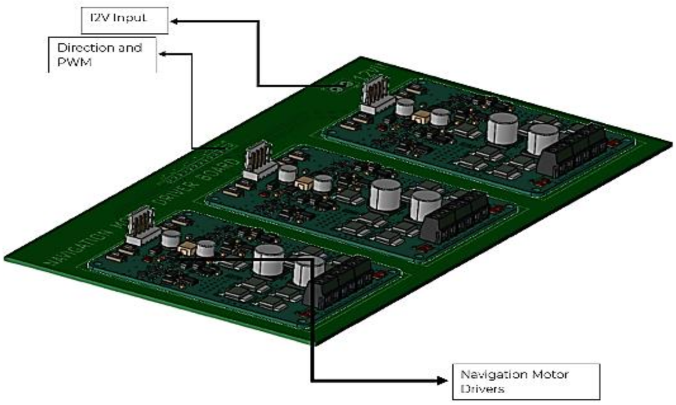

Figure 6.6 - Navigation board
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- The navigation motors consist of 6 brushed DC motors controlled by 3 Cytron MDD10A motor drivers. Each motor driver controls 2 motors with a maximum output current of 30A.
- The board gets an input voltage of 12V.

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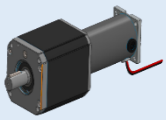
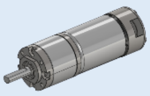
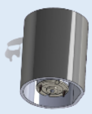
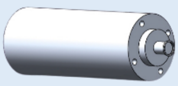
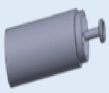
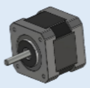
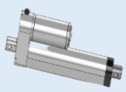
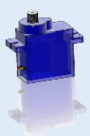
Motors

Image	Motor Name	Specifications	Motor Driver	Requirements
	Planetary gear (DC) For navigation	Voltage = 12V Stall current = 22.45A Stall torque = 75.4Nm Power = 269.4W	Cytron MDD10A Dual channel motor driver	Calculated torque = 23Nm
	Planetary gear (DC) For arm	Voltage = 12V Stall current = 7.5A Stall torque = 13.7Nm Power = 90W	Cytron MD13S	Calculated stall torque 6-10Nm
	Planetary gear (DC) For drill on end effector	Voltage = 12V Stall current = 4.02A Rated torque = 23.01Nm Power = 47.28W	RKI-1004 Dual motor driver	High torque
	Vacuum part of end effector	Voltage = 3V Stall current = 1A Power = 3W	Cytron H-Bridge motor driver	Low power
	Planetary gear motor For Gripper part of end effector	Voltage = 12V Stall current = 5A Rated torque = 4.1Nm RPM=26 Power = 60W	RKI-1004 Dual motor driver	Torque = 4Nm
	Planetary gear motor For lead screw	Voltage = 12V Stall current = 5A Rated torque = 0.92Nm RPM=142 Power = 60W	RKI-1004 Dual motor driver	High rpm
	Stepper motor NEMA17	Voltage = 3.1V Stall current = 6A RMP=100 Power = 55.8W	Pololu DRV8834	Calculated rpm = 100
	Linear Actuator	Voltage = 5V Stall current = 460mA Power = 2.3W 10mm stroke length	-	10mm stroke length
	Servo motor	Voltage = 5V Stall current = 150mA Power = 4.5W	-	-

BRAIN

The BAE Systems manufactured RAD5545 is the brain of the rover. Mars has a thin atmosphere and does not block all of the radiation, which can cause corruptions in the memory and processor of the onboard computer due to bit flips. Hence, RAD5545 acts as the perfect choice of computer for us as it is radiation-hardened, has high processing power to handle all onboard operations and specializes in spacecraft computer systems.

Core	Quad Core
Clock-Speed	466MHz
DDR3 SDRAM	4GB
Flash Memory	1GB
Ionizing Dose	100krad (Si)

Table 6 - RAD5545 Processor specifications

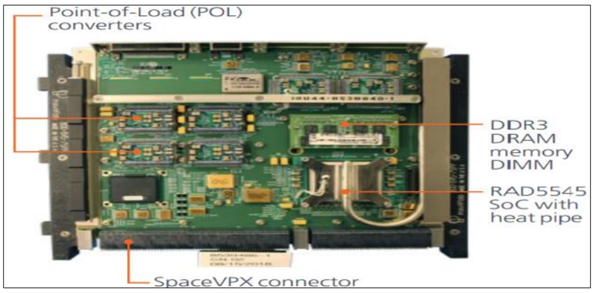


Figure 7.1 - RAD5545 computer board - Brain of the rover

Two of such computers are placed onboard the rover. While one computer performs the onboard processes, the other is used for communication and data transmission purposes. Both the computers have their own health monitoring system. In case of total failure of any one of the computers, the other acts as a backup and compensates for the tasks of the failed board.

A 32-bit parallel PCI (Peripheral Component Interconnect) bus on RAD is used for communicating with the instruments onboard. A PCI-PCI bridge to which all the instruments onboard are connected, is connected to the RAD which uses the PCI bus to communicate.

