European Rover Challenge 2019

Final report

KNR Rover Team

Rover HAL-062

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Warsaw, Poland

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Contents

Project Assumptions

Project assumptions are derived from all of the missions during ERC 2019 competition that the project is built for. They are split into categories correspondent to ERC's tasks.

1. **General rover functions**

   1.1. For the sake of a successful mission, the mars rover will have to access different locations, some of which will require traveling through challenging terrain. We need solutions that will provide us with good traction and control, and guarantee the rigidity of the whole structure.

   1.2. ERC takes place on an extraterrestrially-inspired arena. Our rover has to be capable of traversing rough terrain in order to complete all the tasks.

   1.3. During ERC tasks the rover will not be in direct sight of team members. Therefore, it is mandatory for the rover to be teleoperated. It is essential for the rover to send a video stream of its surroundings and working modules, as well as additional feedback to the operator.

   1.4. Time during ERC tasks is strictly limited. To speed up performing simple tasks the rover should act autonomously whenever possible.

   1.5. Unfavorable atmospheric conditions, such as heat or rain should not affect the rovers performance.

2. **Rover's duties for Science Task**

   2.1. The ability to collect three surface soil samples and one deep subsurface sample(at least 15cm below the surface). Excavation of a trench at least 5cm deep and 30cm long. Density and type of soil is unknown.

   2.2. Storing samples in separate and sealed containers to protect collected soil from contamination. Preserved samples should be safely conveyed to the desired destination.

   2.3. Performing additional in-situ measurements, such as determining the sample's weight and volume as well as photographic documentation of sample collection sites.

   2.4. Automating tasks whenever possible.

3. **Rover's duties for Maintenance Task**

   3.1. The capability of performing maintenance tasks on a console intended for use by humans. On the electrical panel on which several switches and other electrical components are mounted.

   3.2. Conducting precise voltage measurements.

4. **Rover's duties for Collection Task**

   4.1. Detection of the cache in rover's field of view. Taking into consideration that the cache might be partially covered by soil.

   4.2. Approaching the cache until in range of the rovers collecting mechanism range.

   4.3. Picking up unwieldy and hard to grasp, cylindrical objects and placing them into the container on-board.

4.4. Storing caches vertically in a designated, easily accessible container on-board the rover after collection. The container needs to be detachable and placed in a designated area by the robot itself.

4.5. Improving the process of the aforementioned actions through the elimination of the human-factor by implementing automatised tasks.

5. **Rover's duties for Traverse Task**

5.1. Reaching waypoints with given coordinates in a local reference frame.

5.2. Avoiding obstacles

Figure 1: HAL-062 rover

Technical requirements

Taking into account the formula of the competition the project has been divided into four sub-systems(modules). Each module must fulfill following the technical requirements, drawn from aforementioned assumptions. Besides those, there are general requirements that the entire rover must fulfill.

1. **General**

   1.1. Safety
   Safety is the number one priority for our rover. The design of the rover must not allow for: high speed, overheating of electronic components, the inability to be turned off, unexpected movements and actions of the rover and its modules, the presence of loose cable endings and sharp and pointy edges, high temperatures. Detailed information about safety precautions are discussed in the Safety Systems chapter.

   1.2. Modularity
   The design of the mobile platform should allow for the quick changing of modules.

   1.3. Lightweight construction
   Lightweight and durable design, which does not compromise the rover's functionality and ability to perform competition tasks.

   1.4. Weatherproofing
   Electrical components of the rover have to be well protected against damaging weather conditions. That is why the chassis needs to be dust and water resistant.

2. **Mobile Platform**
   The mobile platform is the core, fully-independent sub-system to which other modules are attached. Its main parts are the suspension, wheels, drive and the chassis, each part is supposed to meet the following requirements.

   2.1. Suspension
   The ability to overcome vertical obstacles over 300 mm in height. It must provide stability and withstand at least 60 kg of load. The ability to easily maneuver the rover.

   2.2. Wheels
   Good traction so that the wheels donspin on loose sand. Damping that reduces vibration and provides shock absorption. Durability, so that it will not be damaged by any of the terrain.

   2.3. Drive
   Reliable drive modules that provide high torque to the wheels and adjustable speed, thus allowing change in the rover's position and direction. Providing feedback about speed and position of the drive shaft.

   2.4. Chassis
   Spacious chassis with ergonomic design so that every electronic component stored inside may be easily reached and the covers should be easily removable.

3. **Robotic Arm**

   3.1. To complete the collection and maintenance tasks, we require a manipulating mechanism (manipulator), which allows for variability and freedom of movement.

   3.2. In order to grip versatile objects, we need a gripping mechanism (gripper) at the end of the robotic arm.

   3.3. Our manipulator's movements have to be precise in order for it to be able to pick up cashes with samples, power plug and perform maintenance on consoles.

   3.4. In order to be able to insert the power plug into the socket, our gripper has to provide sufficient gripping force.

   3.5. Our gripper has to be equipped with voltage measuring probes.

   3.6. We have to make sure the manipulator can withstand loads created by picked up objects, even when fully extended.

   3.7. For the collection task, the rover must be equipped with an additional container for storing collected caches vertically.The container needs to be easily detachable and stable when placed on the ground.

4. **Science Module**

   4.1. To collect subsurface soil samples the rover must be equipped with a drilling device. A special drill bit needs to be able to go through any type of soil or rock of varying density while carrying all of collected samples vertically.

   4.2. To collect surface soil samples and excavate a trench the soil sampling module needs to be equipped with a scooping device.

   4.3. Process of drilling as well as scooping must be aided by a mechanism that will separate reaction forces from rovers body by an anchoring device to the ground.

   4.4. All collected samples must end up in sealed containers. As soil samples can be easily contaminated as a result of contact with surrounding atmosphere after excavation, special storage mechanisms must prevent that.

   4.5. For in-situ measurements we need to use instruments that can be easily implemented on our rover, while giving quick and reliable results.

5. **Autonomy Module**

   5.1. The rover has to be capable of recognizing AR-tags.

   5.2. The rover has to be able to determine its position and orientation.

   5.3. An optimal path of traversal between waypoints must be found.

   5.4. The rover should be able to avoid obstacles.

6. **Electronics**

   6.1. Energy Source
   Stable and efficient power source, able to supply sufficient (300 A) current to run all motors, sensors and modules during tasks, that can power the rover for at least 45 min during task operations. The energy source is required to be easily changeable to provide continuous operation.

   6.2. Power system
   Distributing power from an energy source to all of the rover's sub-systems and components. Tracking power usage by each module during completion of tasks.

   6.3. Protections
   The boards should be equipped with necessary protections.

7. **Communication**

   7.1. Transmission of maneuvering commands and sensors'feedback.

   7.2. Full range of view provided by cameras.

   7.3. Stable, high-quality delay-free video stream from cameras.

   7.4. Data exchange between the rover's modules.

   7.5. Communication between base control and rover has to use legally available frequencies and power levels at a distance of at least 100m. It has to work even out of direct sight caused for example by terrain morphology.

Testing methology and test plan

One of the most important stages of large projects such as the construction of a martian rover of this size is the testing phase of each of its components and subsystems. To ensure a healthy development of the project, a proper testing methodology is crucial. It has to check if individual components and their integrated systems meet the requirements and are able to complete their tasks in a set environment.

1. Suspension

   1.1. Measurement of actual torque and speed provided by new motors and gearboxes to confirm our initial calculations.

   1.2. Measurement of a motors temperature under varying load to determine the overheating countermeasures.

2. Drive

   2.1. Testing the off-road capabilities of the whole platform in an expected operational environment to confirm the rovers ability to traverse demanding terrain.

