System Concept Review

Legendary Rover Team

August 15, 2021

MARS SOCIETY
SOUTH ASIA

LEGENDARY
RZESZOW UNIVERSITY OF TECHNOLOGY

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OF TECHNOLOGY

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1 Orthographic/Isometric Image of Rover

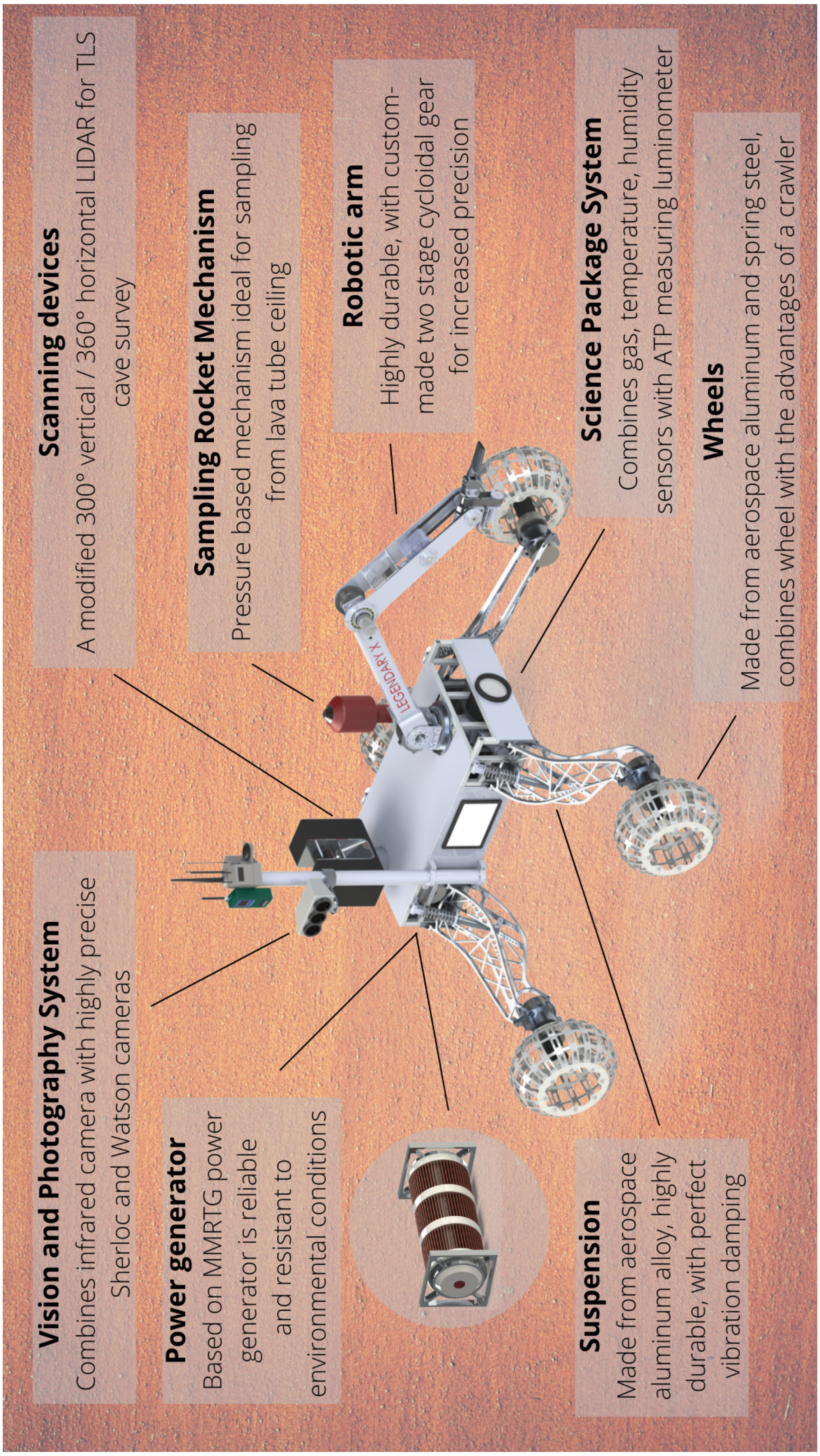

Figure 1: Ortographic/Isometric Image of Legendary X

2 Mars Environment Analysis

This chapter discusses conditions on the Martian surface and inside lava caves as remnants of past Martian volcanic activity.

2.1 Analysis of conditions on the surface of Mars

The atmosphere of Mars is significantly different from Earth's atmosphere. It differs mainly in its chemical composition, gravity, temperature, presence of regolith dust, atmospheric pressure, wind velocities or access to sunlight. Each of these parameters requires Martian rover designers to take a different approach to construction than on Earth. Many technologies, although they work well on Earth are not the best solutions on Mars, such as solar panels, whose efficiency decreases dramatically by dust. Moreover, electronics require protection from large temperature amplitudes and radiation.

Atmosphere

The composition of the Martian atmosphere is still not completely known. This is due to the different locations where measurements were made and the type of equipment that was used (spectroscopes, electronic sensors). However, usually measurement errors and differences do not exceed tenths of a percent. Scientists still do not know the origin of many of the compounds discovered on Mars (e.g. methane) as well as the chemical processes and reactions responsible for them. [1, 2].

Gas name	Chemical symbol	Amount
Carbon Dioxide	CO_2	$95,1\%$
Nitrogen	N_2	$2,59\%$
Argon	Ar	$1,94\%$
Oxygen	O_2	$0,16\%$
Carbon Monoxide	CO	$0,06\%$
Water	H_2O	$210ppm$
Nitrogen Oxide	NO	$100ppm$
Neon	Ne	$2,5ppm$
Hydrogen-Deuterium-Oxygen	HDO	$0,85ppm$
Krypton	Kr	$0,3ppm$
Xenon	Xe	$0,08ppm$

Table 1: Chemical composition of Mars atmosphere in percent or ppm[3]

Others

The gravitational acceleration on the surface of Mars varies with the topography of the terrain. For engineering calculations, the mean surface gravity can be used. According to Mars Gravity Model 2011 (MGM2011) it is $3.72076m/s^2$ [4]. Temperatures on Mars range from $-153°C$ at the poles, all the way up to $30°C$. At night the air is saturated (100% humidity), but during the day is undersaturated. Wind on Mars can be about $30m/s$ and create dust storms that take months to settle[5, 6].

2.2 Lava tubes

Lava tube (lava cave) is a structure that was formed by the flow of lava, which, as it overcrust on the surface, also created underground rivers of lava. These underground rivers carved out tunnels. When examining lava tunnels, it is important to remember that some of them are partially collapsed, which means that the tunnel can be covered with regolith from the surface and expose the interior to sunlight along with an increased dose of radiation. Of course, there are also tunnels with a single entrance, where the internal environment is isolated from external conditions. Such tunnels could provide extremely important insights into the geological, paleohydrological and possible biological history of Mars[7, 8].

So far, there has been no rover mission with gas sensors in a lava tunnel on Mars. Nevertheless, we can expect that the gases coming out of volcanic ash and solidifying magma millions of years ago are similar to those observed from Earth's volcanoes. Gases from active volcanoes on Earth consist of 99% water vapor (H_2O), carbon dioxide (CO_2), and sulfur dioxide (SO_2), with the remaining percentage consisting of hydrogen sulfide, carbon monoxide, hydrogen chloride, hydrogen fluoride, and other minor gases[9].

The tunnel surface may vary depending on lava type, temperature, cooling rate, and geological conditions. The tunnel may consist of smooth, molten, basaltic structures, but may also contain gravel-like features, large rocks, and even have stalactites and stalagmites. The ground may also consist of thin-walled structures that can easily crack under pressure. This pushes engineers to develop wheels suitable for cave exploration and also to minimize the weight of the rover[10, 11].

The size of lava tubes on Mars can be up to 80 times larger than those on Earth, with diameters ranging from 40 to 400m and lengths in the tens of kilometers. The project assumed, according to the regulations, that the minimum diameter of the tunnel would be 50m and the depth of the lava tube is 15m below the surface[12].

