Telerobotic Mars Expedition Design Competition

PROJECT LATE

INNSPACE TEAM

PROJECT SUPPORTED BY:

HOYA

FOR THE VISIONARIES

The main question that humanity is looking for an answer is: Are we alone in the universe? Finding life on the surface of Mars is highly unlikely. Conditions on Mars are not conducive to survival. Large fluctuations in temperature, radiation, and dust make finding life difficult. We need to find a place that is characterized by stable conditions - it is best to go underground. Drilling into the Martian surface is not a simple task, as we already saw in the Insight mission. We decided to look for natural spaces whose construction provides them with protection against external conditions. These spaces are lava tubes.

1 Lava tubes

The lava tubes on Mars are the remnants of flowing lava that form underground tunnels with a circular or arched shape. Similar lava tunnels can be found on Earth, for example in Hawaii. Due to the lower gravity on Mars, which is only 38% of the Earth's, the lava flowing on Mars could create tunnels with a larger cross-section than on Earth. Martian lava tunnels have yet to be explored, and little is known about their geology and formation. Their presence was discovered thanks to the craters created by a meteorite impact that filled the ceiling of the tunnel. Thanks to the holes created, we could confirm the presence of lava tuber on Mars.

Lava tubes can be an ideal candidate for the search for life. Down the tunnel the temperature should be constant and its fluctuations should be small. A thick layer of regolith protects the tunnel environment from radiation. That's why life had a better chance of survival and the chances of finding it by sent robots are higher. They are a very interesting exploration target, not only in terms of science, but also in terms of future Mars exploration. They are considered as a **potential location for building a base on Mars** as well. In addition, there may be frozen water in which we can look for signs of life, and in the future it can be used to supply the base with this element necessary for survival. We can provide answers to key questions bothering humanity, while preparing for a crewed mission to the Red Planet. **The study of lava tubes, however, is a key element in further human exploration of Mars**.

1.1 Why are lava tubes scientifically interesting?

The lava tubes environment represents the primary environment, which allows us to conduct research related to the search for life or its traces. Certain geological processes, due to temperature and pressure fluctuations, as well as chemical modifications of minerals contained in rocks, result in the formation of various rock formations. Thanks to the newly formed deposits and minerals, abiogenesis and the emergence of inhabited micro-worlds can occur.

One example of such phenomena is the transformation of peridotite into serpentine. Peridotite - a fiery, ultramafic rock containing silica, iron and magnesium. Lava tubes offer a potentially wide variety of microbial environments. Due to the geological structure of lava tubes, which allows the above-mentioned processes to occur, there is a possibility of the presence of lithotrophic and endolytic organisms. The research we are proposing will also aim to broaden our current knowledge of lithotrophic microorganisms, and in particular, how they contribute to the release of biogenic elements inside micro-niches that stimulate a prosperous life. These microorganisms crush rocks / minerals containing a phosphate anion such as apatite, vivanite and other bioavailable inorganic and organic compounds. This is the reason why these are the elements we will be looking for. All the conducted experiments will help us discover and model how the first organisms influenced micro-environments in the early stages of the Earth's development and how micro-environments influenced the origins of life. This will help us understand how we can survive on Mars and other exoplanets in general.

1.2 How is it going to meet our plans of sending crewed mission to Mars?

In addition to looking for life, our mission is to prepare for the first crewed missions. The concepts of the first Mars bases take into account the creation of such **a colony in the lava tunnels**. The preparation of tunnel maps will allow us to prepare for the creation of such a base in these tunnels, and learning about the composition and construction of the tunnels will allow us to check whether these tunnels will be sufficiently durable for this purpose. Let's not forget about water - finding it in lava tubes would be of great importance for the success of the future mission, and there is a high probability that we will find deposits of it inside lava tubes.

1.3 Conclusion: our chosen location is Coprates Canyon area

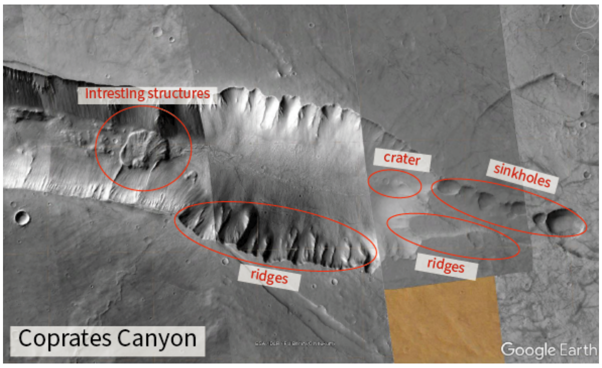


Figure 1: Coprates Canyon

We decide to choose the location where we suspect to find a large number of lava tubes (existing of some of them is already confirmed), in which there are also other areas of interest to us. The mission's target is Coprates Canyon, located next to Coprates Chasma. It is part of the Valles Marineris canyon system. The canyon is easy to exploit, there are small differences in altitude, which is confirmed by the data from the JMARS program presented in the pictures below. You can see that its depth is about two kilometers. Its slope at the steepest parts is about 30%. The robots currently in use on Mars are vehicle capable of 45%, and for safety it is limited to 30% for the duration of the mission. This canyon combines many variants of sinkholes. The satellite photos show the chains and ridges. They are mainly formed when the lava tubes collapse, so we can assume the presence of the lava tubes entrances. In the canyon and Lava Tubes there may be found such materials as: pyroxenes, iron phyllosilicates (along the walls, in the walls - in many places), phyllosilicates, calcium pyroxene, peridotite, serentynite - important in that they contain magnesium, iron, aluminum, silica, apatite, as well as sedimentary rocks/sedimentary minerals (clays, solids). In addition to the Lava Tubes in the canyon and the surrounding area there are also rampart craters which indicate surface volatiles/ground-ice or, in other words, water. Valles Marineris is believed to contain relic ice in regolith - which is extremely important for the construction of a future Mars base. There are mud vulcanos in the area, which are very attractive in terms of mineral exploration, there are organic salts that can be helpful in oxygen extraction. We also have many young impact craters that are important for crater counting. In addition, on the edges of the canyon we can also find craters, ridges and sinkholes.

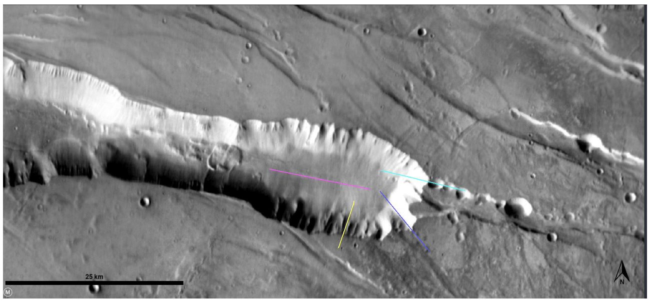


Figure 2: Examining the slopes - selected paths

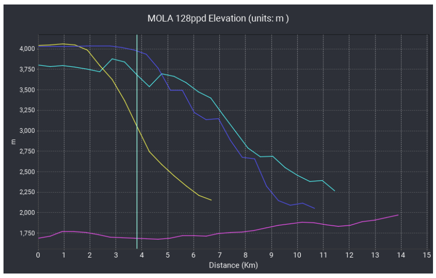


Figure 3: The plot of the slopes of the paths marked in the picture above

That's we we decided to split our mission for two parts. 2 platoons are going to examine the lava tubes inside of the canyon and two platoons will stay at the top of the canyon to explore mentioned areas (craters, mud vulcanos) there in terms of looking for life, as well as prepare for crewed mission. This way we are able to examine bigger area as well as minimize the risk of determining Coprates Canyon as unhabitable for the future crew.