3. Wheels

   3.1. Testing the load and impact resistance of wheels by applying static and dynamic loads from varying directions to determine the toughness of the design.

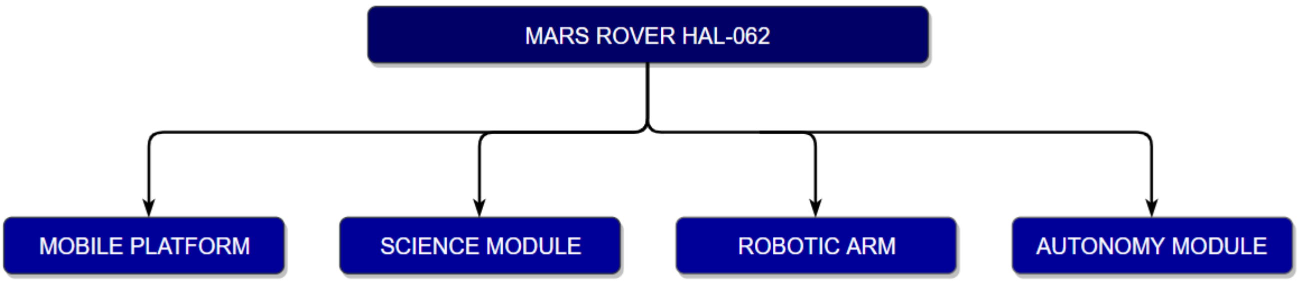
3.2. Testing the wheels coatings resistance to sharp and pointy objects to ensure the threads integrity when traversing rocky terrain.
3.3. Testing the wheels capability to withstand high and low temperatures to ensure wheel integrity during tasks performed in different weather conditions.

4. Manipulator
   4.1. Testing the fatigue resistance by measuring effects of prolonged continuous operation to ensure the constructions integrity during ERCs tasks.
   4.2. Testing the rigidity of the manipulator when exposed to varying loads to correctly calibrate the inverse kinematics algorithms.
   4.3. Measuring the maximum external load a fully extended arm to ensure proper handling of objects during tasks.
   4.4. Testing the quality of pre-programmed trajectories to determine the repeatability when performing automated movements, such as storing a cache on board the rover.
5. Laboratory module
   5.1. Testing various drill profiles to determine the most suitable one for collecting both the surface and subsurface soil samples.
   5.2. Testing the container sealing capabilities to ensure the samples we collected will not be contaminated.
   5.3. Testing the transmission of collected soil to the container to prevent any cross-contamination of the samples.
6. Hull
   6.1. Testing the cooling capabilities of the cooling duct to prevent the overheating of motor controllers.
   6.2. Testing the water- and dust- resistance of the hull to ensure proper operation of electronic components.
   6.3. Testing the impact resistance of the hull to ensure the safety of electronic boards and batteries.
   6.4. Testing the main cameras gimbals operation range to provide vision of the rovers surroundings.
7. Electronics
   7.1. Measurement of a motor controllers current under varying load to determine the overheating countermeasures.
   7.2. Measurement of motor controllers currents peaks by driving the rover on demanding terrain.
   7.3. Checking average operational time of running on batteries.
   7.4. Verifying protections by checking time reaction of current fuse on currents peak or heating electronics board(temperatures protection).
   7.5. Testing hardware current limit regulator.

8. Communication
    8.1. Testing Transmission of commands and feedback delay at different distances and operation scenarios - we are satisfied by the results because transmission is much faster than video stream so it wont affect ability to steer the rover.
    8.2. Measuring Operational distance by moving the rover further and further from the base station - distance far exceeds the required 100 meters, standing at around 700 meters.
    8.3. Verifying video stream stability and delay by performing various operational scenarios - we are still working on making the delay smaller but it is in acceptable values.
    8.4. Testing can bus between different microcontrollers - is being tested from the very beginning of our project and works without any bugs.
9. Autonomy Module
    9.1. Measuring accuracy of the mechanical measure device and module calibration.
    9.2. Testing communication between rover and autonomy module; control system tests.
    9.3. Testing obstacles detection and ability to drawing them on autonomy programs map.
    9.4. Testing path marking by Dijkstras algorithm.

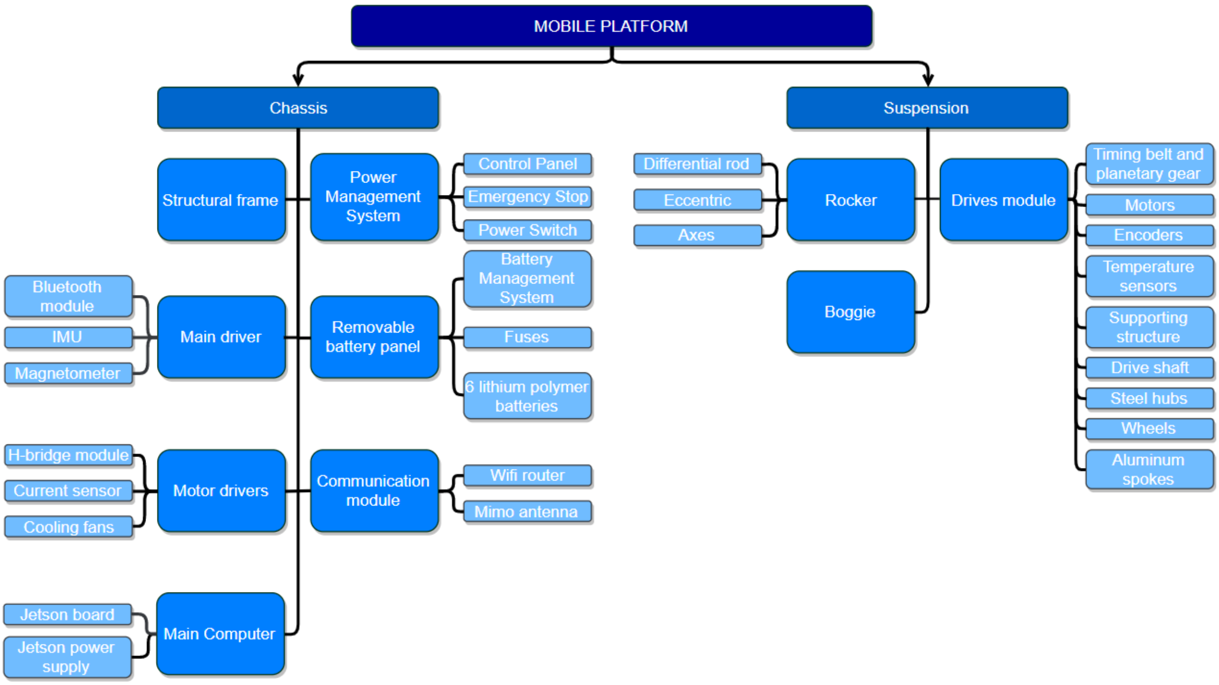
Final design

1. **System Breakdown Structure**
    1.1. **Rover**

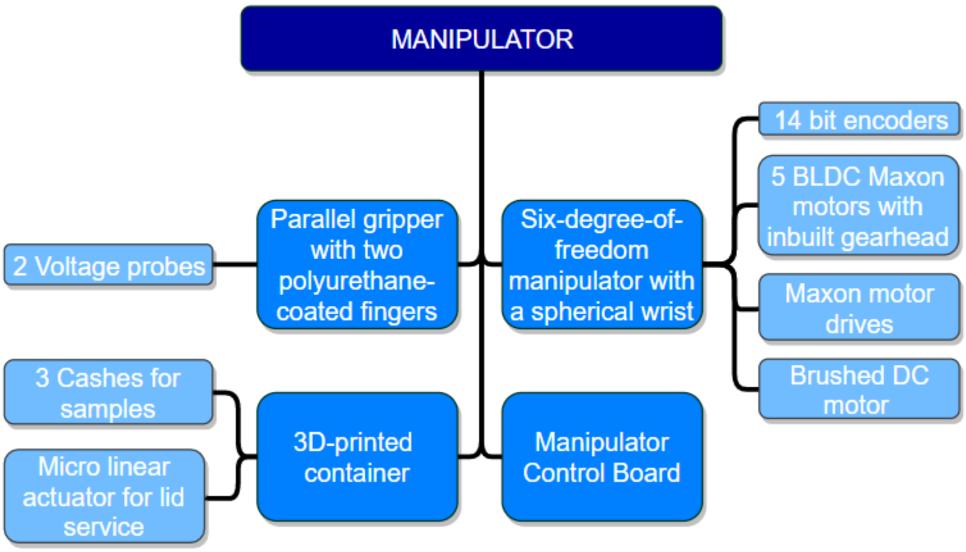


Rover is devided in to Mobile Platform and three attachable modules, which can be easly removed and replaced with other one.