3 Rover System Breakdown Structure

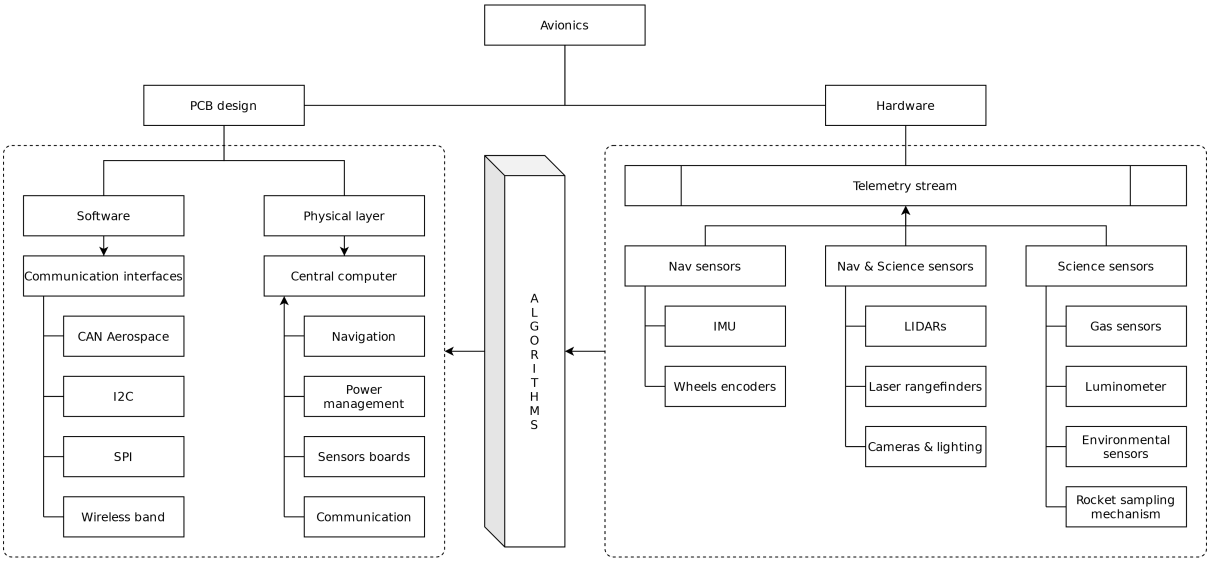

Figure 2: System breakdown structure

4 Rover Mechanical Design

4.1 Frame/Body Design

The rover frame was made of 6060 aircraft duralumin alloy in the form of square profiles. In the design phase after analyzing the usability of the frame i.e. what capacity it should have, which is related to the protection of the entire electronics and MMRTG, the most important systems, places of mounting other components such as robotic arm, rocket, mast or sensors. Then we moved to the phase of strength simulation using FEM. Solidworks software was used to analyze the frame loaded by inserting a manipulator, MMRTG and whole equipment with a total weight of 40 kg. It resulted in a von Mises stress diagram, which allowed us to evaluate that the stresses do not accumulate significantly in critical areas. Instead, a distribution over a larger number of truss nodes, such as the frame, can be observed. Also, the plasticity limit has not been exceeded, so it is clear that the frame and welds will not undergo permanent deformation or damage while driving in difficult terrain. Thanks to this analysis we could also plan the distribution of profiles in the right places to ensure the best stress compensation. The result is extremely robust, durable and relatively lightweight frame, which is a safety cage for the most important subsystems of the rover.

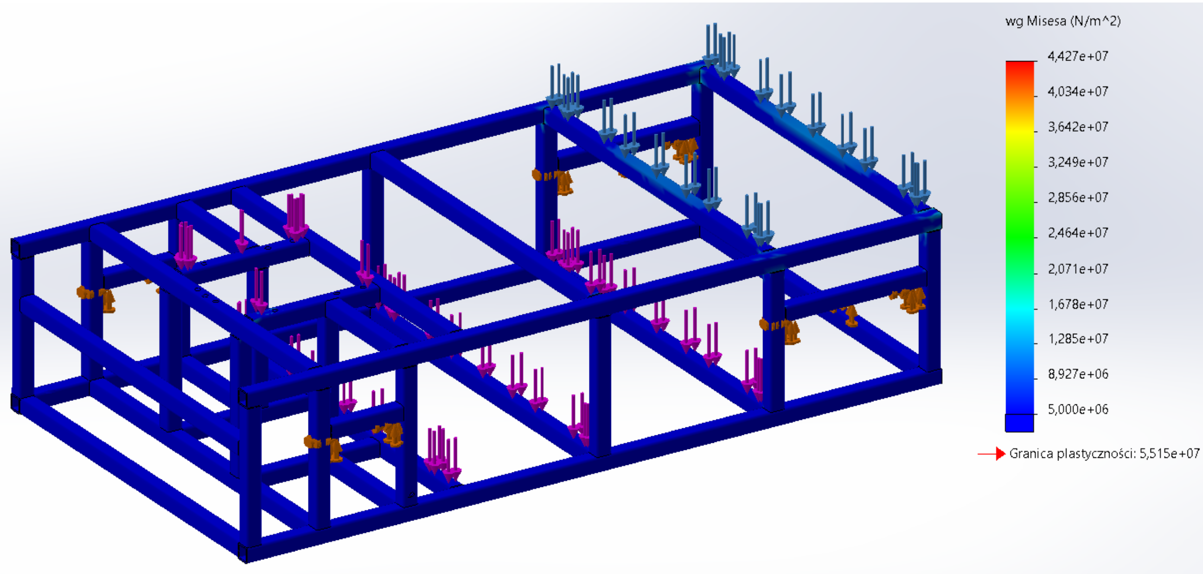

Figure 3: FEM analysis of frame

4.2 Drive System Design

4.2.1 Suspension design

The Legendary rover's driving system consists of a multiple swingarm suspension. The suspension was designed, tested and continuously improved using the finite element method. The control arms were subjected to special strength calculations to reduce weight while maintaining the same strength. This was accomplished by reducing the thickness of the internal structure of each control arm and changing the shape of the cutouts in the structure from triangular to circular, resulting in greater torsional and bending strength. Every part of the suspension system is made of duralumin, and each control arm is individually designed, resulting in a different shape. The front upper control arms are heavier and stronger than the rear upper control arms, and each lower control arm is heavier and stronger than the corresponding upper control arm. This provides a better weight to strength ratio. Each multiple control arm assembly is supported by a spring shock absorber. Two types of springs are available and can be quickly installed by the rover operator at the base:

- soft - ideal for climbing in difficult, rocky terrain
- hard - suitable for fast travel on flat terrain.

The analyses performed using FEM allowed us to visualize the stress distribution in both the upper and lower control arm. In the pictures below we can observe the distribution of stress values. In our case, the highest value does not exceed the limit of plasticity for the material used (in our case it was 7075-T6 alloy). This means that during the operation of the vehicle no permanent deformation of the element will occur, nor will any damage and macro or micro cracks in the microstructure.