Landing will take place next to the crater. We do not have data on the landing ellipse of the lander, so we are unable to determine the possibility of landing in a crater in order to speed up the mission. If the lander were able to land with the same accuracy as the Perceverence rover lander (7.7 *km* x 6.6 *km*), we would be able to land at the bottom of the crater because it is at least 8 *km* wide.

2 Get to know Project LATE

The challenge is to propose a mission with a huge scientific output that will answer the key question about life on Mars, designate a site for a crewed mission and make the first preparations for it. The huge challenge is the limited payload, the significant risk of failure, and the still little information about Mars and what awaits us. Robots are a key component of crewed missions. Before we send a human on such a long and dangerous journey as the flight to Mars, we must carefully examine this planet and prepare the appropriate conditions for our crew. To set foot on Mars anytime soon, we can't ship one robot every few years. We also need a very good reason to mobilize governments from all over the world to allocate significant resources to such a mission, as no country can do it on its own.

That reason would be to find life. Such information would put the whole world on the alert. Therefore, we must move to places that have the best living conditions and search as large an area as possible to increase the likelihood of breakthrough discoveries. We have to go underground. Lava tubes are a promising area, but completely undiscovered. We do not know what we will find in them and how to select the best caves for research. That's why we proposed **LATE (LAva Tubes Explorers) mission with 4 riding, 24 walking and 116 flying robots**.

To carry out a complex operation in a harsh environment on Mars, it is necessary to rely on the diversity of robots in selected platoons and sections, as well as redundancy. To be able to explore a large area of terrain in a short period of time, it is necessary to have a large number of robots. There are 4 robotic platoons in the lander, whose main units (commanders) are large mobile transporters. This platoons consists of five types of robots:

- transporter rovers - riding robots based on Curiosity and Perseverance, responsible for delivering the walking robots to the Lava Tubes and supplying them with power via MMRTG / Kilopower (to reduce the number of necessary reactors = lower total weight of the robots),
- walking robots - adjusted Boston Dynamics Spots, responsible for scouting the lava tunnels and creating 3D maps of lava tubes,
- two types of flying robots - rotorcrafts and tilt-rotor aircrafts, responsible for reconnaissance and sample transport,
- Minibots powered by small jet engines to explore narrow passages.

3 Transporter rover

The transporter rover serves as the platoon leader. Its job is to transport and charge Spots from the walking section, transport Minibots, transport collected samples, drill boreholes, service minor malfunctions in the robots and communicate with the lander. The transporter rover consists of components with a TRL of no less than 6, components were taken from the Curiosity or Perseverance rovers. The rover's rocker-bogie suspension was selected as a reliable, tested on Mars subsystem and scaled to meet the needs of the transporter. The rover body consists of lightweight, high-strength composites attached to an aluminum truss. The rover is powered by two Kilopower units of 1 kW each (one to charge the Spots, the other to operate the transporter). Above the Kilopowers are radiators used to control the temperature inside the transporter. On the front of the rover there is a closable place for placing samples collected by the Spots and on the top there is a place for 27 Minibots. The Spots placed inside are inductively charged using a WiBotic's panel.

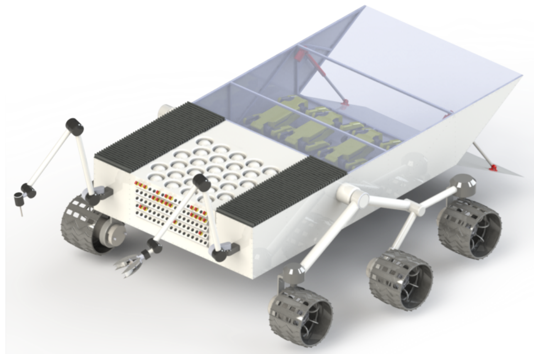
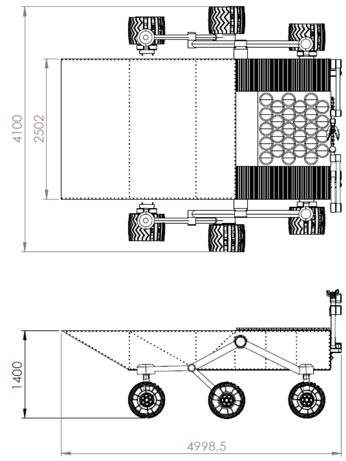
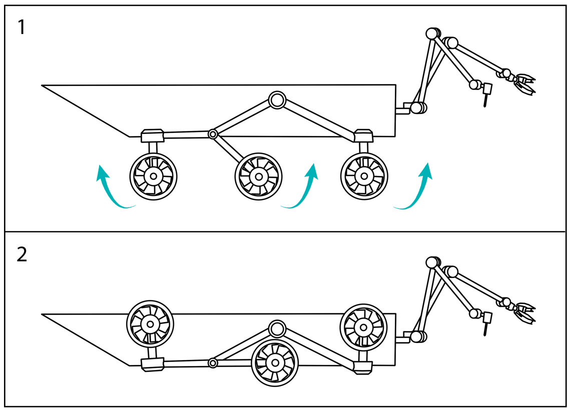


Figure 4: Transporter rover

3.0.1 Power supply of transporter rovers

The transporter rover is powered by a 2 Kilopower 1 kW generator that uses nuclear fission. To minimize the mass of the generator it was decided to use HEU (Highly Enriched Uranium) as a fuel, which can be 700 to 800 kg lighter compared to LEU (Low Enriched Uranium). In the case of the transporter rover, each of the 1kW-HEU Kilopower used has a mass of 339 kg. .





3.0.2 Scientific instruments in transporter rovers

Transporter rovers are equipped with 2 key instruments: **XRF (X-ray fluorescence) spectrometer** for testing the chemical composition of rocks and **NIR (Near-Infrared) Imaging Cameras** for assessment of the mineral composition of rocks, evaluation of specific minerals.

XRF measures elemental chemistry at sub-millimeter scales by focusing an X-ray beam to a tiny spot on the target rock or soil and analyzing the induced X-ray fluorescence. The instrument consists of a main electronics unit in the rover's body and a sensor head mounted on the robotic arm. The sensor head includes an x-ray source, X-ray optics, X-ray detectors, and high-voltage power supply, as well as a micro-context camera and light-emitting diode. In result we are able to determine the presence of such elements as sulfate, sulfide search - the indication of presence of water in the past. Can also detect Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Br, Rb, Sr, Y, Ga, Ge, As, and Zr.

NIR Imaging Cameras is the pencil-beam infrared spectrometer that will measure reflected solar radiation in the near infrared range. The instrument works in the spectral range of 1.15–3.3 μm with the spectral resolution of 25 cm-1. The optical head is mounted on the mast, and its electronics box is located inside the rover's body. Main goal are: mineralogy characterization and remote identification of water-related minerals, contributing to the selection of suitable samples for further analysis and geological research. What's more, NIR Imaging Camera enable us characterization of the composition of surface materials, discriminating between various classes of silicates, oxides, hydrated minerals and carbonates, identification and mapping of the distribution of aqueous alteration products on Mars as well as real-time assessment of surface composition in selected areas, in support of identifying and selection of the most promising drilling sites. Thank to this instrument we are able to conduct studies of variations of the atmospheric dust properties and of the atmospheric gaseous composition.