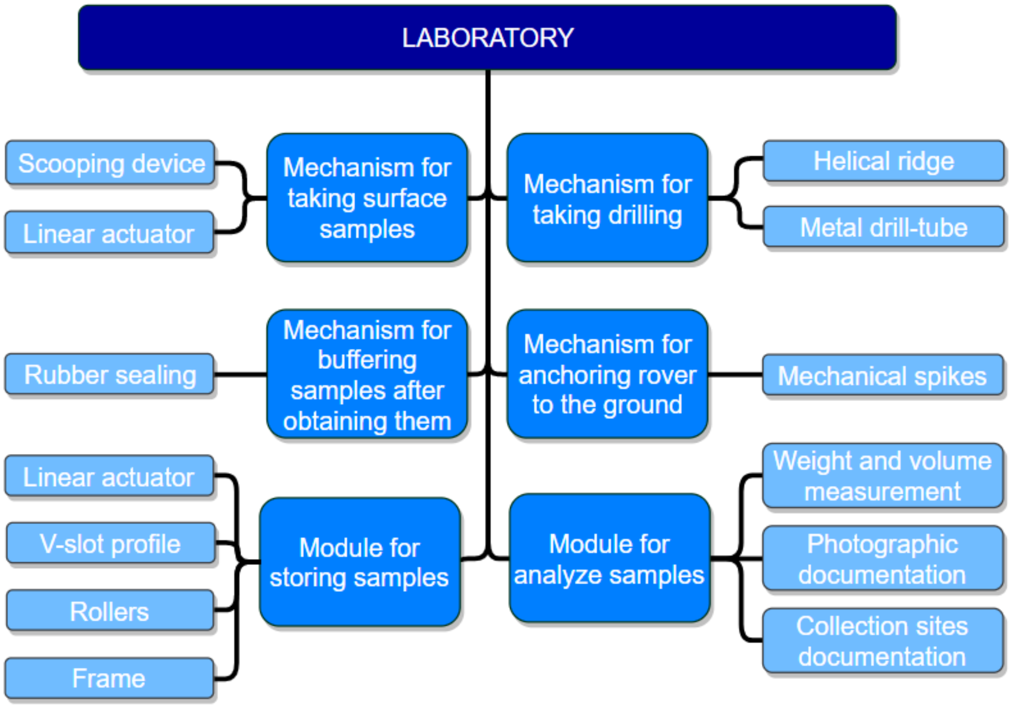
1.2. Mobile Platform



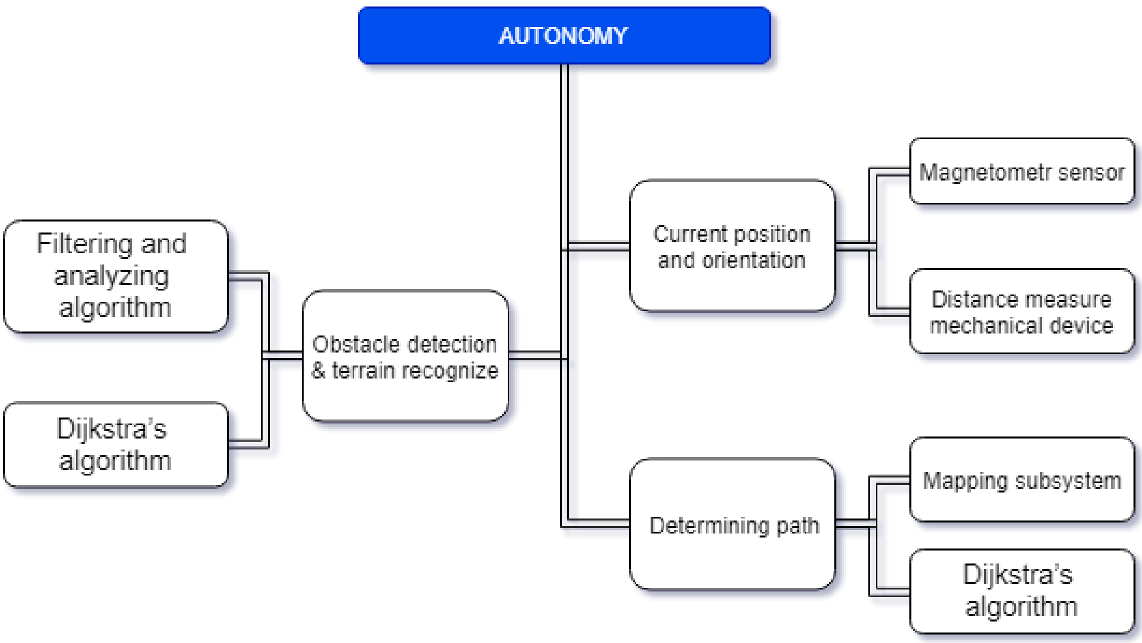
1.3. Robotic Arm



1.4. Science Module



1.5. Autonomy



2. **System Architecture**

The mobile platform is the core, fully-independent sub-system to which the other modules are attached. Its main parts are the suspension, wheels, drive and the chassis. Each part is supposed to fulfill the following requirements.

Figure 2: Rover with Robotic Arm

2.1. **Mobile Platform**

Our rover is based on a six-wheeled mobile platform. It is mounted on rocker-bogie suspension. This solution allowed us to achieve optimal balance between rigidity and light weight of the structure. The rocker-bogie suspension with six wheels provides high bearing capacity, allows for traversing rough terrain with rock-like obstacles 300mm tall. The differential bar has been located inside the chassis, protecting it from external damage. Moreover, this leaves the whole upper surface of the robot available for communication equipment, cameras and sensors. In order to minimize the weight of the suspension, FEM was used during the design process (req. 2.1.3 2.2.1).The suspension itself does not provide any shock absorption therefore it has to be provided by wheels. Since we couldn't find any stock solution that would fulfill our requirements we decided to develop our own wheels. During 1.5 years we have managed to create and evaluate 4 different designs. For ERC 2019 we have prepared our fifth generation: off-road vehicle - inspired wheels, which consist of airless tires and rims. Tires are made of ultralight (req. 2.1.3), yet durable polyurethane foam, cast in 3D printed molds. The tread has been designed specifically for rocker-bogie suspension to allow better turning. The wheels'rims are directly connected to the drive shaft with aluminum spokes supported by steel hubs. The unique design of wheels provides damping, good traction on loose soil and low weight (req. 2.2.2).