COMMUNICATION

The rover is equipped with two antennas for communication. One is a 2.4GHz omnidirectional, high-gain antenna for communicating with the base station. This allows us to communicate up to a radius of 20kms from the base while having a good bandwidth for data transfer. The other one is an UHF antenna of 120° sector directional spread for communicating with the Mars orbiters. It is fed by an Electra radio operating in the range 390-450 MHz . [14]

In the unfortunate event of loss of direct communication with the base, the rover dynamically switches to the other antenna and communicates with the base through the Mars orbiters and on operator’s decision can autonomously return back to the last known communication location.

All the telemetry and communication data stored on the rover is prioritized, with the highest priority sent first. The rest of the data is sent in order during the night time when the rover is in sleep mode.

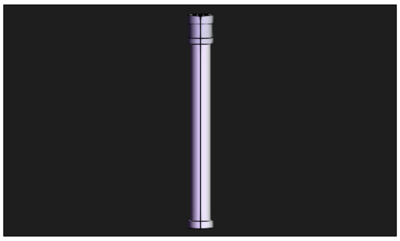


Figure 8.1 - Antenna for base station communication

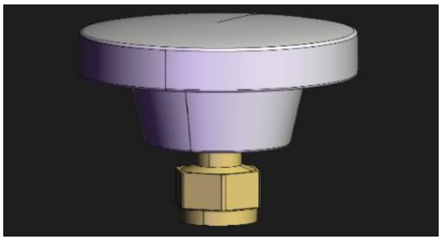


Figure 8.2 - UHF Antenna for communication with Mars Orbiters

NAVIGATION

Overview

The Rover's Navigation System operates in either of the three modes - Manual, Semi-Autonomous and Autonomous, which are selectable by the operator at Base Station using the GUI. This makes the system more flexible & robust while allowing varying degrees of human-rover interactive planning.

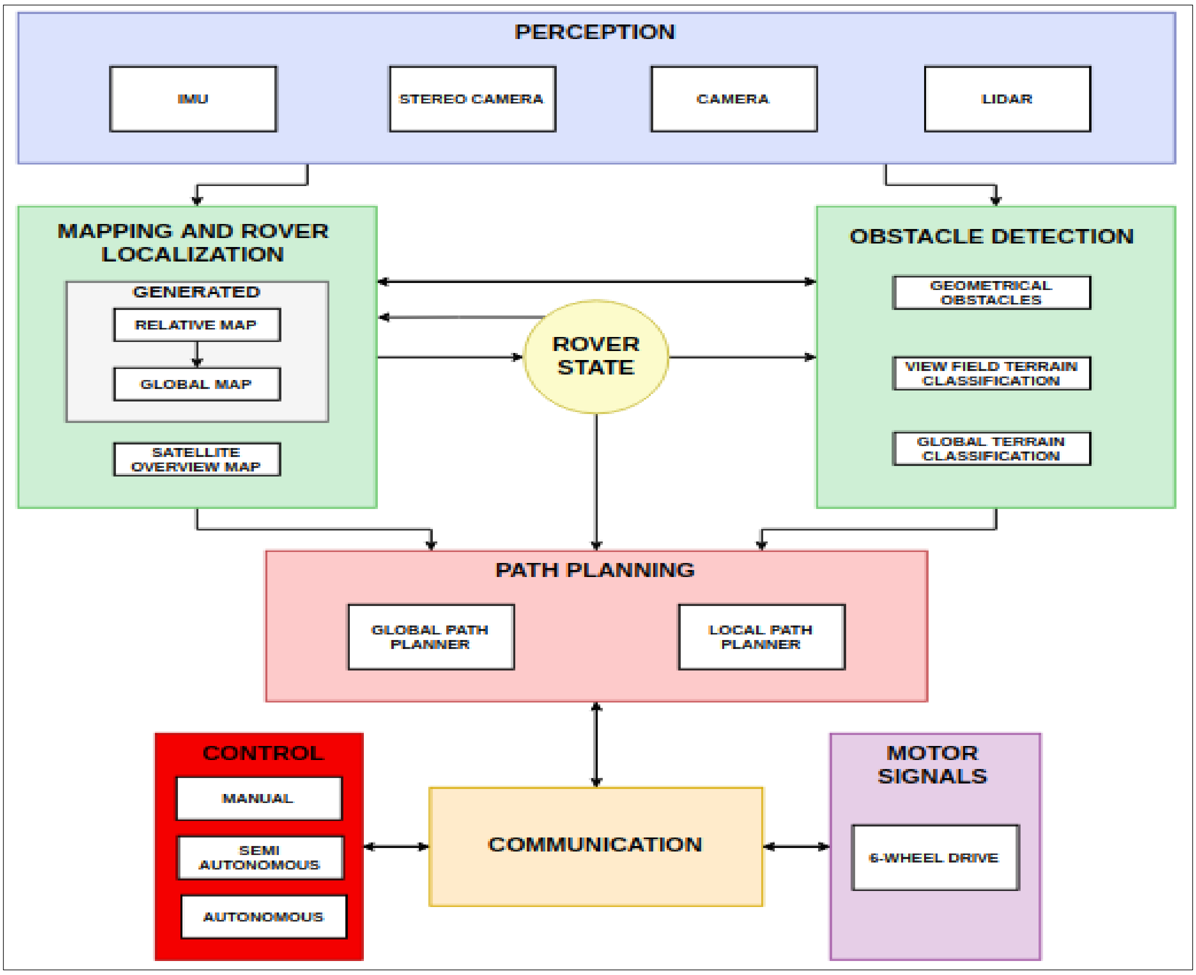


Figure 9.1 - The Navigation subsystem architecture diagram

Manual mode: The rover is directly controlled and blindly follows the instructions while giving feedback to the operator for any warnings. It is useful when the operator wants full control over the rover or in cases where autonomous modes could be risky.