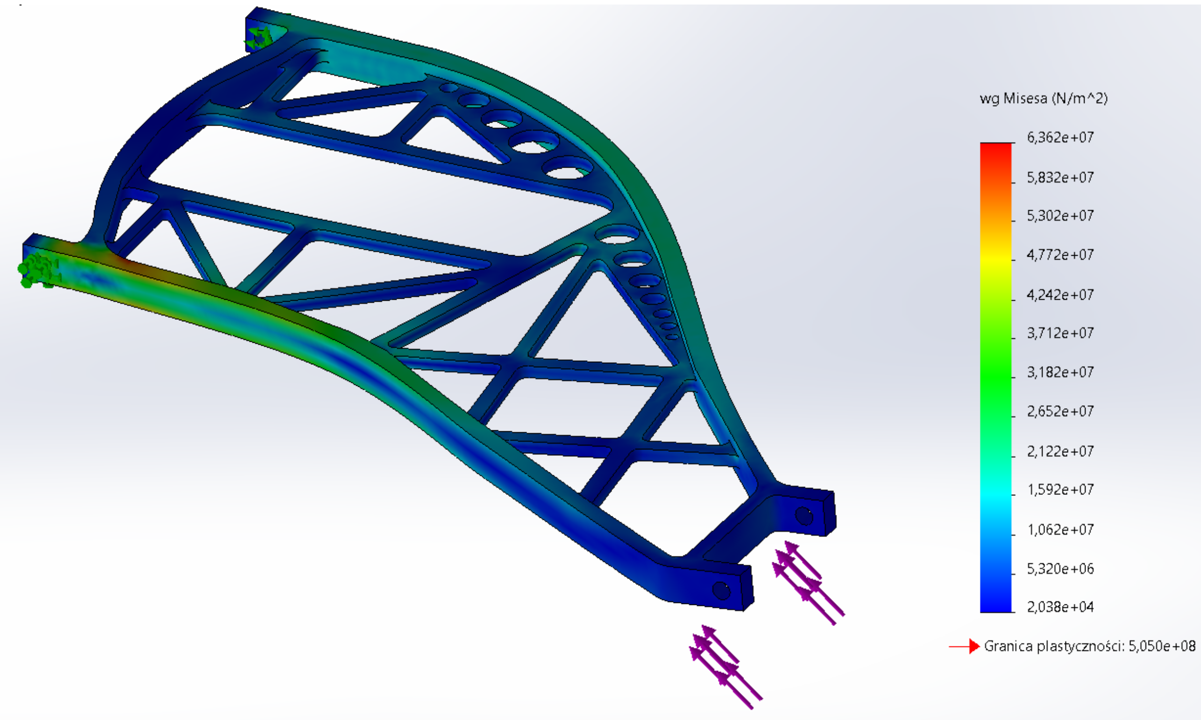

Figure 4: FEM analysis of single upper swingarm

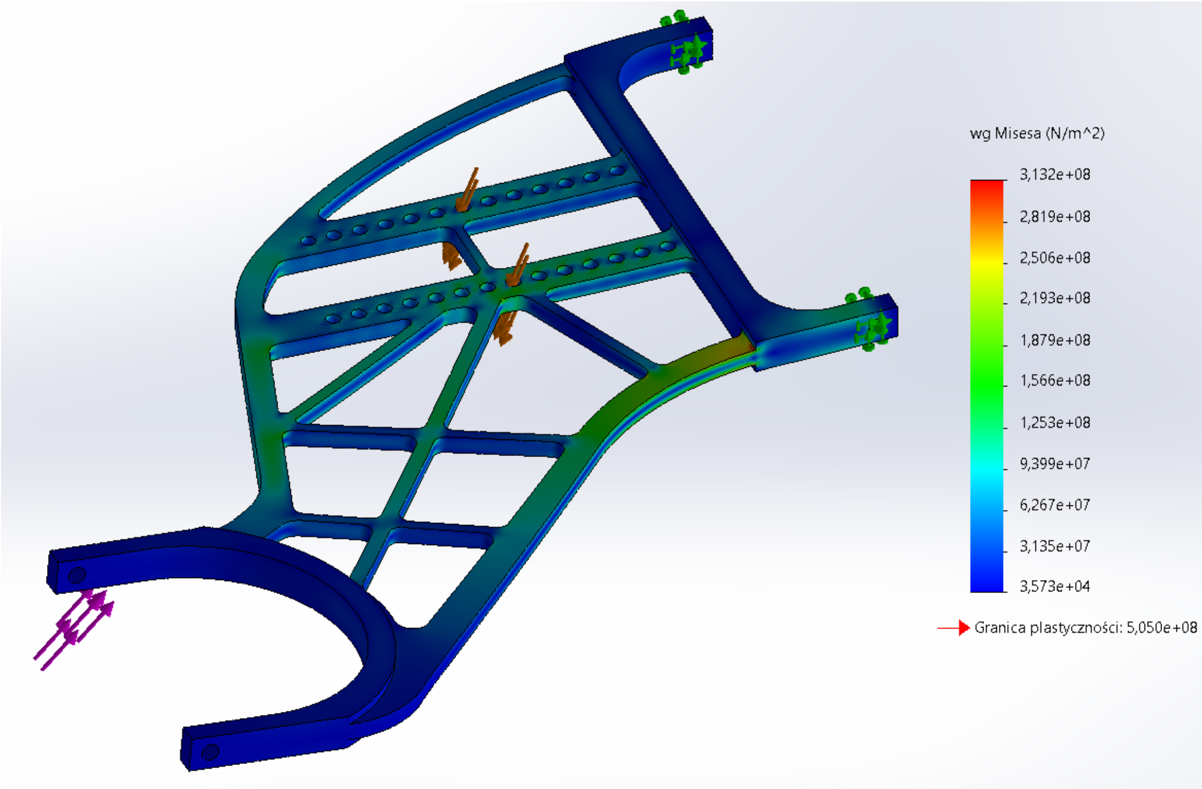

Figure 5: FEM analysis of single lower swingarm

4.2.2 Wheels design

For our rover we have designed special airless wheels. They have to fulfill a variety of requirements, particularly in the areas of deformability, resilience and vibration damping, in order to provide adequate traction and durability in difficult terrain. In order to ensure high strength of the wheels the structure consists of titanium discs/rims and arches made of spring steel that are in contact with the ground. Both of these elements are connected with the motors driving the rover. The wheel does not have a ”classic” tube-shaped rim. Its function has been replaced by three titanium discs connected respectively by bolts, which allows to transfer the torque from the hub to the ground. This design significantly reduces the weight of the wheels (in comparison with traditional wheels filled with air) while maintaining the necessary rigidity and strength. The spring arch system has been further reinforced with three rings made of spring steel ensuring the best possible kinematic performance at a very limited weight. These steels are known for their resilience, high strength and low hardenability, which makes them suitable for the manufacturing of objects with small cross-sections and enables them to be formed into the majority of shapes. With small cross sections, this steel is ideal for use even in one of the most stressed and vulnerable parts of the rover - the wheels. Resistance to various types of deformation is an advantage of spring steel, which allowed for its application in our rover. Such steel is both resistant to cracking, deformation and fatigue, because it quickly regains its shape after being previously deformed by external pressure. An additional aspect improving the driving properties of the vehicle is the fact that during the drive the spring arches bend under the weight of the rover, increasing the contact surface of the wheel with the ground. This reduces sinking in boggy terrain and allows the wheel surface to adapt well to passing obstacles (such as large stones), making it easier to overcome them. In order to improve the traction, the spring steel arches have been shaped along with perpendicularly placed serrations that dig into the ground when operating as a crawler system. As a result of the adopted solution lower weight of the wheel was obtained, while maintaining good driving properties. In addition, the number of elements associated with the drive system has been reduced, which improves the reliability of the rover and affects the ease of its maintenance and possible repairs or modifications.

To ensure the best driving characteristics, the drive unit consists of 4 independent DC motors, one for each wheel. Thus, even in the case of failure of one of the motors, the rover can successfully move with one passive wheel.