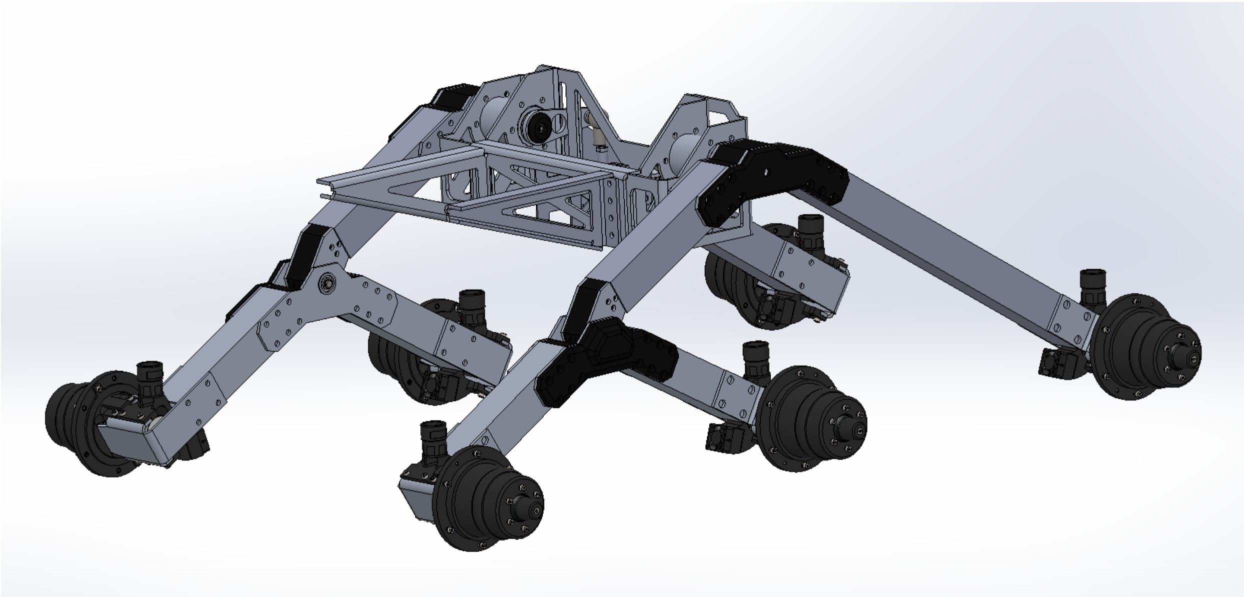


Figure 3: rover's chassis

Six independent drive modules take advantage of high gear ratios of the transmissions. Thanks to that we don't need high power motors, which reduces the overall power consumption. We used DC motors used in drills with three-stage planetary gear transmissions - this allowed for a very good mass to torque ratio of 15g/Nm. Another advantage of the brush DC motors is the ability to operate without problems in dusty conditions, therefore we decided to focus on cooling them with air (req. 2.2.3). The combination of our-self developed suspension, drives and wheels provides rover's stability, and maneuverability necessary for traversing through ERC arena's terrain.

Figure 4: rover's wheel

The chassis of our mobile platform does not have to transmit any loads, thanks to the suspension's design. Therefore we have thus focused on finding and utilizing lightweight yet rigid materials and provide as few construction elements as possible (req. 2.1.3). Furthermore, it has undergone modifications in comparison to last year's design, so that it provides better access to electronics and all the necessary status LEDs may be visible from outside of the rover. Last but not least, the motor drivers cooling has been significantly improved. Motor drivers are located inside an air-tunnel in which forced air flow takes away the heat from the radiators. The air flow is forced by 4 fans. To ensure faultless performance in all conditions the chassis is dust-proof and water-resistant (req. 2.1.4). Mechanical and electronic connectors are placed outside the chassis, thus allowing for quick attachment of additional modules (req. 2.1.2 2.2.4).

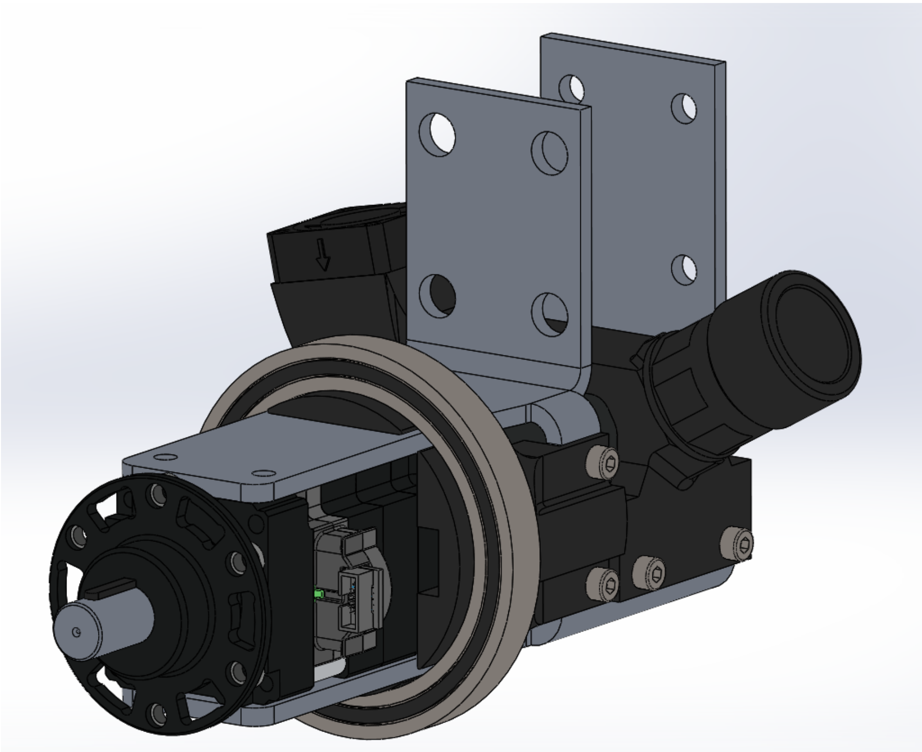


Figure 5: rover's drive module

2.2. Robotic Arm

In order to complete the collection and maintenance tasks it's mandatory for the rover to be able to catch and freely manipulate objects. Based on solutions verified as reliable in the industry we decided to equip our rover with a six-axis articulated robotic arm with a spherical wrist (req. 2.3.1). The manipulator is attached to the front rack of the Mobile Platform, which allows for easy replacement (req. 2.1.2). The first five degrees of freedom are equipped with high quality BLDC Maxon motors with built-in gearheads, 14 bit encoders and dedicated Maxon motor drivers. The movement of sixth DOF - the rotation of gripper is caused by brushed DC motor. Due to usage of high-end motors it is capable of lifting 5 kg at full range of 1.2 m (req. 2.3.6).

Figure 6: Six-degrees of freedom manipulator

The usage of encoders will further improve the overall precision as well as the quality of inverse kinematics algorithm (req. 2.3.3). The end effector of our choice is a parallel gripper with two polyurethane-coated fingers. It provides an excellent and reliable grip on items of any shape(req. 2.3.2 2.3.4). At the end of both fingers a voltage probe is located, the parallel mechanism will allow for measuring the voltage of a wide variety (req 2.3.5). For the collection task the rover will be equipped with easily detachable 3D-printed container. It consists of a cache suspender for three cashes and a closing lid, opened by micro linear actuator, attached to the rover. The lid will press against the collectables during traversal of the rover, thus it won't allow for any movement of the cashes. The design of containers allows for storing collected caches vertically. The container is placed on a stable base and can be detected by the manipulator, placed on the ground and remain stable afterwards (req 2.3.7).