The rover will also have basic sensors for determining environmental parameters and sensors for 3D mapping and movement in the field. For navigation and mapping, it will use a set of stereovision cameras with illuminators, a set of navigation cameras with illuminators, thermal imaging cameras and lidar. They will create a spatial map around the rover. The sensors for studying the space around the rover are based on devices from previous Martian missions.

4 Spots

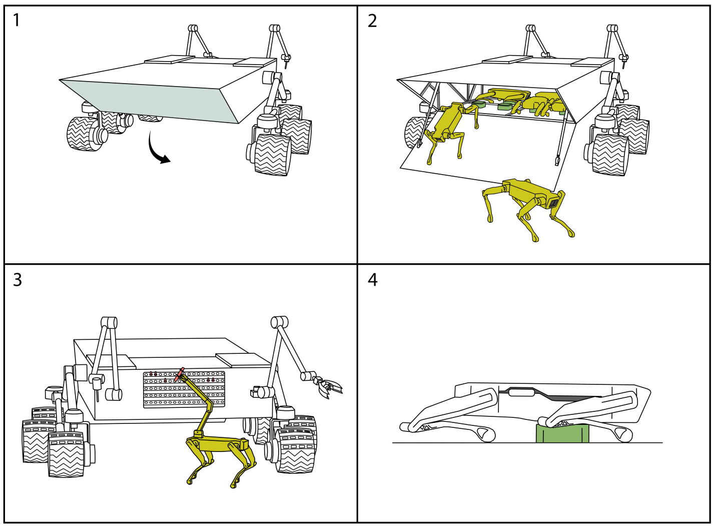


Figure 5: Transporter rover with Spots and Minibots inside

To explore a large area of Mars in a short period of time, the platoon of robo-dogs model was adopted. During the mission, each of the transporter rovers that provide shelter and power to the robo-dogs and Minibots goes to explore a different place of scientific interest. Whether mapping terrain, collecting samples, or taking pictures, the robots are spread out around the transporter rover.

Walking robots are used to explore caves and tunnels and aggregate data about them in order to create 3D maps of the studied areas. These robots will have a set of sensors in the form of stereoscopic cameras with an illuminator, thermal imaging cameras and lidars. Cameras and lidars will be helpful in determining the route of robots, and lidars, thanks to greater accuracy and range than cameras, will create a map of areas inaccessible to cameras. The prepared 3D models of the tunnel interiors will be used both by robots (in real time) to determine the route trajectory and Mission Control Center to identify potentially interesting places. They play important role in future crewed exploration and building a Mars base as well. When a geologically interesting site is found, the rover transporter stops. It then opens the tailgate and allows the robo-dogs to quickly explore a large area. Thanks to their speed of up to 1,6 *m/s* and an operation time of 90 *min* (including 3 *min* to enter the loading dock of the transporter), the 6 robo-dogs are able to cover a distance of about 50 *km* during a single course.

4.1 Robo-dogs charging

Spots are charged wirelessly using the WiBotic onboard charger. Wireless charging has a number of advantages: no charging ports that can get clogged with dust, no protruding parts in the rover transporter, no need for a perfect match between transmitting and receiving coil (no need for contact). This solution has been tested in a simulated lunar environment.

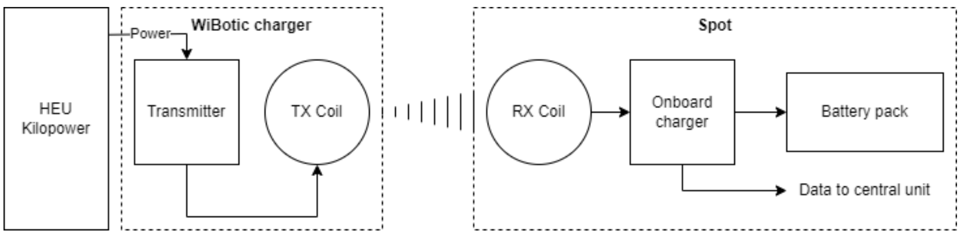


Figure 6: Charging of Spots

4.2 Communication and navigation

The communication system must meet the following requirements: ability to transmit a signal across the surface of Mars into a cave, ability to send a signal over a 5 km lava tube distance (terrain with a possible significant slope) and supporting different types of transmission modes, such as data transmission and real-time data transmission. Proposed design is a mixture of VLF Through-the-Earth (TTE) and Line-of-sight (LOS) communication. 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 10 kHz. 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. 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. Considering the lava tube's unknown shape and profile resulting in high risk of losing the robot that gets in to explore, very low frequency radio communication seems the most reliable and mass efficient.

To navigate, robots will scan full 360° area around themselves and measure cave height to prevent the rover from touching the cave ceiling. During operations in case the rover may lose signal from base, they are able to autonomously calculate and execute a way back to base or nearest transporter rover. Navigation algorithm would use a dead reckoning process. Spot's kinematic model will be implemented to determine which route is accessible by the robots. To achieve that, Spot's are equipped with thermographic cameras for imaging and mapping the inside of the lava tube using infrared radiation and initial assessment of mineral composition and lidars for making high-resolution maps.

5 Aerial vehicles

We proposed two different aerial vehicles: tilt-rotor aircrafts and rotorcrafts. The main purpose of flying vehicles is photogrammetry and terrain mapping. The tilt-rotor aircrafts are used for reconnaissance, their role is to explore as much terrain as possible as quickly as possible, making it possible to create accurate 3D surface maps that will help in further mission planning. Rotorcrafts will be responsible for geological research and a detailed exploration of distant (for the rover) Points of Interest to help in the classification of targets. The tilt-rotor aircrafts will not be able to land just before the entrance, so sending hexacopters there with a camera and a lidar will allow to determine what the entrance to the tunnel looks like and to map its initial several dozen meters.

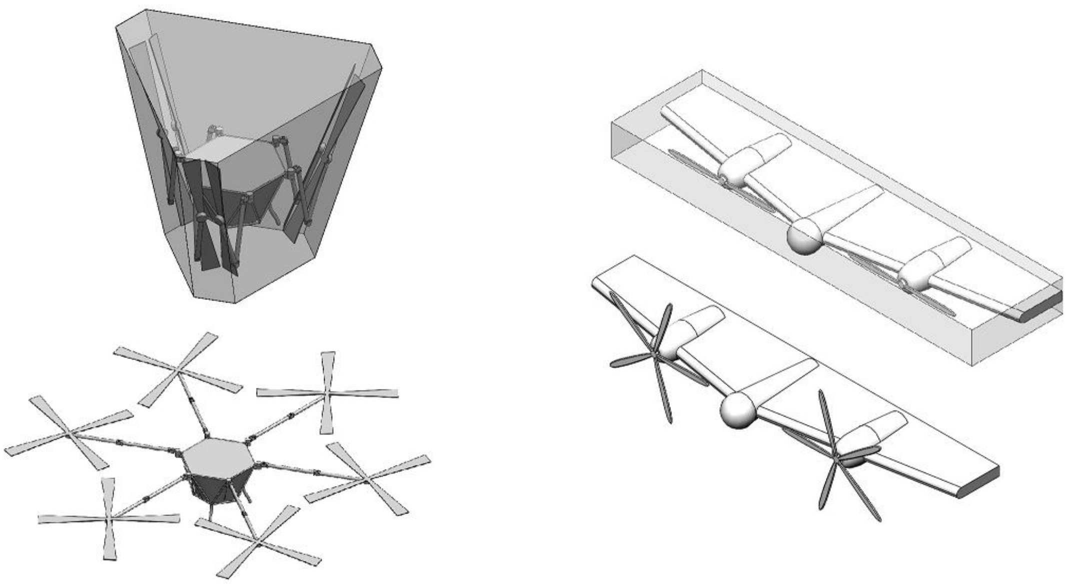


Figure 7: Rotorcraft and tilt-rotor aircraft stowed and deployed

5.1 Rotorcraft

Research shows significant potential for scientific operations on Mars using a hexacopter of about 30 kg, housed in a 2.5 *m* diameter aerodynamic envelope, which can lift a 5 *kg* payload for 10 *min* of flight or a distance of 5 *km*. A rotorcraft allows conducting detailed observation thanks to its hovering ability.