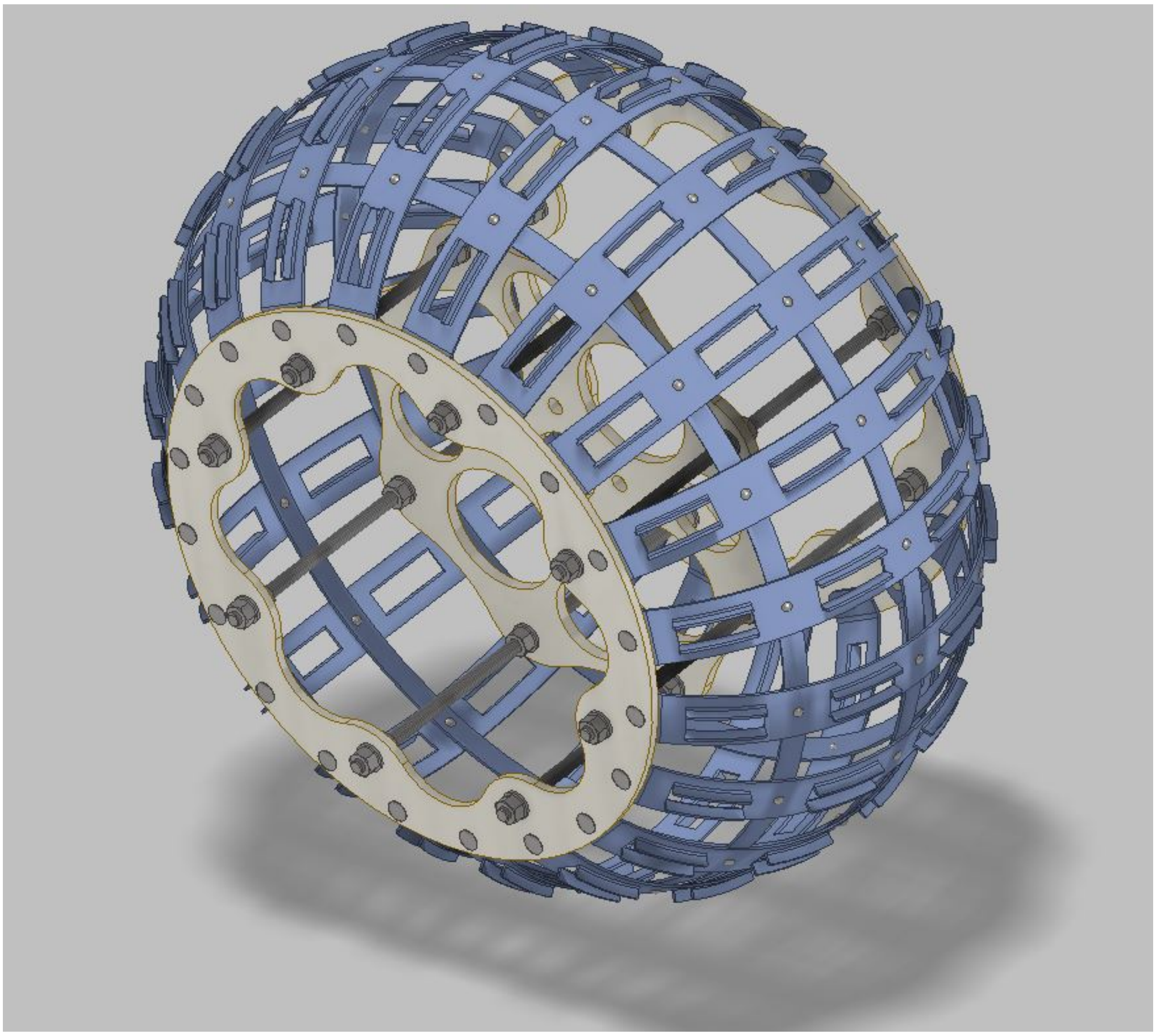

Figure 6: Render of a single wheel

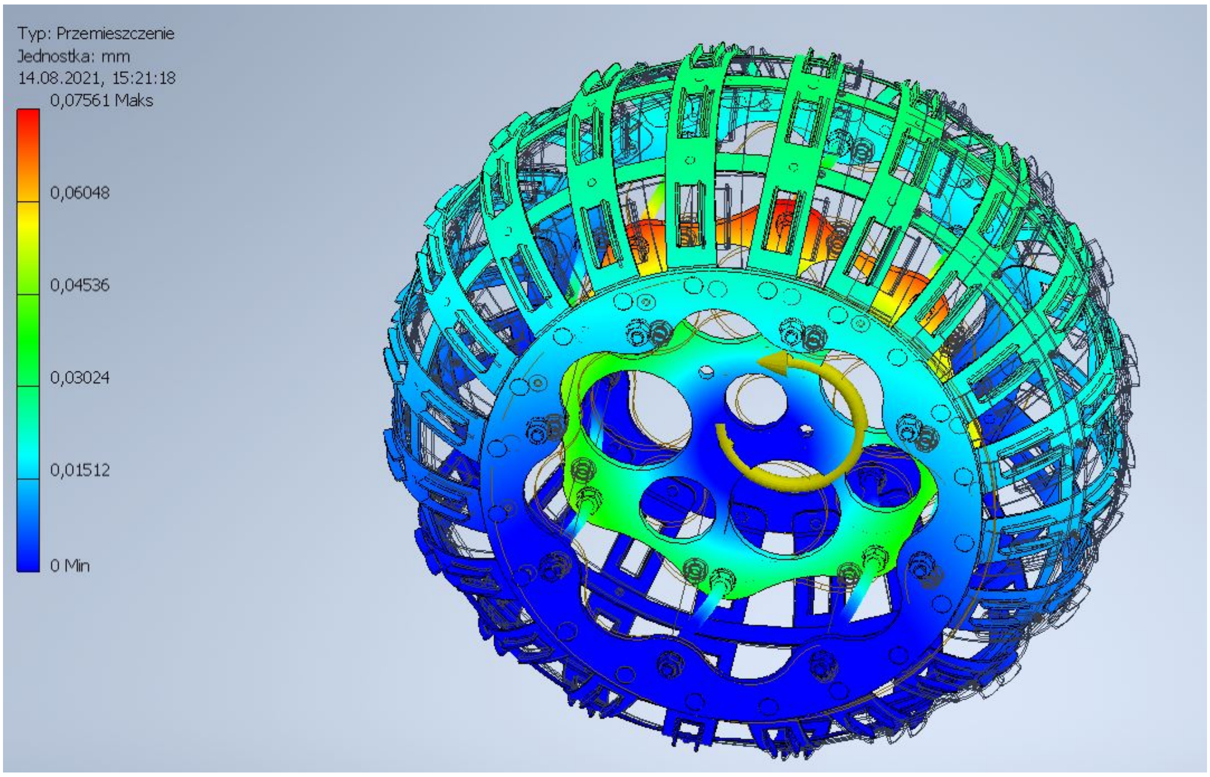

Figure 7: FEM analysis of a single wheel

Figure 8: Suspension and wheel assembly

4.3 Robotic Arm Design

When designing our manipulator we wanted to focus on aspects such as reliability, strength, but also the ability to lift significant loads - more than 5 kg. An important aspect was also the precision of positioning of each subsequent segment of our manipulator which is why we needed to use electric geared motors coupled with precise and lightweight gears. The robotic arm is located on the back of the rover frame. It has 5 degrees of freedom. It consists of a rotary stage used for axial rotation of the entire manipulator relative to the frame, two rigid arms and a precision gripper. The rotary stage is driven by a geared motor that is located horizontally in the rover frame. The geared motor is coupled to a planetary bevel gearbox so that rotational motion is transmitted directly to the manipulator base. The robotic arm is based on a precision, extremely lightweight crossed bearing, which is also compact in size. Lifting of the entire manipulator is performed by a two-stage cycloidal gearbox, which was fully custom-designed by the team. Its design is a new combination and modification of several solutions available on the market. Through our research we were able to create an extremely small gearbox with high gear ratio, low weight and high precision of positioning. It is driven, as in the previous case, by an electric geared motor from a brush motor.

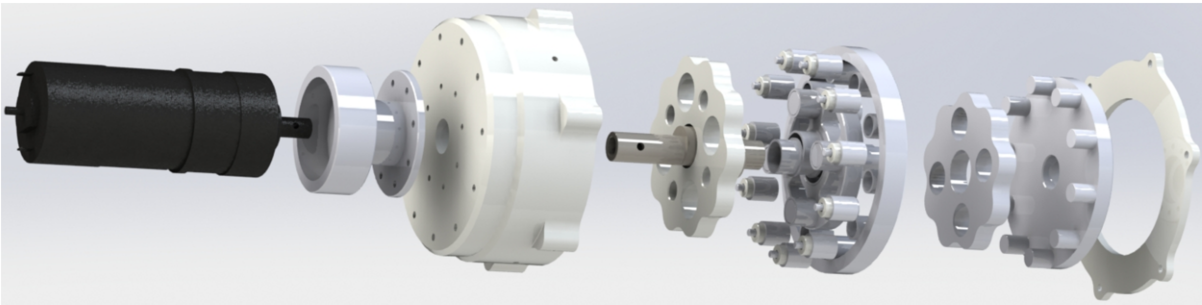

Figure 9: Custom-made two stage cycloidal gearbox

The first arm of our manipulator was created from a square tube to ensure high rigidity, resistance to bending and torsion of the arm. A planetary gear coupled to a brush motor is responsible for the lifting or positioning movement of the second arm. The second arm was created from two coupled flat bars connected with joints. Flat bars provide resistance to bending and at the same time the connectors provide stiffness and resistance to torsion. In this case, we could not use a square tube because the second arm was placed in the drive, responsible for the movement of raising and lowering of the gripper. This mechanism consists of an electric geared motor from brush motor and an angular hypoid gear that provides a change of rotation axis. It is an indirect drive of the gripper, because the direct movement is provided by a belt transmission connecting the source of the drive (motor) and the receiver (gripper). We took this solution in order not to place the motor with the gear at the very end of the robotic arm because this would significantly extend the center of gravity of the robotic arm and thus increase its inertia. Rotation of the gripper is provided by a belt transmission combined with a small brush motor located under the gripper drive. The clenching system consists of a helical gearbox. The linear motion is provided by an extremely light yet powerful linear stepper motor located behind the gripper. The gripper consists of two arms that allow for precise grabbing of objects such as rocks and science lab components. In our project we used mainly light alloys used in the aerospace industry such as 7075 alloy, and in the case of welded structures 6060. All of this has led to the development of an extremely reliable, robust, and precise design that can collect samples using specialized equipment or objects, such as a sampling rocket, when working in really harsh environments like Mars or caves.