2.3. Science Module

To fulfill science task requirements, we build a science module, capable of excavating, collecting and storing different soil samples. The main element of the science module is a frame, which is attached to the front rack of the Mobile Platform allowing for easy replacement (req. 2.1.2). It's using v-slot profiles, rollers, DC motor with encoder and a lead screw. This way we can keep the whole module above the ground during traversing, and lower it down for sample collecting. On the bottom there is a mounted anchor with spikes, that allows us to separate reaction forces from the rover's body (req. 2.4.3). The following mechanisms are mounted onto the frame.

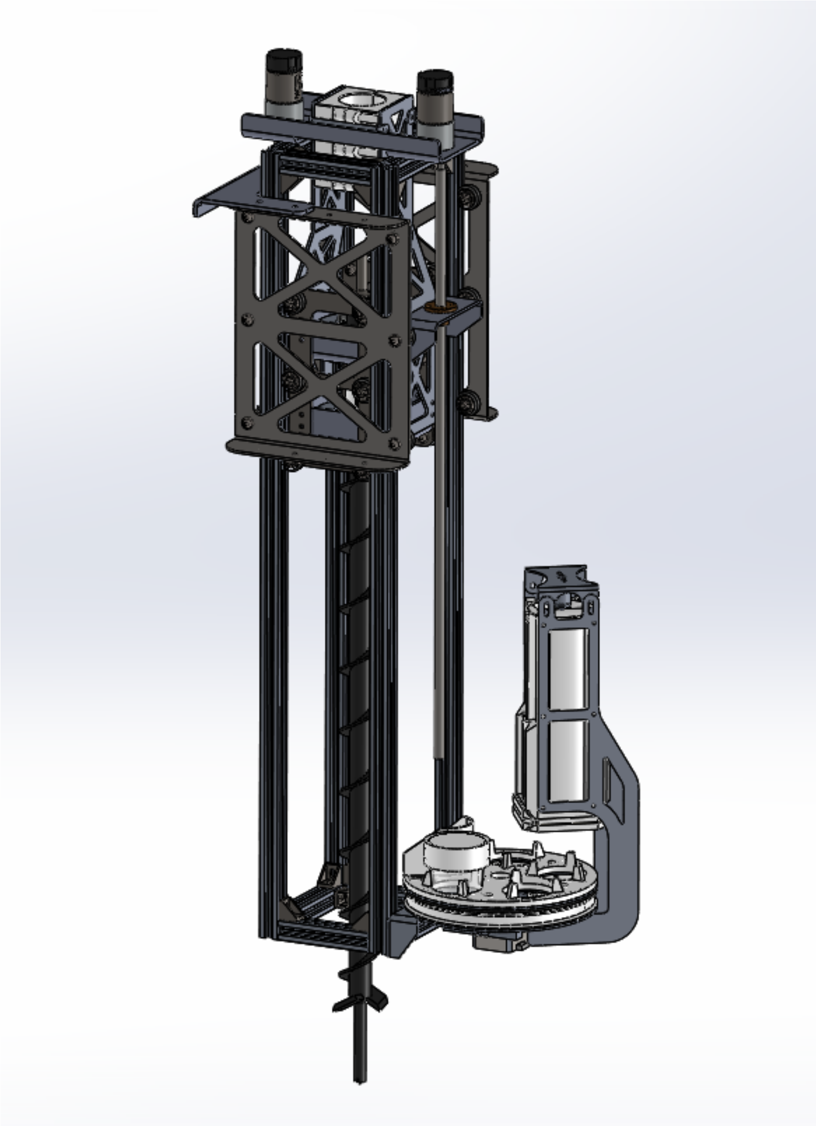


Figure 7: Laboratory module

The science module is equipped with high duty auger drill bit capable of drilling in soil of any density. By using DC motor with encoder and a lead screw we are able to perform precise vertical movement of the drill bit. Thanks to that we have precise knowledge about depth of collected sample. That way we can collect deep and surface samples with one tool. The drill bit is surrounded with a stationary tube, which allows the soil to be transported above surface level for subsequent caching and examination.
Caching mechanism is comprised of a revolver with up to 4 containers, special sealing mechanism, and strain cell capable of weight measurement. Containers are sealed by forcing a special lid like seal on the them. This prevents any contamination and fulfills the no spill policy. Additionally a photographic documentation of collected samples, and collection sites is made. There is an imprinted scale on transparent material from which the containers are made. Thanks to that a volume measurement can be taken from photographic documentation.

2.4. Autonomy Module

Due to inability to use GPS, rover team had to develop special system to determinate rovers position. We achieved that thanks to combination of IMU, distance measure mechanism and autonomy algorithm. We decided not to use special codes provided by organizers to determine our location on the map, so our system was developed to be the only navigation data source.

At the beginning we have used acceleration to count traveled distance by using double integral. But due to huge error we decide to supply this method by mechanical measurement and thanks to that we achieved accuracy up to ten millimeters.

But we didnt give up with acceleration. We use it as autonomy support to detect any anomaly such as collision or lack of movement.

2.4.1. IMU

In IMUs provided data we can find the orientation of the rover against the global magnetic field which is given in degree(where 0 degree mean North) and rovers slope value. As IMU Nucleo Discovery is used(photo on the right).

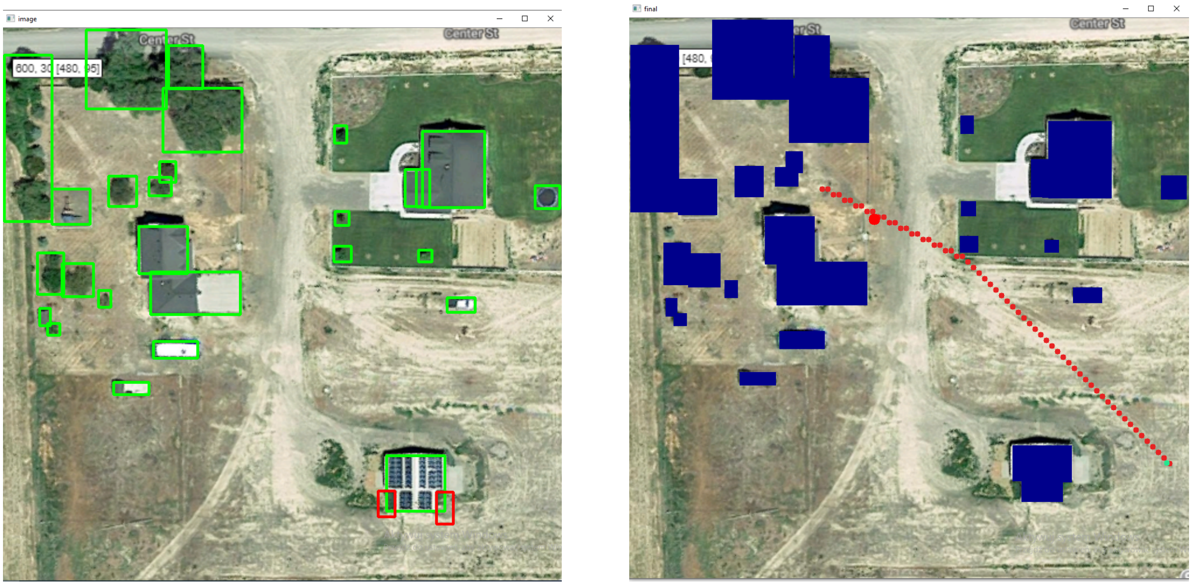
2.4.2. Distance measure mechanism

This special mechanism is a seventh rovers wheel, but instead of giving additional power to rover drive it has rotary encoder which sends impulses to mainboard where they are translated to rovers distance covered.

2.4.3. Autonomy Program

Autonomy program was written in high level programming language which is Python. Thanks to variety of Pythons libraries we were able to write fully functional autonomy program. It has GUI that allows us to conduct tests and analyze the output in real-time. Program also saves logs from the mission in text files and one of our libraries can visualize the numbers and create graphs that are easy to read and interpret. Moreover, tests prove that program was improved to such extent that it doesn't produce unexpected errors and our programmers team is positive it can control rover's operation.