5.2 Tilt-rotor aircraft

The proposed UAV design belongs to the tailless type aerial system. The propulsion system of the UAV consists of two five-bladed counter-rotating propellers, each driven by a single brushless electric motor, located in offset nacelles. The aircraft is assumed to take off from an upright position; then, depending on current requirements during a given phase of flight, it may remain upright, in "hover," or change orientation to horizontal, transforming into an aircraft. The center section of the wing is self-supporting, and the wingtips can be separated, leaving most of the control surfaces necessary for hover-mode flight control. This particular configuration is used, for example, in transport missions - when the wingtips are detached, the drone loses the ability to fly horizontally, which simplifies control, and the center of mass is shifted backward. The horizontal flight capability is useful when you want to scout a large area, or an area remote enough that you need to get to the mission site fast enough to not lose power while flying to your destination. This capability comes in handy when making orthophotos.

5.3 System architecture

Each of the proposed aircraft designs is unstable (every rotorcraft is unstable by design in the case of a helicopter and the flying wing concept is causing instability in the case of fixed-wing aircraft) and needs to be controlled with a closed-loop feedback system. To provide sufficient and reliable measurements necessary to control the aircraft and meet the criteria described in High-Level requirements and risk assessment, a conception of a comprehensive flight control system (FCS) was developed. An identical system has been designed for both rotorcraft and fixed-wing aircraft since they require the same set of data to reduce development time and costs. FCS consists of the following elements:

Flight computer (FC) - it's the main component of aircraft avionics. It receives signals from all sensors and assesses them with the Fault Detection, Isolation, and Recovery System (FDIR) which checks data integrity and accuracy and in case of detected sensor fault reconfigures the system to acquire correct data from redundant sensors or estimates of faulty measurements. All control system algorithms run on FC and steering inputs are sent from FC to actuators (control surfaces, motors).

Mars Integrated Guidance and Navigation Unit (MIGNU) - is designed as Linear Replacement Unit, which means it could be easily unplugged and replaced without requiring system reconfiguration. MIGNU contains all necessary sensors required to control the aircraft and perform basic scientific measurements. The aircraft's avionics system is equipped with two MIGNUs, primary and secondary, to provide redundancy and high-level fault tolerance, guaranteed by internal data validity checking and self-testing capability as well as by external assessments performed by FC.

The following sensors are integrated into MIGNU:

- The attitude measurement section is composed of an inclinometer, gyroscope, and accelerometers to determine the aircraft's orientation. Reading of angular speeds and linear accelerations are combined by an extended Kalman filter to obtain the aircraft's position in the Mars reference frame (similar to the Earth reference frame)

- Air Data sensors include static and dynamic pressure sensors to measure altitude and airspeed, hygrometer, outside temperature sensors, and gas sensors.

- The obstacle sensing unit consists of the LIDAR altimeter to provide the exact altitude above ground level (as the pressure sensor provides barometric altitude readings, which are subject to errors due to differences between the pressure to altitude conversion model and actual atmosphere parameters) and 360-degree lidars to detect the obstacles in the horizontal plane.

- Machine vision unit. Two cameras are used to increase guidance accuracy. The Dome nav camera performs a dual function. During day flights it's used to track the Sun and determine an aircraft's yaw angle (course). During the night, when aircraft are staying on the ground it tracks stars to determine the aircraft's geographical position on Mars which is used to reset Inertial Navigation algorithms as they are integrating sensors measurements (also measurement errors) and thus need to be regularly updated with precise initial conditions. Orthophoto cam is used in surveillance of interesting areas and combined with Interial Navigation System allow to further increase its accuracy.

Sensor fusion plays important role in providing reliable and accurate data used in control systems.

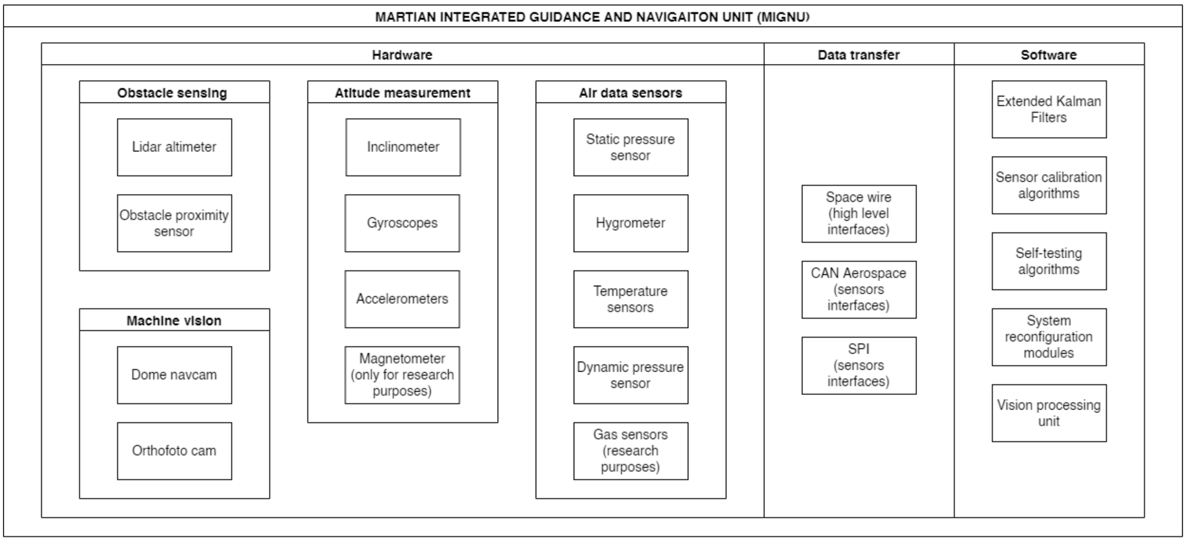


Figure 8: Mars Integrated Guidance and Navigation Unit (MIGNU)

5.4 Power system

The drones' primary power source will be solar panels. By locating them in the vertical plane in the case of an airplane (after landing) and under the propellers - in the case of rotorcraft - the problem of dust covering the panels will be eliminated. As an emergency option, wireless charging by a rover sent from the base can be used.

5.5 Scientific instruments

As one of the function of flying vehicles is conducting research, in addition to mentioned above sensors, Ground-penetrating radar is attached to them. **Ground-penetrating radar (GPR)** is a non-destructive geophysical method of surveying media such as soil, rock, fresh water, and ice that uses radar pulses to image the subsurface. In short, it's our eyes through the surface of the ground. A drone-mounted GPR can perform surveys in a fast manner with a high degree of automation by following pre-planned missions while also being usable in inaccessible areas where land vehicles (martian rovers) might struggle on difficult terrain. For geological surveys and bathymetry, the recommended speed is 2 m/s. For underground infrastructure mapping – recommended speed is 1 m/s. Depending on materials, space-tested GPR (as of RIMFAX) will image the subsurface stratigraphy to more than 10 meters in-depth, with vertical resolutions better than 30 cm, and a horizontal sampling distance of 10 cm along the rover track.