Figure 10: Robotic arm side view

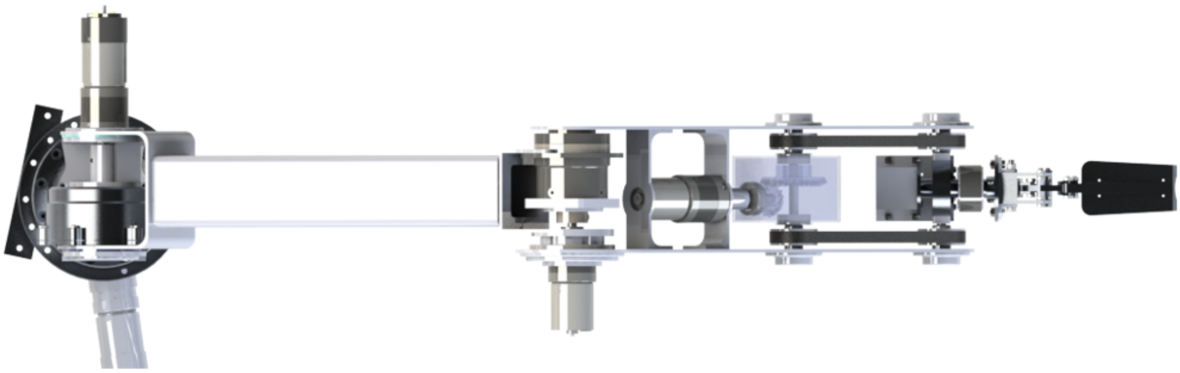

Figure 11: Robotic arm upper view

4.4 Rocket Sampling Mechanism

The system consists of several simple parts, which in sequence are:

- a mechanism for setting the angle of the launcher
- steel rope retraction mechanism
- rocket launcher
- sampling rocket

The launcher angle mechanism is a simple servo motor with a gear that sets the angle from 15° to 165° allowing the sample to be taken from the ceiling or cave wall where the rover is located. The launcher consists of a compressed gas container, solenoid valve and a tube. The gas canister allows the collection of 3 samples and then must be replaced by the rover manipulator or astronaut in the base. Rocket launching is possible by opening the valve, which releases some of the gas accumulated in the container which propels the rocket mounted on the tube. The rocket contains a sampling mechanism based on inertial force. At the front of the rocket there is a container closed by a spring-loaded pawl pressed against the top of the container. Inside the pawl there is a tungsten rod ended with a spike which, when it hits the ceiling of the cave, behaves like the cumulative charge in ballistic rockets and crushes some of the rock which then falls into the container opened by the force of the impact. After that the container closes tightly, and the entire rocket falls to the ground where it waits to be retrieved by the rover. The rocket is reusable after it passes its condition check and is re-armed with a tungsten rod by an astronaut at the base or the rover's robotic arm. In addition, the rocket is attached by a thin (2mm in diameter) 300 meters steel rope to the rover. The flight of the rocket is stabilized by the rope, similar to rocket launchers used to flip ropes between ships at sea[13]. As the rover recovers the rocket, a rope is pulled into the retracting mechanism with servo motor.

Figure 12: Rocket system render

Figure 13: Probing mechanism: left - before impact into the ceiling, center - moment of impact with tungsten rod hitting the ceiling, right - closed mechanism after impact

5 Electric/Electronics Design

Four main PCB boards are used in Rover:

Power distribution integrated with Battery management
This board controls and monitors energy required by rover's subsystems. It controls energy flow between reactor, batteries and subsystems.

Central computer
This is the heart of the autonomy and all flight controls. NVIDIA Jetson Nano Module with Quad-core ARM Cortex-A57 MPCore processor serves as the low-level central computer, which includes guidance and navigation control, motors control and battery level monitor. Such a powerful unit also handles all the sensors data and actuators.

Sensors
This board is the powerhouse for motion related sensors, cameras and science task sensors. It consists a single core STM32F303 family MCU with an ARM® Cortex®-M4 core and is responsible for collecting data, basic computations and parsing data to central computer.

Communication (VLF)
Communication module uses COTS 802.15.4 (Zig-Bee) standard 900 MHz chipset. Another STM32F303 MCU is used for monitoring charging current without having to turn on the FC unit, thereby saving power.

Following sensors are used by rover:

IMU — (*Inertial Measurement Unit*) Bosch BMI270 unit combines gyroscopes, accelerometers and inclinometer to measure plane specific forces and angular rates. Signals from IMU are used by AHRS to calculate orientation angles which are used by central computer to motion planning and state estimation.

Modified Focus Plus laser scanner (360 LIDAR) - subsection 5.1

Science Package Sensors - subsection 8.1

5.1 Rover Scanning devices

Based on previous NASA missions focused on the possible exploration of lava tubes, the TLS technology cannot be overlooked. This technology was used in the Lofthellir cave in Iceland by NASA in 2018 using drones.

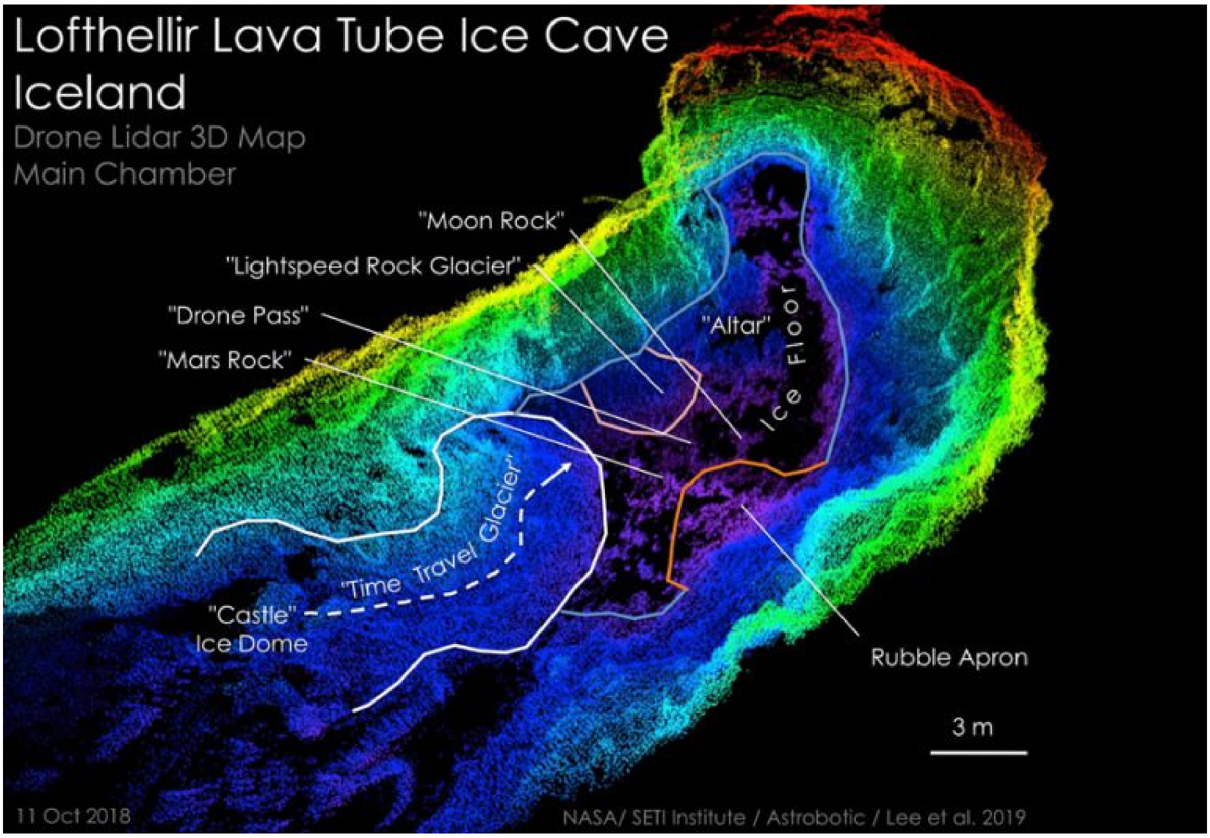

Figure 14: Visualisation of data collected in a lava tube using TLS technology - Lofthellir cave [14]

Terrestrial laser scanning (TLS) techniques are increasingly used in geomorphological studies, mainly because TLS devices are active remote sensing tools, emitting their own electromagnetic radiation and collecting data with high accuracy. TLS offers a number of advantages over traditional cave mapping, including the ability to measure high ceilings, high operational speed, accuracy, a large number of measured points and the construction of realistic 3D models of caves, including cave walls with a resolution of a few centimetres. Special software packages also allow advanced processing of the data obtained and various analyses, such as volume and reflectivity calculations and detailed studies of voids and physical and chemical deposits. Traditional cave surveys using a laser rangefinder and compass inclinometer would be more tedious and would only provide lower density data. The lack of light in caves also makes photogrammetric surveys more difficult, the range and noise at low reflectivity is much poorer. TLS data will be used to assess the volume of caves formed by various speleogenetic processes (e.g. stalactites and stalagmites, voids formed by weathering of basalt rocks). It will also be used for navigation , cave mapping (including walls, ceiling) and mineral crust studies. For the reconnaissance mission of mapping the lava tube, the rover will drive with the LIDAR module at the front relative to the travel direction (to avoid other rover's devices being mapped).[15].