Additionally we are able to assess tags position on the virtual map. Then we know when we achieve given way-points and we are able to recognise potentially dangerous obstacles like small craters. Then we put them on to programs map (req. 2.5.4).



(a) Finding obstacles (b) Determining the best route

Figure 8: Visualisation of path finding algorithm used in autonomy

To find the shortest trail to given way-points we use Dijkstras algorithm which is able to avoid known obstacles and find new route if autonomy program detects any block on rovers way. Picture below depicts how algorithm works. On the left we have marked obstacles which should be avoided and on the right we have second part of program where algorithm marks out the shortest and the safest route for the HAL-062.

Every time when another subsystem finds block, algorithm again finds shortest route but this time allow for new area which ha to be avoided.

Among IMUs provided data we get rovers slope value. Thanks to that we can detect if rover is going down or up. Then we know if hills slope is too high or if it is easy to go through it.

We resigned from using a subsystem based on data fetched from Hokuyo URG-04LX-UG01 lidar. This solution was very inconvenient for our team because of the lidar price and low accuracy that was proved in conducted tests. We substituted that system with set of cameras and Pythons OpenCV library that performs absolutely better than its predecessor. At the moment we are able to recognize obstacles on the rovers road and use that information to avoid them and slightly alter the route marked out in other part of the program.

2.5. Electronics

For powering such a complex system we needed an energy source with high discharge current. That is why we decided to use 4 Lithium-Polymer batteries, which are managed by the battery management module of our own design. It allows for connecting two packages in parallel, each comprised of two serial connected LiPo batteries. Each battery has a capacity of 6750mAh, which is sufficient for sustaining the rover's operation for at least an hour (req. 2.6.1). The electronic board that is responsible for distributing power from the energy source to all of the rover's sub-systems and components is called the power management system(PMS). It tracks the power usage of each module during operation for further analysis (req. 2.6.2). Technical problems encountered during last year's competition forced us to redesign the whole internal electronics system. We have thoroughly analyzed all issues and now we are realising the new technical requirements, that are set for this year's design. Each board is equipped with surge protection on every signal connector, and overcurrent protection on all power outputs to sensors. reverse voltage protection on the power supply, and voltage regulators with short circuit protection on converters.

Additionally every critical functionality of the rover is located on a different board (req. 2.6.3). This way, a failure will not damage the whole system. We have decided to place 8 motor drivers inside our rover, 6 of which will be used. The other two function as a backup; in case of failure a broken module can be quickly switched to a different one. Each driver has a nominal current of 50A, and can control both DC and BLDC motors. Currently our Mobile Platform is equipped with 6 DC motors, but should this change, modifications in drivers would not be required. Drivers are equipped with additional over- and undervoltage protection as well as temperature monitoring.

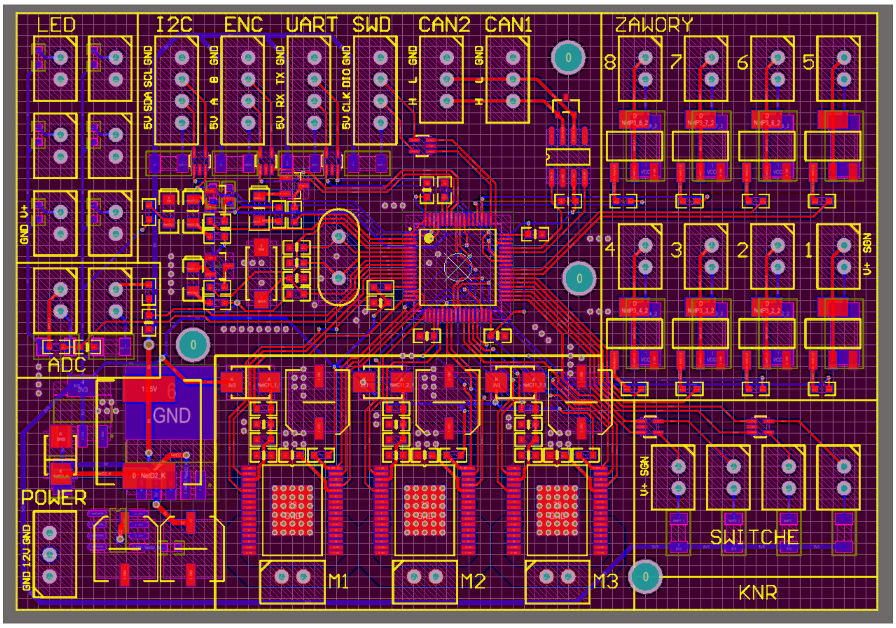


Figure 9: Laboratory module PCB

2.6. Communication

Our rover communicates with the base using 5 GHz WiFi routers with 0.8 kilometre range (req. 2.7.5). The HQ video feed from all cameras on board the rover is gathered by Nvidia Jetson TK1 board and then relayed via a webcam server, thus enabling for a steady and delay-free video stream (req. 2.7.3). The main camera is located at the top of the mast of the rover, and has 2 axes of rotation, providing us with a full field of view. Additional cameras are mounted on both the manipulator and science module, pointing at key areas, thus enabling to operate these modules properly. For the autonomous traversal mission a dedicated camera located in front of the rover is used (req. 2.7.2). All commands and data is sent between rover and base station using SSH protocol. The rover can also be controlled using Bluetooth. This comes as a useful feature for testing and development.

Internal rover boards communicate via CAN bus, which provides comprehensive and reliable communication, which is our top priority (req. 2.7.4). Moreover, the architecture allows us to add new components easily.

3. Operational Scenarios

3.1. Science Task

For this task our Mobile Platform will be equipped with the designated Soil Sampling Module. After traverse to the sample collection site, the module will be lowered to the ground and forced down, anchoring whole construction in the soil. Subsequently a special heavy duty auger drill bit, powered by high power DC motor, will be used.

Very precise vertical movement of drill bit is guaranteed by using encoders and control algorithms, thus allows us to collect sample from desired depth with accuracy up to one millimeter. This makes our design universal, perfect for deep and surface sample collection.

At the surface the drill bit will be surrounded by stationary acrylic tube. This will allow vertical movement of the soil above the ground. Special profile of the tube at the end, will force the earth to fall out right into our caching mechanism.

Caching mechanism is comprised of caches in a revolver. However in one spot revolver is equipped with a ramp that prevents any of unwanted soil from getting into caches. This allows us to collect sample from specific depth only.

After the soil gets into its cache, module will automatically seal the container by forcing a special lid like seal onto it preventing any contamination. Volume will be read by operator by using additional camera and imprinted scale on the transparent cache. Module will also weight the sample by using highly accurate strain cell.

After successful sampling at one site, the module will be brought up, allowing the rover to traverse to the next site for subsequent sample collection and examination.

3.2. Maintenance Task

For this task our Mobile Platform will be equipped with the designated Manipulator ended with a gripper. After reaching to task panels, the manipulator with the use of its grippers nger will be able to set switches to appropriate positions. In order to set knob to a value specied by the judge we can take advantage of the grippers force and ability to perform a strong encompassing grip on the knob. And then turn the knob around with manipulators wrist. The last task of grabbing the high power plug and inserting it into a socket will require a lot of precision and some turning around, but we tested it and we were able to do put the plug in to the socket.