Semi-Autonomous mode: Multiple paths are generated by optimizing over different factors like path length, tilt, roughness and the operator can select the best path according to the situation. Multiple waypoints are provided. The rover then autonomously traverses the path avoiding any obstacles & hazardous terrains.

Autonomous mode: The operator only provides the goal location to the rover and only a single path optimized over all factors (instead of one) is generated. The rover can then plan and traverse the entire path completely autonomously while avoiding obstacles and terrains that could damage the wheels.
In the Autonomous and Semi-Autonomous modes, if at any point the rover finds itself unsafe to move, it prompts the operator for further action.

Perception

The Perception stack of the rover mainly consists of an Inertial Measurement Unit (IMU), a main Stereo Camera, a Lidar and several other wide-angle cameras capable of working in stereo pairs.

Lidar and Stereo Camera are placed on the top of the mast of the rover form the GNCS (Guidance Navigation and Control System). The Stereo Camera is capable of rotating 360° about the mast with a pitch of ± 45°. The Stereo Camera acts as the main navigation cam, capable of generating 3D depth colour images with a range up to 80m. It also has a high zoom-in power which helps in site selection for science tasks. The Lidar provides a 360°-point cloud of the environment.

A total of 12 wide angle cameras, 4 placed on the front and rear of the rover body and 2 placed on the either sides of the rover body collectively form the Hazard Avoidance Camera System(HACS).These cameras have a wide FOV and collectively cover 360° view around the rover. They are used for terrain classification and rock classification.

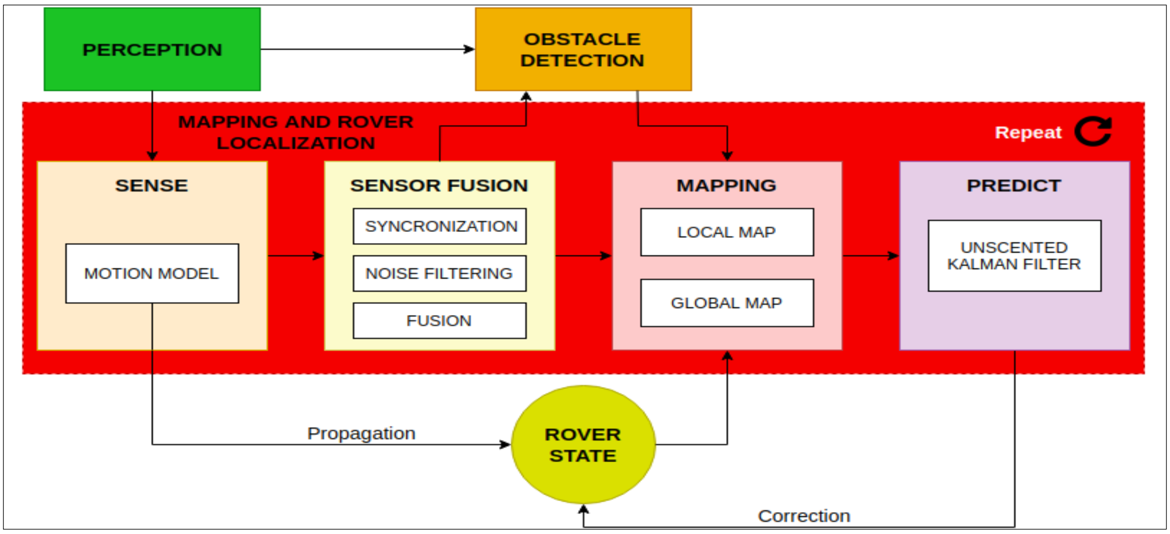


Figure 9.2 - Mapping and Rover Localization architecture diagram

Mapping and Rover Localization

Mapping and Localization is the task of estimating the position of a rover based on multiple sensor data along with the motion model of the rover to pinpoint the location of the rover on a map.

1. Initial guess of the rover state is provided to the localizer.
2. Input is taken from IMU, Lidar, Cameras, Stereo Camera and Control.
3. Sensor Fusion:
    1. Temporal and Spatial Synchronization
    2. Noise filtering
    3. Data Fusion
4. Semantic Segmentation:
    1. Ground, sloped terrain and geometric obstacle segmentation
5. Mapping:
    1. Using SURF [15], key points are detected in every frame and provided with descriptors.
    2. Key points from the previous frame are matched with the key points of the current frame using the descriptors.
    3. Geometrical Obstacles and Sloped Terrains are majorly used as landmarks.