In the case of our mission, drone-mounted GPR will be used to find lava tubes and possible entrances quickly. This greatly speeds up the selection process of a lava tube to be explored, as obtaining such data directly from the near surface can even tell us how long a particular lava tube or its branch is.

5.6 Minibots

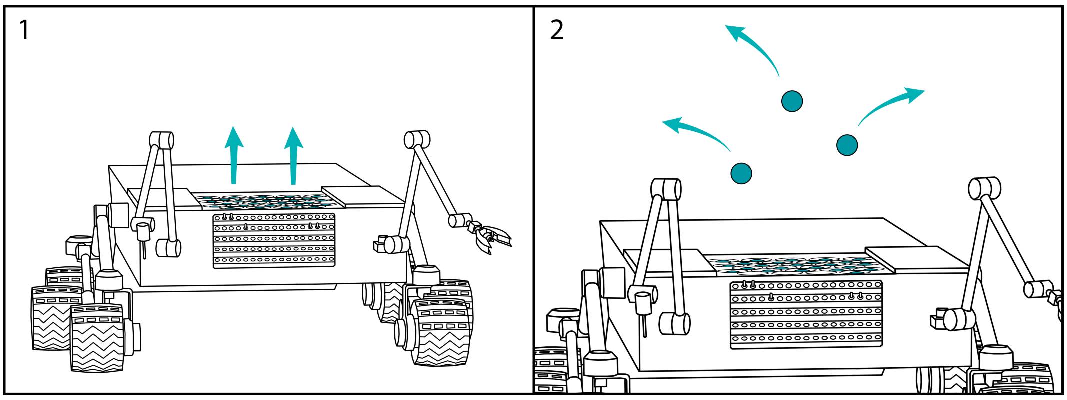


Figure 9: Minibots in transporter rover

Despite using different types of robots to explore lava tubes, we decided to expand our platoons with additional flying robots that are able to explore very narrow or hard-to-reach lava tubes. Minibots are ball-shaped robots with a diameter of approx. 20 cm. They only consist of a few components. They include the housing and frame of the robot, and inside there is electronics in the form of a control computer, batteries, elements for communication with the robot transporter and a stereo camera with an illuminator, as well as a miniature lidar. The main drive is responsible for the propulsion, and the position of the robot during the flight is corrected with a set of small RCS. The camera and lidar are used to study the surroundings and create its 3D maps. This will allow you to assess what is in hard-to-reach places and decide whether in the future it is worth preparing a dedicated scientific mission to this place or it is a place worth exploring by a human during a future crewed mission.

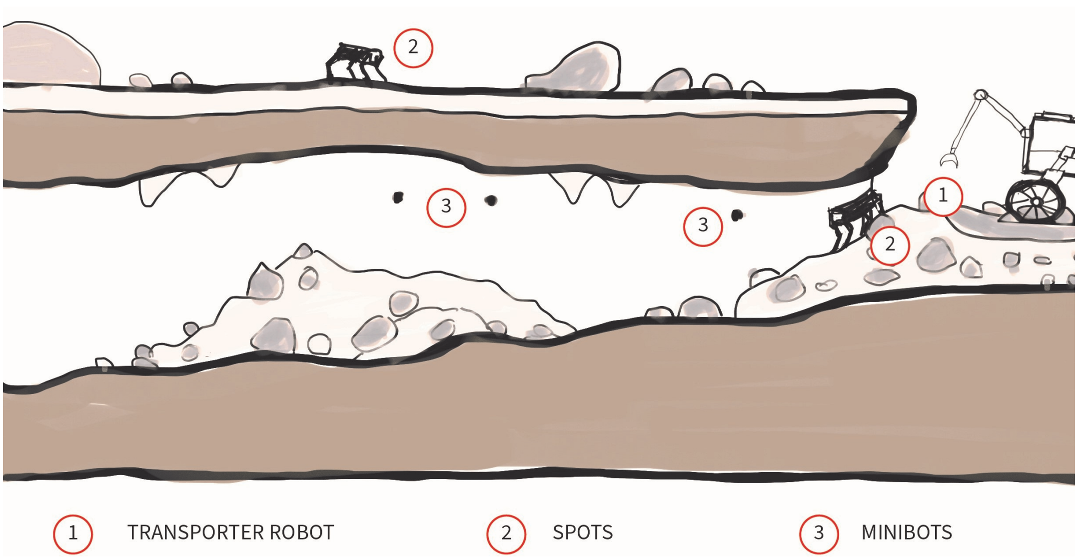
6 Mission stages

6.1 Mission stage I (Landing and reconnaissance)

After landing, the operation of the systems in the hold is checked. These systems are responsible for the maintenance of vehicles during transport (cooling and power supply) and for its proper unpacking after landing. After confirming the operation of all elements, the robots leave the hold. Tilt-rotor aircrafts and hexacopters leave on special disposable platforms. After the landing, all the devices must be checked and calibrated again to adapt to Martian conditions. With calibration targets, the camera adjusts itself to show the correct colors. Meanwhile, the satellite passing over the landing site determines the exact landing site of the lander, and on this basis, scientists set the closest targets to check in the form of promising tunnel entrances. The first recognition is made using tilt-rotor aircrafts due to the large range and speed. The area near the entrance is mapped from the air, as well as the entrance itself. On this basis, it is determined whether a given entrance to the tunnel is located in an area where the robot transporter will be able to move, and the route to it does not have places where the transporter rover could get stuck. Scouting with tilt-rotor aircrafts takes place, which lands before entering the tunnel and scans the first few dozen meters of the tunnel. If the tunnel is clear and there are no obstacles in the fragment we have examined, the journey to the tunnel takes place using a robot transporter. This journey to speed up the entire mission begins with the tilt-rotor aircraft take off due to the differences in speed between flying and riding vehicles.

6.2 Mission stage II (Lava tubes exploration)

After reaching the tunnel entrance, the transporter rover enters an unexplored tunnel. Then the spots are unloaded and scanning of the tunnel begins. They create a map of the tunnel and photograph the tunnel. Then the Spots return to the transporter rover where this data is processed, on the basis of which the next steps are determined. If the Spots come across a place that they are unable to explore, Minibots are sent there. If the Spots come across a place of geological interest, or one where we could look for life, a decision is made to investigate this place more thoroughly by the transporter rover. If nothing interesting is found, the Spots are loaded and the transporter rover moves on and the whole process is repeated.



6.2.1 Mission stage III (Samples collection)

The transporter rover is equipped with a robotic arm, at the end of which is a head with a sampling mechanism. Inside the robot there is a system for collecting and packing the sample into transport containers. The containers is then be intercepted by the walking robots that deliver them to the exit of the Lava Tubes.

The sampling process is complex and has several stages. The first stage is selecting a potential place, during which we follow the following objectives:

- Mars geology, learning about the geological processes and the history of the creation of mars and lava tubes, especially searching for water courses. Learning about the evolution of the geology of Mars.
- Searching for life, discovering the biological history of Mars, along with the return of the sample with potential life back to Earth (the chemistry of carbon and bio-signatures).
- The explanation of the processes that influenced the modification and formation of the mantle crust and the Martian core.
- Searching for dangers that may threaten the future human mars mission, so that we can counteract them but also determining the types and possibilities of using Martian resources to support a potential future Martian mission.