3.3. Collection Task

For this task our Mobile Platform will be once again equipped with the designated Manipulator ended with a gripper. We are going to approach the location of the dropped cache and look for it with our onboard cameras we also trained neural network to detect cache for us. Once we nd it we can take a picture, gently pick up the cache with our gripper and place it in its place in the container. Later we are going to approach the second and third cache and the procedure will repeat. At the end of the task we can dismount the cache container from rovers body and place it in marked point.

3.4. **Traverse Task**

For this task, our rover will be equipped with high resolution and wide tonal range camera - Kurokesu C1. After receiving the 4 way-points from the judges we we will provide those points to the system as well as height map and articial landmarks positions. After that algorithm will search the most convenient path between destinations. By the most convenient path we mean that it avoids too big hills or too steep slopes, that may be encountered in the task eld. In order to recognize AR-tags OpenCV library is used. Our program saves logs from the mission in text files and one of our libraries can visualize the numbers and create graphs that are easy to read and interpret. It will allow us to prepare data for presentation after reaching all way-points.

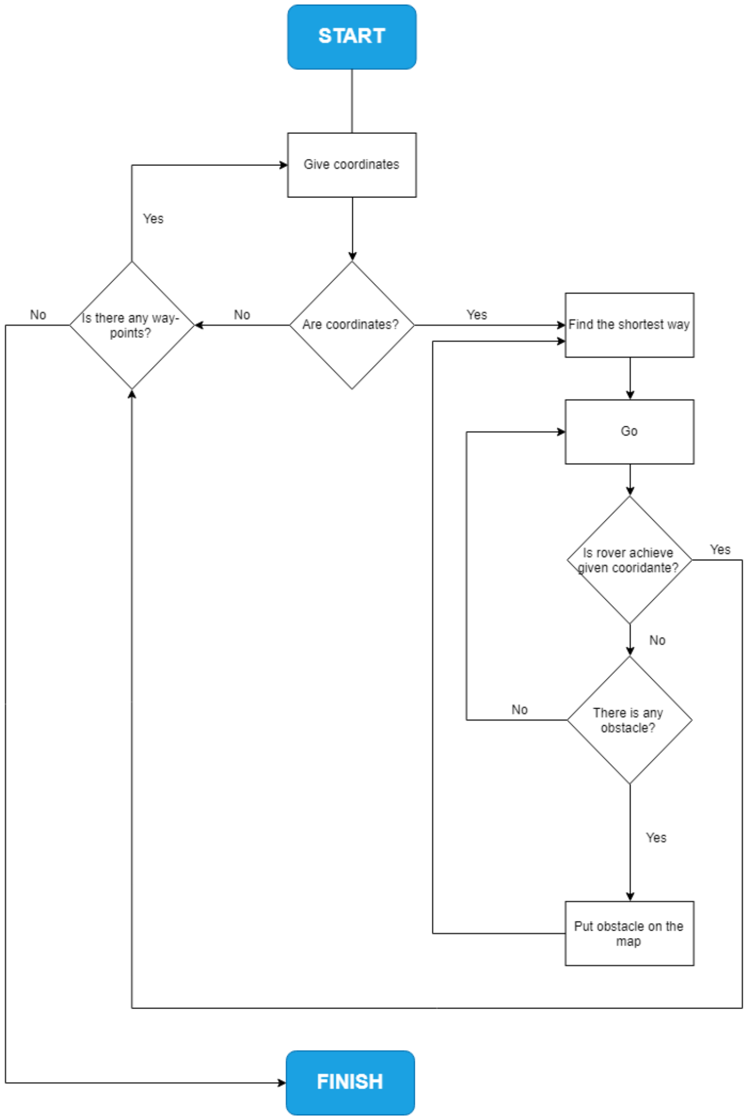


Figure 10: Autonomy block diagram.