   4. Positions of landmarks from the previous frame are predicted for the current frame and matched to the current frame landmarks. If new landmarks are found they are added to the map.
6. Localization:
   1. Motion model of the rover is used to propagate the rover state.
   2. As when a measurement is read from any sensor the rover state is corrected using the Unscented Kalman Filter equations [16] and is localized on local map and global map.
   3. Further, as and when a measurement is available from the orbiters, the rover state is further enhanced.
7. Repeat from Step 2.

Obstacle Detection

The Obstacle detection module takes input from the Perception stack and the Localization module to determine any kind of obstacle in the path of the rover. There are two major kinds of obstacles, Geometric and Terrain Based.

Geometrical Obstacles include medium to large size rocks which are easily visible on the cameras. The Geometrical Obstacle detection uses the semantic segmentation output from localization projects the 2D image onto 3D Stereo depth images to create 3D bounding boxes around them.

Terrain Based Obstacle detection is used to classify the regions on an image where the terrain is deemed unsuitable for the rover to drive. This is done to take care of traversability and stress on wheels during the motion of the rover. There are 5 major terrains found on Mars, namely, Sand, Loose Rock, Bedrock, Angular Embedded Rock and Round Embedded Rock.

A Random Forest Classifier is trained for semantic segmentation which then can classify the regions in an image to any one of the 5 classes of terrains [17]. Along with detection of obstacles in the view field, this module also uses the HiRISE image to classify terrain for global path planning.

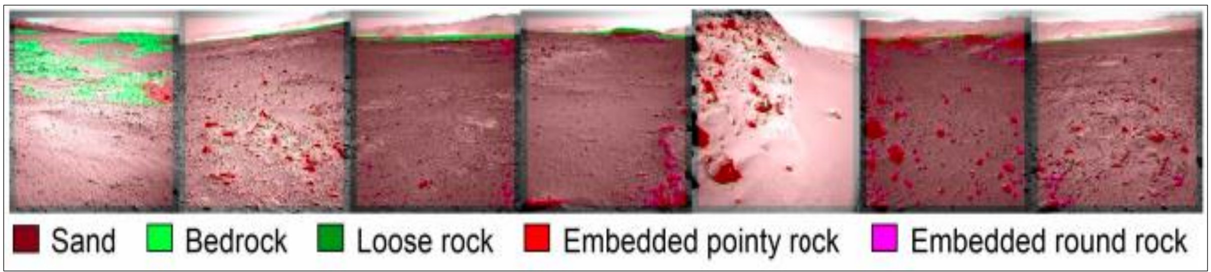


Figure 9.3 - Result of trained classifier [17]

Path Planning

Autonomous path planning on Mars while avoiding obstacles is a challenging task given the complex environment and the constraints on rover safety, power and the 15-sol mission time amongst other factors. Therefore path planning responsibilities are shared by 2 subsystems, namely, a local path planner and a global path planner while simultaneously allowing human interaction through a GUI from the base station.

Local path planner algorithm

It plans paths on a local scale (in the vicinity of the rover) and is performed completely online on the rover.

1. The local map is generated using SLAM.
2. Red areas are identified. These include geometric obstacles (rocks, steep hills etc.) and terrain classes to be avoided (decided by the base station controller using the GUI).
3. Then using the PRM* algorithm a dense roadmap is constructed in the obstacle free area consisting of nodes and edges. While constructing the map, we consider wheel placement also to make sure the wheel tracks are obstacle free. Edges are assigned a cost of traversal, which is a weighted sum of various factors like steepness, roughness, length etc.
4. A* search is performed to find the optimal path.

Local path planner is used in the situation where the rover needs to drive short distances like between multiple, closely located, potentially exciting scientific or otherwise operation sites as global information is not needed. In other scenarios requiring longer traverses, a global path planner is used.

Global path planner algorithm

It plans paths on a global scale (beyond the range of the visual system of the rover).

1. Accurate, detailed map is obtained from HiRISE camera on the Mars Reconnaissance Orbiter (MRO). Hazardous areas/terrains are marked red on it by base station controllers/specialists.
2. PRM* algorithm generates a roadmap considering wheel placement. Edges are assigned cost of traversal.
3. Map is uploaded onto the rover. Start and goal locations and other settings are specified.
4. D* Lite algorithm is used to find the optimal path.
   It is often the case that the global map lacks information or has inaccurate information about the area. This motivated the use of D* lite algorithm for searching in the global map as it enables efficient path replanning which the A* algorithm lacks.[18] As new information about the local region is retrieved from the cameras and other sensors, the global map is updated with it and D* lite algorithm replans the path.

Steps 1 and 2 are performed offline to reduce the computational burden on the RAD5545.