Using cameras and lidar, the space around the robot is mapped. The sampling site can be selected in two ways, either using artificial intelligence algorithms or manually, with the help of scientists on Earth. The selected site is then examined with NIR and XRF instruments to determine elemental chemistry and mineralogy characterization and identification of water-related minerals. Measurements with this instrument are made without contact.

The robot is equipped with two robotic arms with 5 degrees of freedom, about 2.5 m long. At its end there is a set of mechanisms for taking the sample, but also for preparing the surface for sampling. It consists of a brush, a drill for discovering deeper layers, a drill for collecting the core sample and a drill for collecting regolith, i.e. the surface layer of Martian soil. These drills are interchangeable, as well as they are additional 2 spare pieces of each, so that in the event of problems with the drill bit jamming in the material, the robot could detach the drill and continue the mission without any problems.

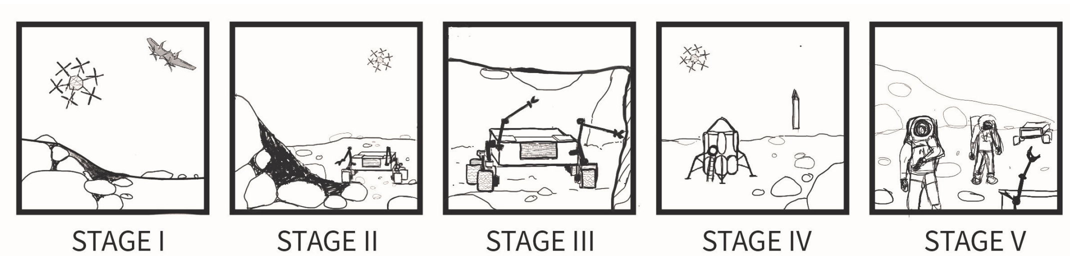
After sampling, the sample goes to the sample handling system. There is a drill hole in the front of the robot, and the system draws the collected material into a clean and sterile tube-shaped container, and then seals it tightly to prevent contamination. The closed sample containers are placed on the front of rover, from which the empty containers are also taken.

6.3 Mission stage IV (Sample return mission)

After the rotorcraft has landed at the lander, the sample is handed over using a robotic arm in the laboratory placed in our lander. The sample is then tested using the Raman Laser Spectrometer, XRD, MOMA and gas chromatograph instruments. We collect and transport several samples from each place. Thanks to this, we will be able to send one of the samples to Earth in the case of interesting test results. After the sample is qualified for sending to Earth, after collecting the appropriate amount of loads, they are transported to the return rocket. Then the rocket leaves the hold in a special cart and moves away to a safe distance from the laboratory, where the rocket launches. The rocket enters orbit, where it waits to be picked up by spacecraft, which will transport it to the ground.

6.4 Mission stage V (Future exploration)

In addition to the research mission and the search for components necessary for future crewed exploration, the robots have been prepared to assist in future crewed missions through a modular construction method. This concept assumes that after searching the Lava Tubes, the robots will return to the lander, where they will be waiting for new task. Before the arrival of the crewed mission, we will have detailed 3D maps of the surface and the canyon, which will allow us to choose the best place to land. Heading towards the Lava Tubes, the rover will look for water, in the form of ice, found in the regolith. In addition, we will examine the Lava Tubes, we will know their geological structure as well as their shape thanks to the creation of accurate 3D maps. One of the concepts of Martian bases includes the creation of such a base in Lava Tubes, which will ensure stable temperature conditions and protection against radiation. Having knowledge about the location of the Lava Tubes entrances, their shape and construction will allow us to design such a base. We will also learn the composition of the surface in that area, which will allow us to determine what materials we can create In-Situ. After completing the mission, the robots are so universal that they can begin preparations for the construction of the base without major changes, and will be able to help people during their stay on Mars. Then, astronauts will be able to replace the modules with those that will be helpful in building the base, e.g. arms with 3D printers, or regolith-collecting excavators, or transform the robot into a material transport vehicle. Rotorcraft can be used to transport light items, e.g. tools, between e.g. a lander and a base.



7 Mars lander

7.1 Payload's weight and placing

One transporter rover with Spots and Minibots weighs 2000 kg. The rotorcraft weighs 30 kg and the Tilt-rotor aircraft weighs 80 kg. In total, all 4 platoons with flying vehicles weigh 8,440 kg. The mass of the return rocket with the rack weighs 550 kg. The laboratory in the lander, together with the power supply and all the necessary elements, weighs 890 kg. **In total, the entire mission weighs 9,930 kg.** We modeled the transported cargo to check that not only the weight, but also the dimensions of the robots and instruments we propose did not exceed the required dimensions.

7.2 Scientific laboratory

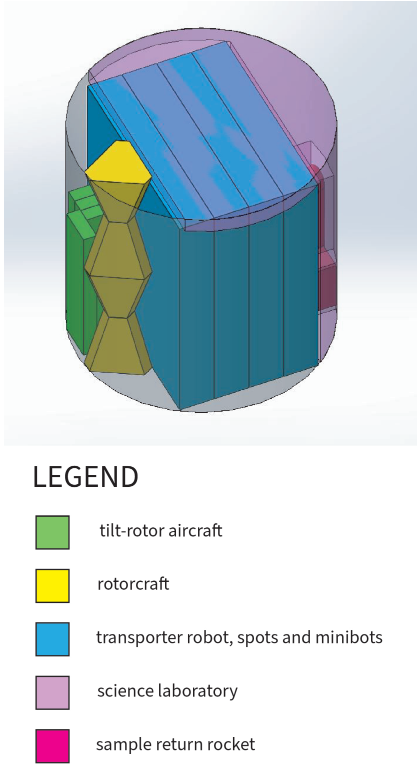


Figure 10: Lander payload

We decided to place some of the scientific instruments in a specially dedicated laboratory located in the lander. This allows us to use larger and more accurate instruments while reducing the weight of the robots. The number of instruments that we are able to put on the transporter rover is limited by dimensions and weight as well as power supply. We do not test so many samples that it would be necessary to have 4 of the same sets, so we decided to create a dedicated space in the lander where the delivered samples are tested by:

- Raman Laser Spectrometer - measurements of solid powdered probes to obtain geological and mineralogical data, identification of biosignatures.
- XRD - used to validate data obtained by Raman Laser Spectrometer.
- MOMA + gas chromatograph - identification of organic molecules in collected solid samples with a mass spectrometer. Gas chromatograph - separation of complex mixtures of organic compounds into molecular components. The device contains a pyrolysis oven to preprocess the sample.

Raman Laser Spectrometer analyses the vibrational modes of a substance either in the solid, liquid or gas state. It will collect and analyse the scattered light emitted by a laser on a crushed Mars rock sample; the spectrum observed (number of peaks, position and relative intensities) is determined by the molecular structure and composition of a compound, enabling the identification and characterisation of the compounds in the sample. RLS measurements will be conducted on the resulting crushed sample powder and it will be a useful tool for flagging the presence of organic molecules for further biomarker search by the MOMA analyser. It allows us to identify organic compounds and search for life, identify mineral products and indicators of biologic activity, characterize mineral phases produced by water-related processes, characterize igneous minerals and their alteration products and characterize the water/geochemical environment as a function of depth in the shallow subsurface.

Powder diffraction of X-rays would have determined the composition of crystalline minerals. XRD instrument includes also an X-ray fluorescence capability that can provide useful atomic composition information. X-ray source, producing a $\sim 70\ \mu m$ X-ray beam that impinges on a sample. This way we are able to identify the concentrations of carbonates, sulphides or other aqueous minerals in order to examine the past Martian environmental conditions and establish the true mineralogical composition of soils and rocks.