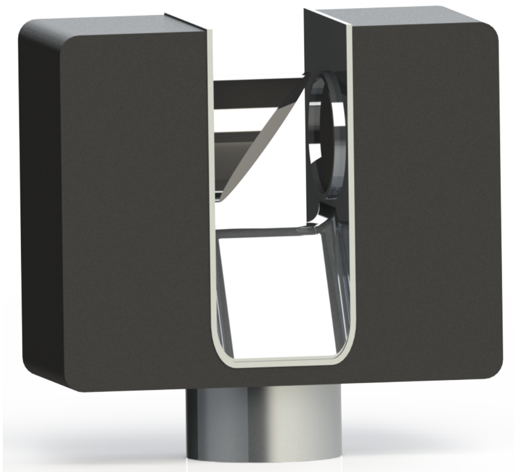

Figure 15: Customized Faro Plus LIDAR, based on [16]

A modified Focus Plus laser scanner from FARO was used for cave mapping. The modification was necessary because although the manufacturer had adapted the scanner to autonomous vehicles (e.g. integration with SPOT from Boston dynamics), it was still adapted to be operated by humans. A reinforced housing was used to ensure IP Rating 65 and extended temperature range, touch screens were removed and power supply was integrated. 32GB flash memory is on board to store gathered data for processing. This device uses Phase Shift technology to measure distance. Its maximum theoretical range is over 350m, depends on environmental conditions, especially ambient lighting which can be a source of interference, with the worst case (2% reflectivity - black) being 50m. Device emits laser light in the short infrared range (1550nm) and the measurement speed can register 2 million points per second, 300°vertical / 360° horizontal filed of view, with 0.009 step size and maximum scan speed 97Hz. This gives an impressive measurement accuracy of 2mm at 10m, with not more than 10mm remaining at maximum range[16].

5.2 Rover Navigation

Reliable and robust navigation system is necessary for rover to operate in harsh environment, especially in caves. Incorrectly planned route may cause rover to stuck or damage it's crucial subsystems. Implemented algorithm must guarantee that system will not plan alternative move or stop working. Navigation system must scan environment around a rover, recognize obstacles and plan the best path for rover. Navigation system must meet following high level requirements:

- Navigation system must assume only local knowledge of environment [17]
- System must know it's global goal
- Rover must recognize obstacles in real time and be able to calculate alternative route
- Scanning full 360° area around rover. System must measure also cave height to prevent rover from touching cave ceiling.
- During operations in case rover may lose signal from base so must be able to autonomously calculate and execute a way back to base. Navigation algorithm would use dead reckoning process.
- Rover kinematics model will be implemented to determine which route is accessible by the rover (rover must avoid too high obstacles or too hilly areas) and predict which wheels will have contact with ground.

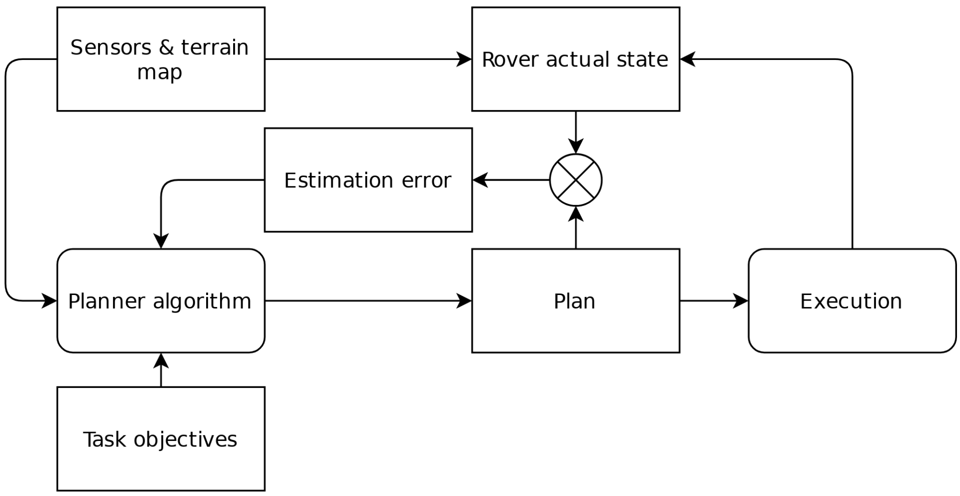

Figure 16: Basic assumptions for rover navigation algorithm

RoverBug is autonomous navigation algorithm designed for rovers which operate in unknown environment. It's based on two main assumptions:

- *Motion-to-goal* - rover should follow the shortest possible way to designated place. It means that with every step distance from rover object of interest should decrease.
- *Boundary following* - in case of detecting an obstacle rover should act like a bug and follow along obstacle boundaries in direction which would bring it closer to the final location.

Combined with sensors (inertial measurement unit and LIDARs) and rover kinematics model allow to precisely navigate through rough and unknown terrain [18]. Simple flow diagram of the algorithm is shown on fig. 18.

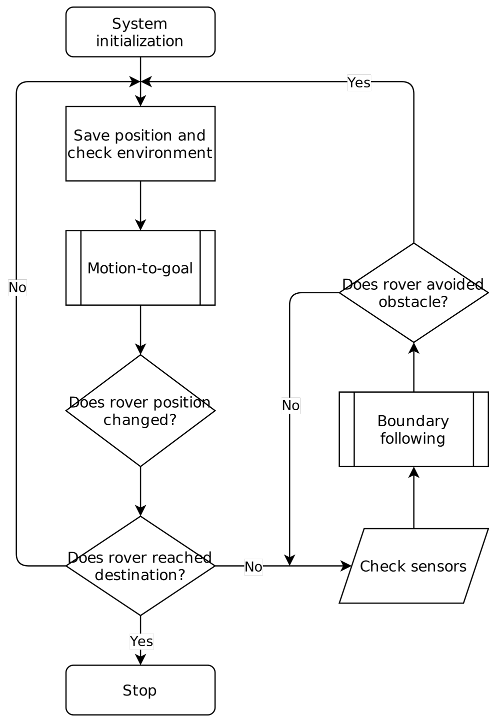

Figure 17: Bug algorithm flow chart

In cave exploration main problem is designating of global goal for rover. In case of on the ground activities photos could be sent to control station and operator could point object of interest. Caves may have blind corridors so rover must autonomously go back and pick other final location. To adapt existing algorithms for cave conditions classic systems would be enhanced with 3D environment scans by LIDAR sensors. Below is brief description of additional steps:

1. Acquisition of 3D points by LIDAR sensors
2. Creating ground map and calculating predicted rover's roll and pitch angles (rover has physical limitations and can not traverse too tilted surfaces)
3. Creating map of cave ceiling. It allow to calculate map of obstacles for bug algorithm. Any places with too short distance between ground and ceiling will be treated as obstacles (however they don't block rover sensors)
4. Navigation system will designate as a global goal most distant vertical surface or direction where sensors doesn't detect any surface (it will be treated as a corridor)

Exact behaviour of RoverBug algorithm is described in many papers [18][17][19][20]. It's starting point for more efficient and sophisticated navigation system.

5.3 Rover 360° Vision and Photography

We wanted to create a set that met the objectives. The cameras will be adequately protected against mechanical damage, rock fragments falling off. Protection against moisture in the cave is also important. The cameras will be placed on tripods with a ball head in order to achieve the appropriate stabilization.In addition to the built-in flash, integrated lamps will be added to provide additional illumination when taking photographs.

Photographs taken with the built-in flash are usually flat and two-dimensional, which is why the use of flash on a commercial camera is abandoned. With an external flash, more shadows can be introduced, giving depth to the images. It will be possible to use more than one flash at a time to illuminate a cave.