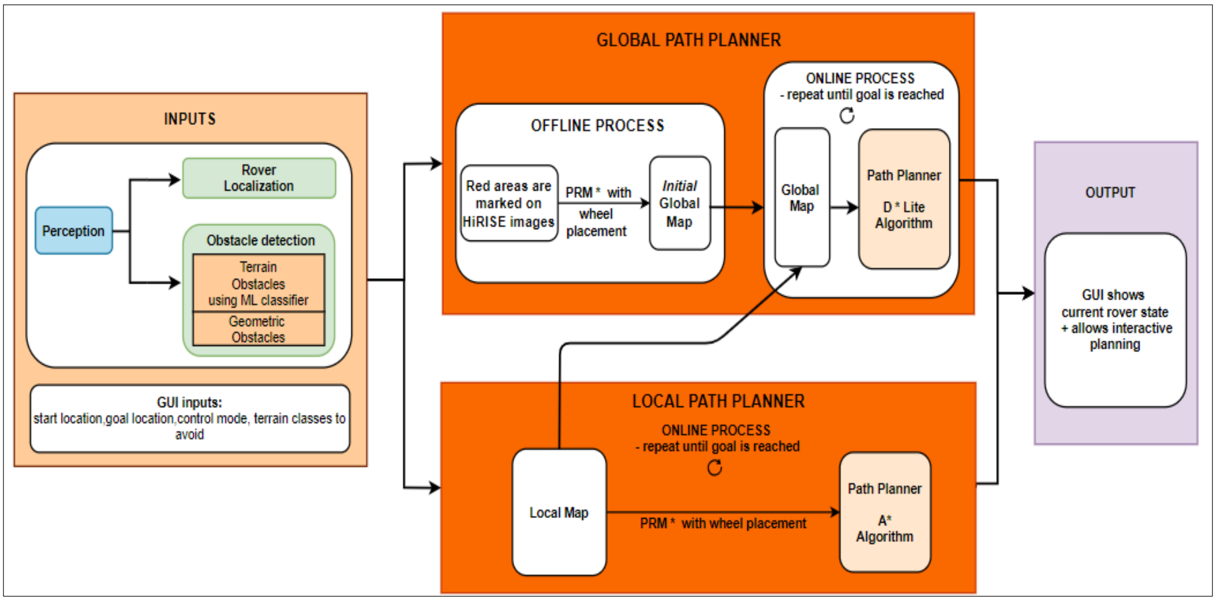


Figure 9.4 - Path planning architecture diagram

SCIENCE SUBSYSTEM

Site Selection

The rover takes leverage of its perception stack and instrumentation suite to search for interesting sites while navigating. Features like soil colour density, soil patterns, soil moisture, heat mapping through thermal imaging(with the help of the thermal cam), panoramic image, histogram segmentation, terrain classification, contour mapping, edges, key points, multiple view perspective transform, HiRISE information etc are extracted from the environment and sent to the base station for detailed analysis. All the features are then downsampled by some estimations to create heuristics which are then fed to an optimization algorithm. About 1000 particles are distributed uniformly over the field of view terrain of the rover and the optimization algorithm then gradually moves the particles towards the regions of interest in the rover's view. After a certain number of iterations, the particles concentrate in regions of interest along with descriptors for the region. An Anomaly Detection algorithm [19] is also trained based on the current knowledge about the Martian land and is used to detect any anomaly or deviation from the known data. If any anomaly is detected, the rover prompts the base and waits for further commands.

pH determination –

- Helps assess secondary mineral characteristics on the Martian surface_(particularly Fe-O-H-S minerals as their stability depends upon pH).
- Performed through digital image processing. [20]

Sampling System

Soil Sampling

The terrain is first induced with compressive stress using a hybrid drill (explained under Robotic Arm) The T-joint is then rotated and the Vacuum is placed over the loose soil (explained under Robotic arm). Furthermore, the base of the robotic arm rotates by 180º and the vacuum aligns itself on top of the funnel with the help of cameras attached on the end effector.

Figure 10.1 - Funnel with mesh

Rock Sampling

A compelling set of rock samples are collected by the gripper by percussive drilling(explained under Robotic arm).The gripper then places those rocks in the three different containers(designed to avoid any kind of contamination of the samples) made in front of the chassis. The containers have a micro servo motor attached to the lid so that it can open and close.

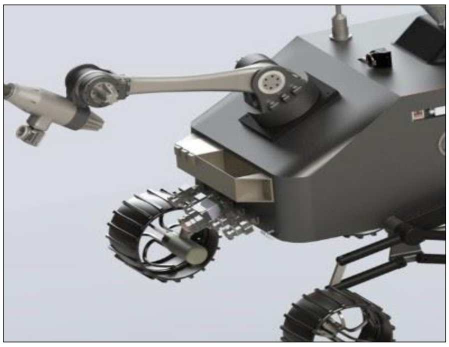


Figure 10.2 -Science caching containers

These rocks will be taken to the base station for further analysis for any evidence of past life (for example, microfossils) and organics that get concentrated in the rocks over time. This is a part of the science cache task.

In-Situ Analysis

Rock Analysis System (RAS)

The Petrological study includes elemental and surface analysis.