MOMA will first volatilize solid organic compounds so that they can be analysed by a mass spectrometer; this volatilisation of organic material is achieved by two different techniques: laser desorption and thermal volatilisation (in the oven), followed by separation using four GC-MS columns (gas chromatography- mass spectrometer). The identification of the organic molecules is then performed with an ion trap mass spectrometer. MOMA helps us to find molecular biosignatures and enables further analysis of Raman Laser Spectrometer.

7.3 Sample return

Returning the samples to Earth allow us to test them in a laboratory on Earth. The assumptions of our return vehicle is a 30 kg vehicle, which is able to carry 5 kg of cargo into the orbit of Mars. The entire rocket, including its propellant, weighs approximately 300 kg. In addition to the rocket, a structure is created that supports the rocket and move it away from the lander during take-off. The rocket is two-stage, with both solid fuel engines. It is admittedly a greater mass cost than in the case of a liquid fuel rocket obtained on Mars, but we gain significantly in reliability and simplicity, and a heavy rocket fuel generator is also unnecessary.

8 Cost and schedule

If we want to send out a few platoons of robots in the coming years, we need to use technology that is at a high level of maturity. In our project, we relied on developed and tested solutions and used scientific instruments that had flew in previous robotic missions to Mars. As many as 3/4 of the technologies have TRL 6 or higher, as shown in the table below. R&D activities consume the most time and resources in space projects, so we are able to implement the assumptions of the competition to send our mission within the next decade. We also estimated how many working days (i.e. single working days of one person) are necessary to complete this task. According to estimates, we need 1,500-2 000 people working on the mission for 10 years. With an increase in the number of people, we can shorten this time, but according to our calculations, 6 years is the minimum to refine all the elements. For comparison, 3,000 NASA employees and 4,000 external specialists worked on the Curiosity rover. Thanks to the proposed approach, the mission is affordable and achievable in the coming years.

Lp	Elements	Previous use/Current development	TRL	What we should do to use this technology in our project	Estimated time [working days]	Estimated development cost [mln]	Estimated manufacturing cost [mln]	Units	Total cost [mln]
1	Rover suspension	Curiosity, Perseverance	9	Rocker-bogie suspension was succesfully used during previous Mars missions. We need to scale the suspension to our needs.	62455	124,9	35,4	4	266,5
2	Rover Body	Curiosity, Perseverance	9	Rover body was succesfully used during previous Mars missions, however we need to prepare onw body taking into account walking robot accomodation and our instuments.	72378	144,8	30,9	4	268,4
3	Rover flap	Used on Earth	4	Rover flap needs proper sealing and possibility for emergency opening by spots in case of linear actuators failure.	75505	151,0	30,9	4	274,6
4	Rover Cameras	Curiosity, Perseverance	9	Rover cameras were succesfully used during previous Mars missions.	97766	195,5	37,9	12	650,3
5	Rover Lidar	Curiosity, Perseverance	9	Lidars were previously used on Mars landers. We need to adapt it to our needs and system.	75571	151,1	34,5	4	289,1
6	Rover Arm	Curiosity, Perseverance	9	Rover arm was succesfully used during previous Mars missions. We need to scale the arm to our needs and develop the end effector.	90220	180,4	37,7	8	482,0
7	Rover Drilling system	Curiosity, Perseverance	9	Drilling systems are currently used in Curiosity and Perseverance rovers with success.	89412	178,8	28,1	4	291,2
8	Rover Sample handling	Curiosity, Perseverance	9	Sample tubes were tested on Mars missions. Sampling and sample handling were also tested during Mars missions. We need to adapt sample handling mechanism but sample size and closing system will be the same	96861	193,7	35	4	333,7
9	Rover power generation/kilopower	Testy	3	Kilopowers prototypes were succesfuly tested on Earth. Kilopower is currently being developed for future lunar and Mars missions. We need to adapt the sizes and structure of kilopower to our needs and prepare to windstand start loads and harsh Martian conditions.	95903	191,8	22	4	279,8

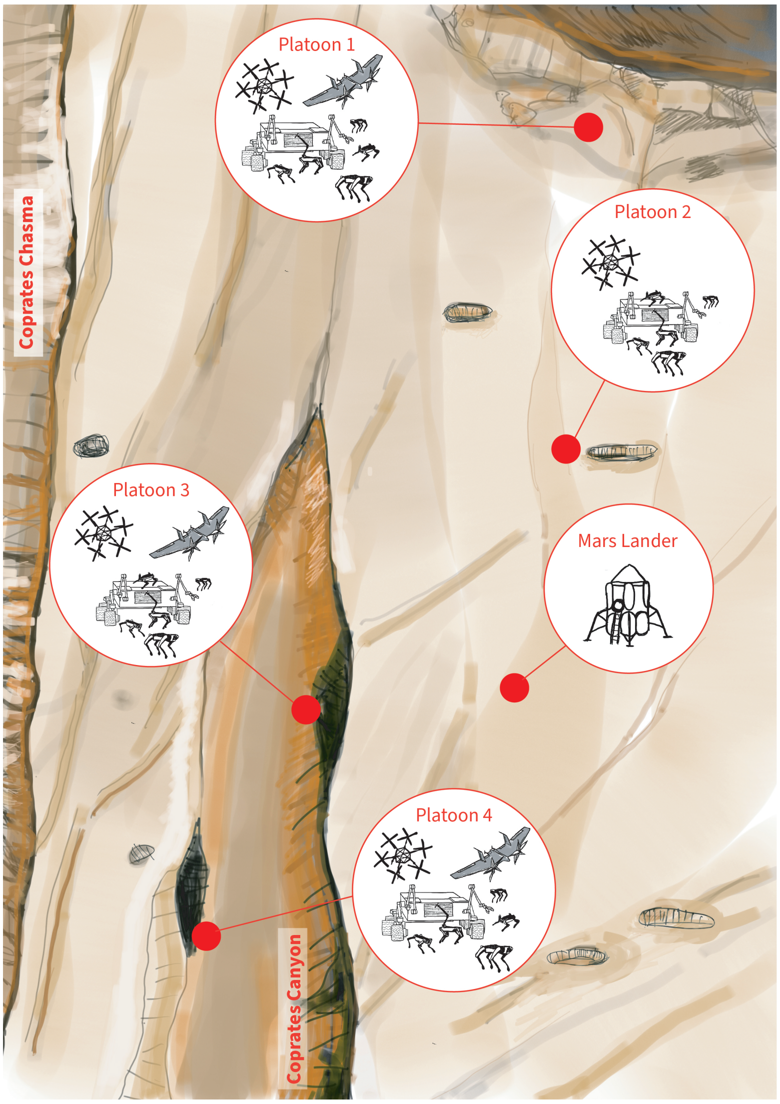
10	Rover Thermographic camera	ESA/National Psysical Laboratory	8	National Physical Laboratory in the UK, successfully converted a boson thermal imager with a weight of 44g by raising its maximum operating temperature from 48.5°C to 60.3°C. It was also able to reach the ESA outgassing standard and calibrated to an uncertainty of ±0.75°C and ±1.05°C at the low and high end of its operating range.	66411	132,8	33,4	4	266,4
11	Rover cooling/heating system	Curiosity, Perseverance	9	Rover radiators was succesfully used during previous Mars missions. We need to scale and adapt the radiators to our needs.	95732	191,5	29,8	4	310,7
12	Rover electronics	Curiosity, Perseverance	9		82962	165,9	20,5	4	247,9
13	Rover software	Curiosity, Perseverance	9		88472	176,9	31,5	1	208,4
14	Rover comunication	Curiosity, Perseverance	4		85440	170,9	26,5	4	276,9
15	Rover -> Spot recharging	NASA tests, Astrorobotic's CubeRover	6	NASA initiative developing wireless charging for lunar robots (therobotreport.com) https://spacewatch.global/2022/06/astrobotics-wireless-charging-system-survives-lunar-night/ We need to adapt sizes for Spots	71384	142,8	28	24	814,8
16	Rover -> Spot electromagnetic connection		6	Electromagnets. Simple magnets were used on Spirit and Opportunity https://mars.nasa.gov/mer/mission/instruments/magnet-array/	78436	156,9	34,5	24	984,9
17	Spot Thermographic camera		6	awio króle/science muszą wpisac	97850	195,7	31,1	24	942,1
18	Spot lidar	Curiosity, Perseverance	9	Lidars were previously used on Mars landers. We need to adapt it to our needs	91279	182,6	39,9	24	1140,2
19	Spot walking system	Used on Earth	6	Joint sealing needs to be improved to withstand martian dust and weather	91537	183,1	32,2	24	955,9
20	Spot cooling/heating system	Curiosity, Perseverance	9	Rover radiators was succesfully used during previous Mars missions. We need to scale and adapt the radiators to our needs.	66842	133,7	23,9	24	707,3