Camera parameters for cave photography:

White balance must be set to flash. The ISO sensitivity will be reduced to the maximum. To avoid black spots in the lenses, a setting of 640 or less is recommended. It is also important to use the widest possible lens.

Our picture taking system consists of:

- Context Imager Camera - Sherloc

  SHRLOC is a device consisting of: a spectrometer and laser, and an integrated 'contextual' macro camera to take extreme close-ups of the areas being studied. This provides context to what the laser was aiming at, but also helps scientists see textures that can tell the story of the environment in which the rock formed.

- Engineering Camera Watson

  WATSON (Wide Angle Topographic Sensor for Operations and engineering) captures images that combine scale, from the highly detailed images and maps of Martian minerals and organic matter collected by Sherloc to the broader scales that SuperCam and Mastcam-Z observed from the mast. WATSON provides fine-scale views of textures and structures in Martian rocks and the rock debris and dust that cover so much of the Martian surface. These capabilities mean that WATSON not only supports SHERLOC, but also helps identify targets of interest for other rover instruments. Because WATSON can be moved by the robotic arm, it also provides images of the rover's instruments and parts.

- thermal imaging camera Testo 868

  The testo 868 thermal imaging camera offers professional technology and features simple and fast operation. It has options for generating comparable and error-free thermal images with handy functions. Built-in functions avoid measurement errors, effortlessly achieve the optimal emissivity setting ( ), reflected temperature(RTC) and temperature scale and colour palette.

  It connects wirelessly, so you can prepare and send a report directly from the measurement site.

  Due to the fact that the temperature scale and colour palette of the thermal imaging camera can be set individually, it can happen that the thermal image of e.g. a building is misinterpreted. With ScaleAssist function, this problem is solved - the image scale is adjusted with respect to the indoor and outdoor temperature of the measuring object, as well as the difference between them. This guarantees comparable and error-free thermal images.

  Sampler description: The non-contact voltage tester testo 745 is ideal for initial checking of voltage presence. It has a low-pass filter that enables reliable voltage determination. When the presence of voltage is confirmed, it gives a warning with a bright visual and audible signal. An integrated torch, located on the front of the voltage tester, also enables safe operation in dark environments. It is waterproof and dustproof (IP 67).

Special features Filter for high-frequency interference signals Voltage range up to 1000V Water and dust-proof to IP 67 Adjustable sensitivity Optical and acoustic signals Waterproof and dust proof up to IP67 Measurement point illumination Adjustable for phase detection or voltage indication

- Vivitar 283 and 285 models will be used. 433. A good cave photo can be taken even with 1 lens, but 2 or 3 give more possibilities. or 3 give more possibilities. For close-up photography (at distance of a few metres at most), the minimum guide number of the main lens is 30, because dark cave walls absorb a lot of light. The others can be weaker. Large spaces require strong lamps.

- LED YONGNUO YN-900 lamp with color temperature control

6 Communication System Design

The communication system must meet the following requirements:

- Must be able to transmit a signal across the surface of Mars into a cave
- Must be able to send a signal over a 5km lava tube distance (terrain with a possible significant slope)
- Must support different types of transmission modes, such as data transmission and real-time data transmission.

Areas such as mining communication, underwater communication (e.g. submarines) and military communication have been explored. As a result, the proposed design is a mixture of VLF Through-the-Earth (TTE) and Line-of-sight (LOS) communication. Due to the narrow bandwidths available, real-time video transmission is impossible, only slow data is supported. The VLF data rate is about 300 bits/s, so data compression is crucial. The system provides for the use of VLF frequencies up to 10kHz. Natural background noise increases with decreasing frequency but is negligible in a given environment, the most noticeable noise will be that of the rover's electric motors, which can be easily filtered out using FFT analysis. An interesting fact is that lightnings release VLF (background noise) energy that travels thousands of miles, which allows lightning to be characterised, geolocated and incorporated into weather forecasting. Lightnings are very rare on Mars, given that VLF has global coverage, it can be used to map thunderstorms on the Martian surface and better understand them. [21, 22, 23, 24, 25, 26]

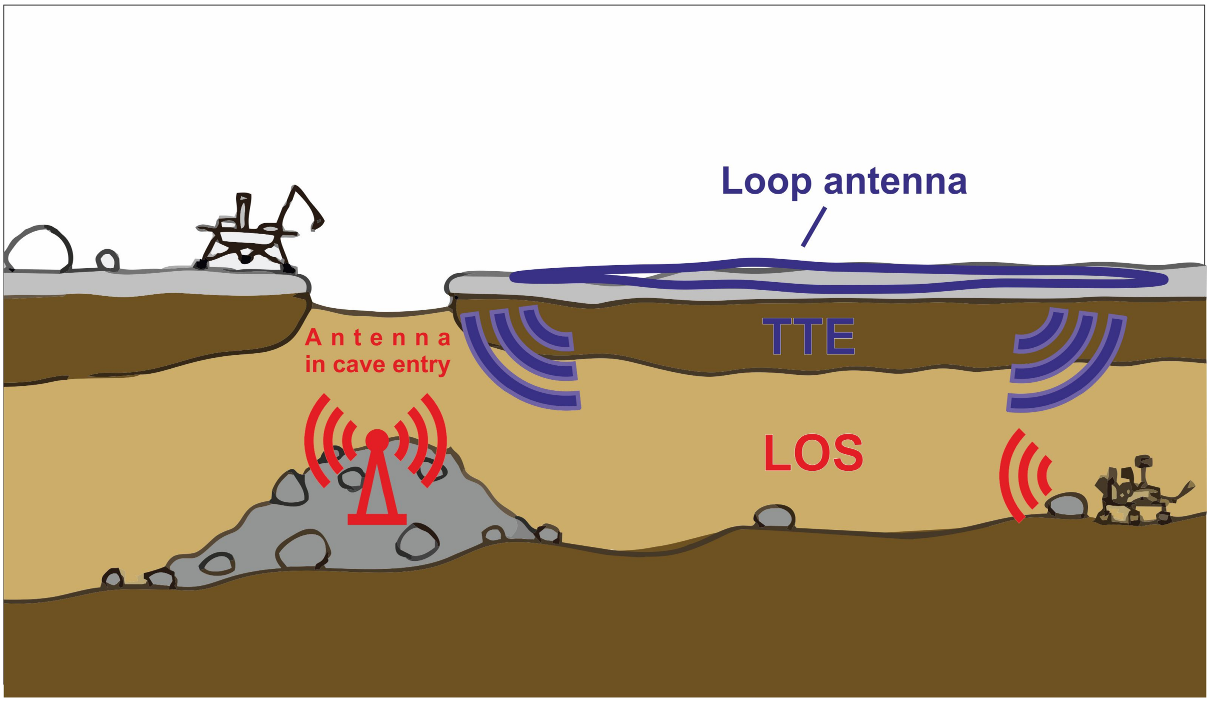

Figure 18: Implementation of the communication system, based on [27]

Through-The-Earth (TTE) signalling is a type of radio signalling used in mines and caves that uses low frequency signals (300-10000 Hz) that can travel through tens of metres of rock layers. The antenna cable can only be on the surface and provide coverage in the cave. The antenna is placed in a "loop" formation around the perimeter of the cave for better coverage. Transmissions propagate through the rock layers, which are used as a medium to carry very low frequency signals. Because the signal travels through the rocks, the antenna does not need to run in all parts of the cave to achieve wide coverage. An important factor for TTE is the electrical conductivity of the rock layers. Research in this area is very limited when it comes to basalt/regolith and other materials found on Mars. Temperature and pressure are also important factors. Knowing that basalt is generally a poor conductor and based on available research, we can estimate its conductivity as similar to dry limestone, and based further estimates on that material. This estimate may be wrong, but at worst it may reduce TTE throughput and coverage, but will not make it inoperative. In case of poor TTE performance, we are left with a LOS antenna that shouldn't have major obstacles. By using low frequencies due to diffraction, radio waves can travel as ground waves that follow the surface contour. This provides excellent coverage over the entire length of the lavatube, even for sloping surfaces. The TTE antenna is connected to the base power supply, the LOS antenna uses battery power, charging is done while the rover is basing. Lastly the rover itself has it's own LOS VLF antenna. The system is estimated to provide real-time data transmission at a rate of 2.5 kbps through at least 600m of rock layers, with a horizontal orientation range of 100km [28, 29]

7 Power System Design

In our rover we decided to use MMRTG - Multi Mission Radioisotope Thermoelectric Generator. This power source is used in NASA rovers such as: Perseverance and Curiosity.