Elemental analysis - The custom-made APXS (Alpha Particle X-Ray Spectroscopy) instrument will measure the abundance of chemical elements in rocks [21]. A vacuum pump is being used to remove dust from the rocks (functioning explained under robotic arm-vacuum) before carrying out the spectroscopic analysis. The data obtained from the APXS is plotted as a reflectance vs wavelength graph. The peaks in the graphs gives us the elements present in the sample observed, which helps in determining the chemical composition of the samples. By analysing the elemental composition of rocks, we can understand how the material formed and if it was later altered by wind, water or ice and seeks evidence of rocks which essentially requires water for their formation and also preserve signs of biomolecules(the chemical building blocks of life) [22].This can give us a hint to Mars' geologic past and how it might have affected life.

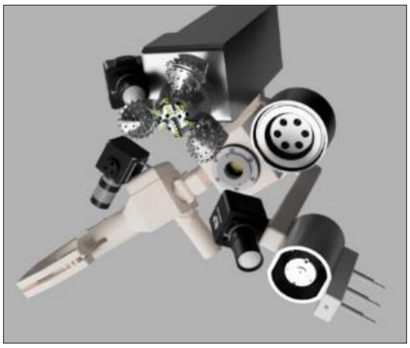


Figure 10.3 - APXS instrument on the end effector

Surface Analysis - A specialized science cam placed facing down on the T-joint is used for rock surface analysis. The science cam can take close-up images of the rock surface allowing us to capture the colour and texture of the rock. Life might have a hand in creating these signatures(patterns) and textures. Fluorescence Imaging and UV-VIS-NIR absorption spectrophotometry is performed by the cam to study the presence of minerals, organics (biomolecules) and any other possible biosignatures on the rock surface. The images taken are then sent to the base for detailed analysis.

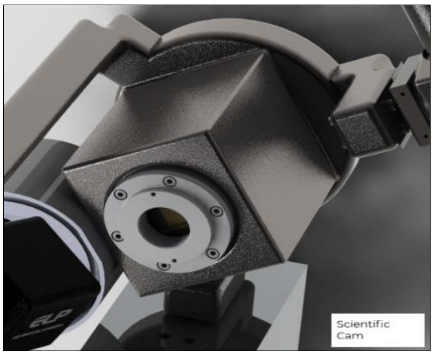


Figure 10.4 Scientific camera

Soil Analysis System (SAS)

Method used – Detection of Biogenic Metal Nanoparticles (MNPs)

If MNPs are formed, there will be some specific colour changes and this will mean that the initial solution retrieved from the sample contains any likely biological substances that allow for the chemical reaction to happen and form the nanoparticles(NPs). This will check for extant or no life. The Analysis will be done by a CNC mechanism, which keeps it simple and avoids sophistication of the science subsystem [23].

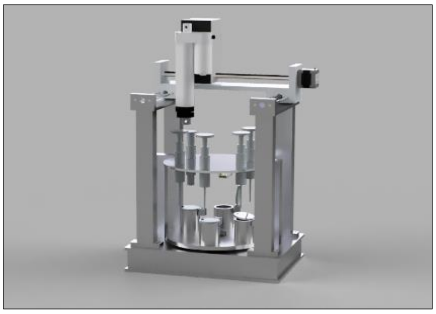


Figure 10.5 -Soil Analysis System (SAS)

Functioning of the SAS

The soil sample from the miniaturized vacuum pump falls into the funnel which opens using a micro servo motor. The funnel has a mesh which removes larger fragments of the sample. After getting refined it will fall directly into the container via a carefully angled pipe. The funnel is placed just behind the RGB sensor so that the sensor detects the surface of the container and aligns the container below it. Doing so all the containers lie below the pistons and the soil sample falls into the container(the design is made such that all the containers and pistons will be aligned if one of the container is below the RGB sensor).The containers are on a base plate which is attached to a motor with the help of two flange couplers.

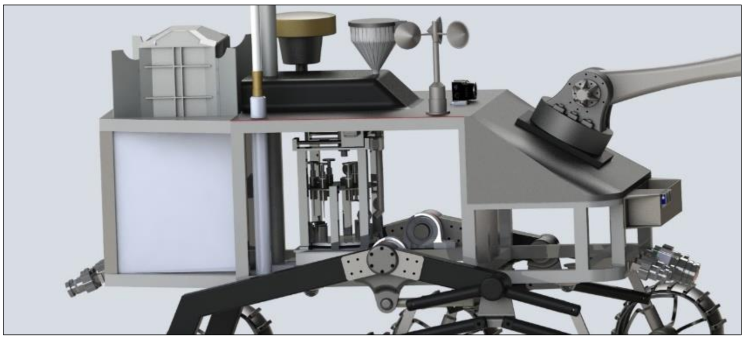


Figure 10.6 – Soil gets collected in the containers after passing through the funnel

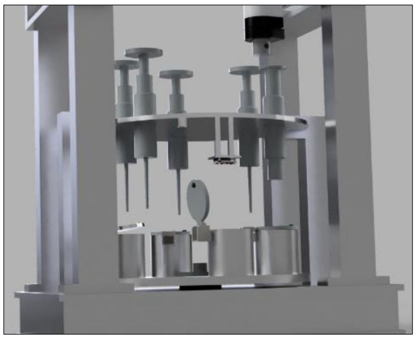


Figure 10.7 – Placing of the containers below the RGB sensor.