21	Spot battery pack	Curiosity, Perseverance	9	Adapt batteries from well tested rovers eg. Curiosity Perceverence	94180	188,4	28	24	860,4
22	Spot arm system	Curiosity, Perseverance	9	Rover arm was succesfully used during previous Mars missions. We need to scale the arm to our needs and develop the end effector.	68998	138,0	26,4	8	349,2
23	Spot sample transport system	Curiosity, Perseverance	9	Sample tubes were tested on Mars missions. Sampling and sample handling were also tested during Mars missions. We need to adapt it to our needs	81580	163,2	31,4	8	414,4
24	Minibots structure	University of Arizona	2/3	Minibots have the lowest TRL in our system, however they aren't crucial part of our system and in single "wataha" we use a lot of them so faliure a few is acceptable. Overall the bots are very small with limited numbers of subsytem that should be developed. Part of them like sensors, electorincs or battery need to be scaled to bot size.	85068	170,1	5	108	710,1
25	Minibots thruster	University of Arizona	2/3		71233	142,5	4,8	108	660,9
26	Minibots electronics	University of Arizona	2/3		82535	165,1	2,5	108	435,1
27	Minibots sensors	University of Arizona	2/3		80786	161,6	2,8	108	464,0
28	Minibots battery	University of Arizona	2/3		96199	192,4	2,8	108	494,8
29	Minibots communication	University of Arizona	2/3		63278	126,6	1,3	108	267,0
30	SRAV first stage	NASA MAV/ Lockheed Martin	9	Rocket stages was succesfully used in earth and Mars mission, but it shuld be prepare to launch/landing loads and start form the Martian surface	71498	143,0	29,9	1	172,9
31	SRAV second stage	NASA MAV/ Lockheed Martin	9	Rocket stages was succesfully used in earth and Mars mission, but it shuld be prepare to launch/landing loads and start form the Martian surface	85078	170,2	36,7	1	206,9
32	SRAV sample contener	NASA MAV/ Lockheed Martin	4	Sample contener should be developed and qualified	65694	131,4	36,2	1	167,6
33	SRAV sample allocation	NASA MAV/ Lockheed Martin	4	Sample allocation system eg. Robotic arm should be developed and qualified	67553	135,1	27,6	1	162,7
34	SRAV trolley	-	4	Trolley should be developed and qualified	80322	160,6	30,6	1	191,2
35	Rotorocraft Structure	-	6	Multirotor concept is proven and viable design as shown by many Earth based aircrafts.	84642	169,3	32,7	4	300,1
36	Rotorocraft Folding system	Pathfinder	6	Folding systems were used during numerous Mars missions (e.g. Pathfinder)	82871	165,7	20,9	4	249,3
37	Rotorocraft navigation system	Ingenuity	6	All components in less advanced version were used in Ingenuity UAV.	68610	137,2	23,5	4	231,2
38	Rotorocraft flight system	Ingenuity	6	All components in less advanced version were used in Ingenuity UAV.	88200	176,4	32,3	4	305,6

39	Rotorocraft lidar	Ingenuity	9	Lidars were previously used on Mars landers. We need to adapt it to our needs	70880	141,8	31,7	4	268,6
40	Rotorocraft sample transport system	-	2	Untested idea, however used in Earth conditions	77960	155,9	36,4	4	301,5
41	Rotorocraft battery	Ingenuity	6	All components in less advanced version were used in Ingenuity UAV.	51855	103,7	33,6	4	238,1
42	Rotorocraft solar cells	Ingenuity	6	All components in less advanced version were used in Ingenuity UAV.	64843	129,7	35	4	269,7
43	UAV Structure		6	Design proven in many Earth based designs	84324	168,6	22	4	256,6
44	UAV lidar	Ingenuity	6	All components in less advanced version were used in Ingenuity UAV.	71151	142,3	26,1	4	246,7
45	UAV navigation system	Ingenuity	6	All components in less advanced version were used in Ingenuity UAV.	78276	156,6	35,3	4	297,8
46	UAV battery	Ingenuity	6	All components in less advanced version were used in Ingenuity UAV.	96617	193,2	38,2	4	346,0
47	UAV solar cells	Ingenuity	9	Ingenuity UAV	82518	165,0	24,8	4	264,2
48	XRF	Perseverance, Curiosity	9	Adapt to our rover	60033	120,1	36	4	264,1
49	NIR	Rosalind Franklin	8	Adapt to our rover	84882	169,8	32,6	4	300,2
50	Raman Laser Spectrometer	Rosalind Franklin, Perseverance	9	Adapt to our lander laboratory	63391	126,8	36,5	1	163,3
51	XRD	Rosalind Franklin, Curiosity	9	Adapt to our lander laboratory	68792	137,6	32	1	169,6
52	MOMA + gas chromatograph	Rosalind Franklin	8	Adapt to our lander laboratory	98976	198,0	22,4	1	220,4
53	Geology scanners	Perseverance	9	RIMFAX was used during last Mars mission	53391	106,8	35,4	12	531,6
54	Mars wheater sensors	Perseverance, Curiosity	9	During previous Mars mission this type of instruments was used for atmospheric pressure, temperature, humidity, winds, and ultraviolet radiation level mesurements.	80880	161,8	16,8	4	229,0

Total cost [bln $]	21
Number of workers	1705
Cost of one worker per day [$]	2000

9 Additionals



Meet thee team of Mars explorers

Innspace is a group of young scientists fascinated by space exploration. Our portfolio includes award-winning projects for bases on the Moon and Mars, as well as space vehicles. Meet the team responsible for the project:

- Piotr Torchała as a leader, Justyna Pelc and Beata Suścicka as project support,
- Science team: Ewa Borowska, Magdalena Łabowska, Nikola Bukowiecka, Aleksandra Klassa, Bartosz Rybacki,
- Engineering team: Hubert Gross, Nikodem Drąg, Michał Słomiany, Kamil Ziółkowski, Kajetan Szostek, Milena Michalska,