After years of testing and operating in Martian conditions it is recognized as reliable, stable and resistant to harsh environmental conditions.

The technology is based on the radioactive decay of plutonium. A large amount of heat is generated during the decay process. This heat is transported to one end of the thermocouple while the other end is cooled. Due to the temperature difference, electricity is generated according to the Seebeck effect. The MMRTG used on the rover uses a skutterudite material to connect the cold and warm ends of the thermocouple. This material conducts electricity like metals but is heat resistant like glass, making it possible to generate electrical voltages while maintaining the high thermal resistance of the device. Another advantage of the generator itself is its weight. With a load of only 5 kg of plutonium dioxide, the generator can operate continuously for about 13 years of the Martian mission[30, 31]

The rover's power source, thanks to the MMRTG, generates 110 watts of power at the start of the mission[30]. Thanks to the very low rate of plutonium decay and the efficient way of generating voltage using skutterudite material, the efficiency of the generator decreases by only a 1 watt per 80 sols[32], which even after years of operation allows for full use of the device. Compared to solar-powered generators, MMRTGs are much more reliable for missions on the surface of Mars and inside caves. Solar power generators are efficient, but their very big disadvantages are that they are very sensitive to high temperature changes, susceptible to meteorological conditions such as dust storms, and depend on access to sunlight. Moreover, solar power generators must be kept clean because any contamination reduces their performance[33]. On the other hand, a radioisotope thermoelectric generator can operate under all meteorological conditions with the same efficiency, it is not sensitive to temperature changes and is not dependent on access to a light source.

Another reason we have chosen MMRTG is to continuously power the rover's subsystems and equipment. With solar panels at night, the rover would have to rely on pre-charged batteries during the Martian day and access to light (e.g., outside the cave or in a cave-in area where light would enter the cave). With our generator, all devices on the rover are powered by constant voltage. Additionally, a lithium-ion battery is charged for use during unexpected peaks in electricity demand.

The generator as a radioactive isotope is insulated with materials such as boron or cadmium alloys to prevent radiation from escaping the MMRTG and being exposed to other parts of the rover. If the insulation of the generator breaks, there is a possibility of radiation escaping. However, based on NASA's MMRTG document, the chances of this are minimal and even if the insulation breaks, the radiation escaping would be at a dose of 210 millirem[34], which compared to the annual radiation dose that average U.S citizen experience on Earth (620 millirem)[35] is very low dose and would not affect, for example, soil/wall/ceiling samples stored in the rover during the mission.

Summing this up MMRTG is better energy source solution for Martian mission than solar energy generators due to bigger reliability, constant power supply and efficiency in any conditions. At last, another advantage of MMRTG is its weight, which in our rover amounts to 20kg.

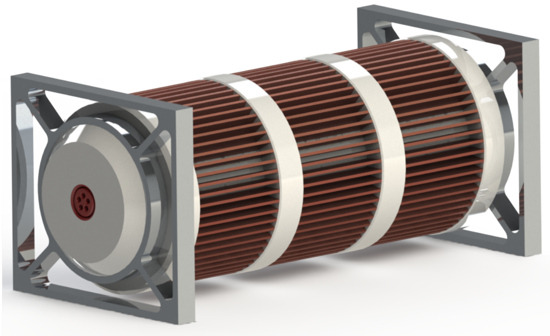

Figure 19: MMRTG with radiators and clamping rings used in Legendary Rover

8 Science Package Design

8.1 Science Package System Overview

Martian Atmosphere Analysis

The system for Martian atmosphere analysis consists of a sealed container, a sealed closure, a HEPA filter, a temperature sensor and a heater and a gas and humidity sensor assembly. It can measure relative humidity, temperature and relative abundance of various gases on Mars surface and inside the lava tube. The container is placed horizontally inside the frame under the robotic arm and houses all the sensors and the heater. The horizontal position prevents damage and falling into the container small debris broken off during sampling from the cave ceiling. On the inlet to the container there is a HEPA filter in purpose to prevent from entering the dust which can be carried by the wind. A description of how the system works, why the heater should be used and how the test should be conducted is discussed in the Environmental Analysis Process Design subsection.

The sensors used in the container are:

- group of combined AGM sensors (measures Xe, Ne, Ar)
- group of combined AGM sensors (measures O_2, N_2, NO, SO_2)
- OEM gas analyser (measures CO, CO_2, additionally CH_4)
- used on the Curiosity Rover Vaisala HUMICAP 180RC humidity sensor (full measurement range $0-100\%RH$) with integrated $PT-100$ temperature sensor (measurement range from $-200°C$ to $850°C$)[36, 37, 38, 39]

Each gas sensor has an operating range that allows it to measure the relative abundance of selected gases.

Martian Soil Analysis

Martian soil analysis system consists of:

- Rocket Sampling Mechanism
- Robotic Arm
- modified Luminometer with 10 slots based on PD-30

The test that was used on the rover involves ATP/ADP/AMP measurement. Adenosine phosphates are the main energy compound of living organisms, so their presence in the tested samples shows the presence of living organisms. The analysis lasts several minutes. A luminometer with test inside containing the luciferase enzyme that will be used for this purpose. Luciferase is an enzyme that catalyzes the transformation of luciferine into oxyluciferin, which has a side effect of light emission. The luminometer used in the study has a reactivity 10-15 times higher than standard luminometers due to the detection of AMP.

8.2 Environmental Analysis Process Design

During the atmosphere analysis the gas measurement process is as follows. Rover during its work opens the container and closes it with the collected sample of the atmosphere. If the temperature measured by temperature sensor is above $-70°C$ the measurement of relative abundance of gases is carried out immediately. If the temperature is below $-70°C$, the air in the container is heated until it reaches at least $0°C$. The entire heating process is monitored and the data is recorded. Measurements of the amount of gas due to the constant volume of the container (only the temperature and pressure change) will be the same at each sample temperature, and the measurement itself will be performed correctly due to the sensor range matching the appropriate temperature. Then, knowing the constant volume of the container and the temperature at the point in time, the thermodynamic equations are used to determine the graphs of humidity versus temperature for the range from $-70°C$ to $0°C$. The rest of the graph for temperatures beyond the range of the sensor is approximated with high accuracy using previously collected data and based on the graphs from $-70°C$ to $0°C$ range.

During the soil analysis samples collected by a rocket from the ceiling/walls of the cave or by a manipulator from the ground are placed in a special container from which they then fall into a luminometer. The container is constructed in a way that allows the rocket to be placed with its head down, so that the sample falls into it by gravity. After the sample falls into the luminometer, it rotates and places an empty probe under the container ready for measurement. The luminometer can take up to 10 measurements, then the astronaut at the base must replace the probes with new ones.

9 Rover Budget Summary

Mass budget

Section	Subsystem	Part	Count	Unit [g]	Overall [g]
Mechanical	Manipulator	Gear reducers	7	514	3598
		Gears	7	-	5015
		Duralumin elements	N/A	1650	1650
		Accessories	N/A	224	224
	Suspension	Swingarm	8	312	2496
		Shock absorber	4	86	344
	Drive	Wheel	4	1355	5420
		Motor	4	3000	12000
	Frame	-	1	2200	2200
	Plating	-	1	324	324
	Mast (fully assembled)	-	1	1200	1200
	Rocket complex	Rocket	1	400	400
		Rocket launcher	1	2000	2000
		Rope mechanism	1	2200	2000
Power	Power module	-	1	20000	20000
Electronics	Electronics hardware	Computing Unit	1	800	800
		Logics MCUs, sensors	11	N/S	1350
		Cameras	6	49/55	300
		Radar	1	5000	5000
		Accessories	N/A	N/A	~300
		Radio tranceivers	3	N/A	350
Total					64971

Table 2: Rover's mass budget

Power budget

As mentioned earlier, MMRTG provides 110 watts of constant power. Additional Li-Ion batteries provides provide power for additional electricity demand. All used system require about 160 watts of power but it's important to notice that they rather wouldn't work at the same time (for exaple robotic arm and communication antenna will be inactive during rover motion)

Subsystem	Power consumption
LIDAR	Idle- 15 Active - 25
Comms	20
Central computer	15
Electronics (Boards)	20
Sensors	20
Drive	37
Robotic Arm	21
Summary	158

Table 3: Rover's power budget

List of Figures

List of Tables

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