The lid of a container opens using a magnet attached on top of the lid and the base plate (where the pistons are attached) and closes using another piston just beside the RGB sensor. Two out of 4 pistons have water and other two have reagents. Following this we use a CNC mechanism to push the pistons and let sand get diluted with water. Once mixed with water the base plate (which has the containers) rotates one-sixth of a circle in one second so that the containers are aligned. It is then treated with a precursor(reagent): $AgNO3$ (final concentration of 0.1–5 mM) for AgNPs. After the above process the second container is filled with sand, diluted and the base plate rotates so that the second soil sample is mixed with tetrachloroauric acid trihydrate ($AuCl4\cdot 3H2O$) (final concentration of 0.2–4 mM) for AuNPs.

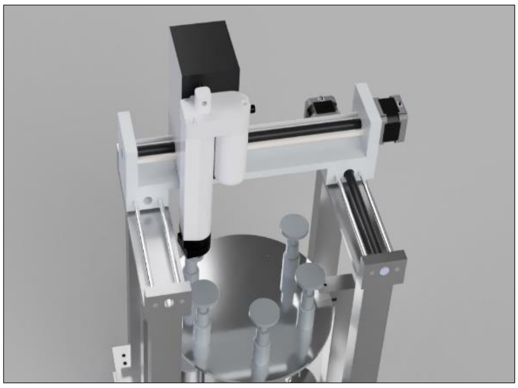


Figure 10.8 - Two linear actuators (CNC mechanism)

The mixture is left to incubate, and the base rotation speed is increased to 100rpm for 4-5 days. A more or less constant temperature is provided by a finely designed insulation system,
the insulating material being Solimide which will be wrapped around the container and lid. Any colour changes during the incubation period will be noticeable by direct observation with the help of a camera attached on the chassis. The lids of both the containers are closed and sealed to prevent any spill. The lid can open if we want to detect any colour change using an RGB colour sensor. Moreover, two more sets of containers are provided (total 4) to carry out another set of the above process, if needed.

It is expected that the soil solution containing AuNPs (gold nano particles) will show a red-colour, and the one containing AgNPs will be yellow/brown-coloured after the required incubation time. After the incubation period, if no colour change is detected, the solution is further concentrated by opening the lid to reduce its volume through evaporation. This will make any changes more noticeable.

Actuator	Provides a stroke length of minimum 10mm, enough to push the piston which in turn will push the liquid into the container
Motor	Provides a base rotation of 100 rpm which is the incubation period
Weight	Overall weight of the set-up is estimated to be around 15kg on earth and 5.7kg on Mars
Materials used	The overall body is made using Titanium for its better strength to weight ratio Other parts like flange coupler are made using stainless steel. The container will be made using Tantalum Carbide, the most heat resistant material (can withstand up to 4000 ºC)

Table 7 - Mechanical specifications of the Soil Analysis System (SAS)

Weather Monitoring System (WMS)

The instrumentation suite of the rover includes sensors chosen such as to provide output at high accuracy and consume low power.
These are placed on the rover to withstand the weather conditions while working. The data obtained is reliable. The sensors are mounted at an angle according to the data sheet where it can take the most accurate readings.

Figure 10.9 - WMS - a set of gas sensors, anemometer, and other weather monitorina devices

Atmospheric data analysis - A set of gas sensors are being used for a detailed atmospheric study. Table 8 summarizes the reasons for measuring the mentioned gases. Refer [24] for Martian gaseous biosignatures.

Gas	Sensor	Explanation
Carbon dioxide (95.5 %)	**CCS811**	Capnophilic bacteria require carbon dioxide and an oxygen free atmosphere for their metabolism. There are living metabolisms releasing CO_2. Responsible for phenomena like polar ice–cap formation, CO_2 ice- clouds.
Methane	**MQ4**	CH_4 gas concentration is found to vary seasonally as a cycle and a possible source –Methanogenic bacteria (produces methane as a by-product in hypoxic conditions). Atmospheric methane is often present in the form of subsurface methane clathrates.
Hydrogen	**SGAS701**	A global distribution study of hydrogen on mars indicated that Martian H_2 is equivalent(proportional) to the volume of water.
Carbon monoxide	**DGS-CO 968-034**	Present in very trace amounts. Possibilities of the presence of some special kinds of extremophiles that can use up and convert CO to CO_2 and yield energy.

Table 8 - Gas sensors for atmospheric study

Weather monitoring data - The Table 9 summarizes the parameters considered for a detailed meteorological study and characterization of the Martian climate along with the sensors used for their measurement. The reasons for choosing the parameter and sensors are also explained.

Parameter	Sensor Model	Explanation
Temperature	**PT1000**	Basic parameters to study the seasonal atmospheric changes. Moderate temperature makes the region quite habitable although extreme temperatures could favour growth of extremophiles. PT1000 in thin-film technology offers better long-term stability and better behaviour over temperature cycles.
Humidity	**BME280**	Shows how water vapor is exchanged between the soil and the atmosphere. A damper and more humid condition is suitable for microbial growth.
Pressure	**BME280**	Climatic conditions are largely affected by this parameter. The sensor can measure from 30,000 to 110,000 Pa.
Wind data	**Anemometer**	To monitor wind speed and direction. Influenced by weather conditions which includes clouds and precipitation. Major factor in weathering of rocks. Can also impact Martian dust storms.
Dust Sensor	**GP2Y1010AU0F**	There are frequent dust storms in mars so sensing a dust storm beforehand can help choose places for later human settlements. The dust sensor can measure up to 0.8 µm. The sensor gives analog voltage as output, which is linear with the dust density.
Surface UV Radiation	**VEML6075**	UV-induced photolysis changes the chemistry of the soil and atmosphere, inducing its oxidizing nature. Radiations from the sun and space can alter traces of any past life in Mars rocks and soil. This sensor is reliable even during long hours of exposure to the radiation. It provides stable data even when the temperature changes.
Moisture sensor	**TEROS12**	Moist soil indicates humus, and it is one of the key factors in detecting life supporting factors.
Ground Temperature sensor	**MLX90614**	Can indicate microbial presence in the soil as metabolic processes can involve a lot of exothermic reactions. This is basically an IR temperature sensor module. The IR thermometer is in a TO-39 packing, preventing any contamination of the thermometer and temperature measurement contactless.

Table 9 – Sensors for measuring various weather parameters and how it affects the climate

APPENDIX

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PRODUCT LINKS

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1. BME280 Humidity and Pressure
   https://ae-bst.resource.bosch.com/media/_tech/media/datasheets/BST-BME280-DS002.pdf

2. PT1000 Temperature
   http://www.keb.com.tw/Files/Other/PDF/Data%20Sheet-PT1000-RW.pdf

3. CO Gas Sensor
   https://www.isweek.com/product/digital-carbon-monoxide-co-gas-sensor-module-dgs-co-968-034_2390.html

4. H2 gas sensor
   https://www.idt.com/us/en/document/dst/sgas701-datasheet

5. Methane Gas Sensor
   https://www.sparkfun.com/datasheets/Sensors/Biometric/MQ-4.pdf

6. CO2 gas sensor
   https://cdn.sparkfun.com/assets/2/4/2/9/6/CCS811_Datasheet.pdf

7. Surface UV radiation
   https://www.sparkfun.com/products/15089

8. Dust Sensor
   https://www.sparkfun.com/datasheets/Sensors/gp2y1010au_e.pdf

9. Moisture Sensor
   https://www.metergroup.com/environment/products/teros-12/

10. Wind Speed Detector
    https://robu.in/product/wind-speed-sensor-voltage-type0-5v-anemometer-kit-waterproof-industrial/?gclid=Cj0KCQjw3Nv3BRC8ARIsAPh8hgI5JrbUUoPOxb977tIaxRVONgs4iBoMAXF7vzEdID0_sW95QBw6DYoaArfAEALw_wcB

11. Colour Sensor
    https://ams.com/documents/20143/36005/TCS3472_DS000390_3-00.pdf/6fe47e15-e32f-7fa7-03cb-22935da44b26

12. Ground Temperature Sensor
    https://www.sparkfun.com/products/10740

MOTORS

13. Arm
https://robokits.co.in/motors/rhino-ig32-planetary-gear-motor/rhino-planetary-gear-dc-motor/rhino-heavy-duty-ig32-planetary-dc-geared-motor-10rpm?gclid=Cj0KCQjw0Mb3BRCaARIsAPSNGpVQC8ENthAoDqAS5WpixDbDkDHLqENoi1z7SifGr-SUWKUqfizViaEaAvuJEALw_wcB

14. Nav Motor
https://www.groschopp.com/motor/62508/

15. Drill
https://robu.in/product/orange-planetary-gear-dc-motor-12v-92rpm-234-n-cm-pgm45775-50-9k/

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https://robu.in/product/370-diaphragm-3-5v-self-priming-small-micro-vaccum-pump/

17. Gripper
https://www.servocity.com/26-rpm-premium-planetary-gear-motor

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https://www.servocity.com/142-rpm-premium-planetary-gear-motor

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https://www.servocity.com/100-mm-stroke-17-lb-thrust-light-duty-linear-servo

21. Servo
https://www.amazon.in/Robodo-Electronics-Tower-Micro-Servo/dp/B00MTFFAE0#detail_bullets_id

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https://www.cytron.io/p-13amp-6v-30v-dc-motor-driver

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https://robu.in/product/dual-channel-enhanced-13amp-dc-motor-driver-30a-peak/

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https://www.pololu.com/product/2134/specs

25. Micro Vacuum Pump Driver
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26. Drill, Lead Screw, Gripper Motors Drivers
https://robokits.co.in/motor-drives-drivers/dual-motor-driver-electronic-5-amp?gclid=Cj0KCQjw0YD4BRD2ARIsAHwmKVldxmLyIENz36H82tS4iikLxQnLsUZfJTtdOCkOHx1aAAViGFpl_7saAklzEALw_wcB

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27. RAD5545
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