4. CAD Drawings

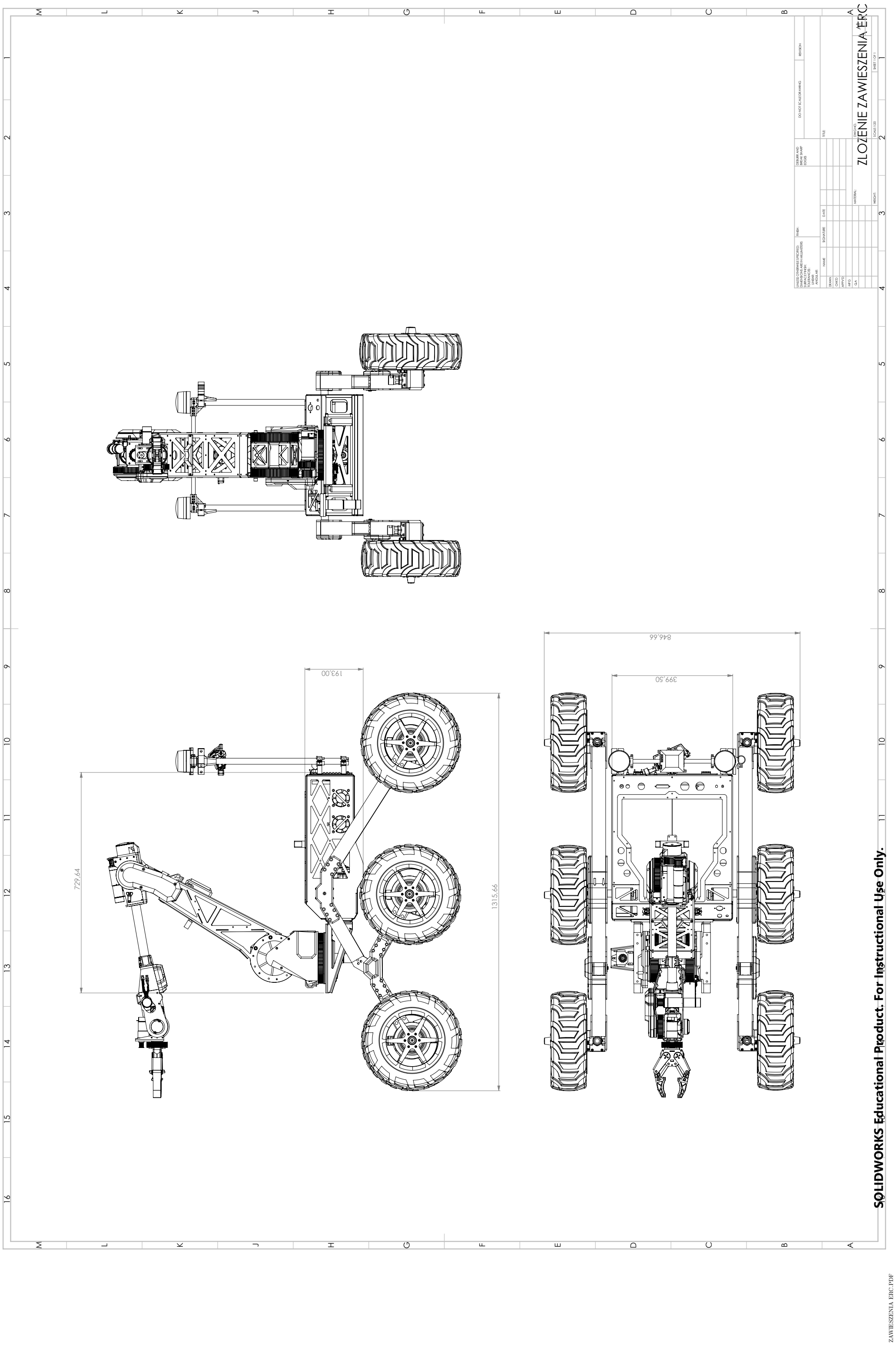


Figure 11: rover assembly with robotic arm

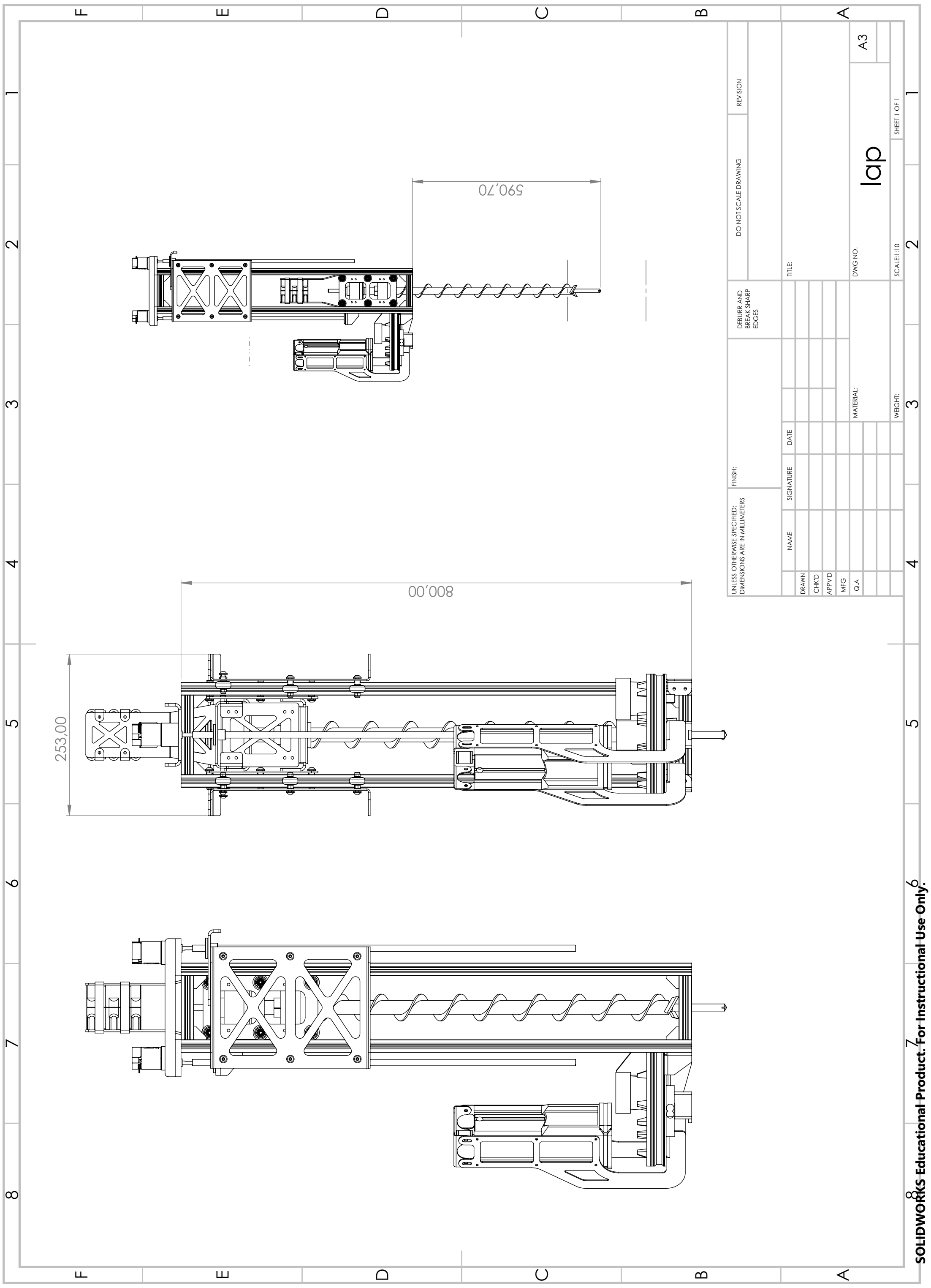


Figure 12: assembly rover's science module

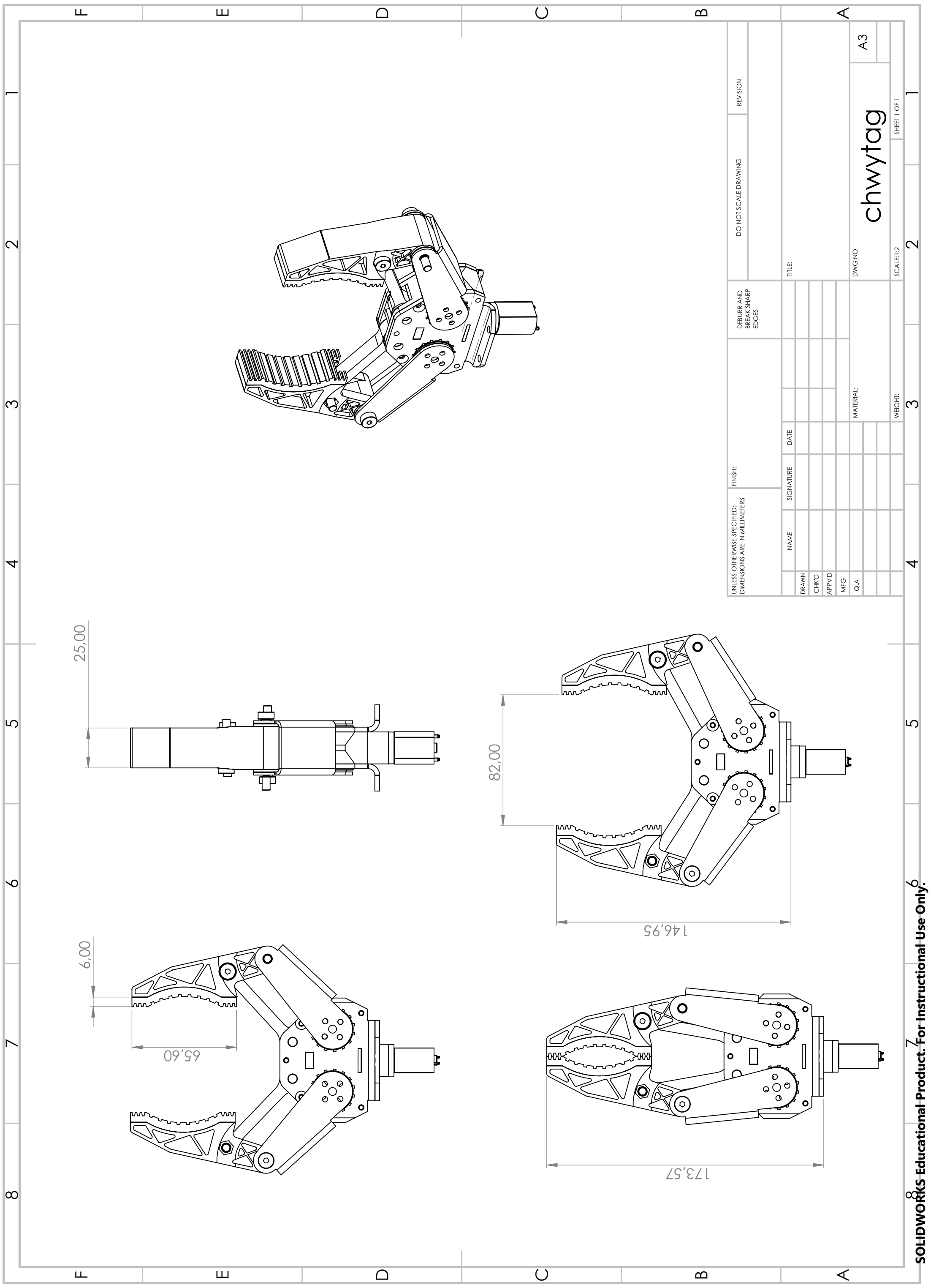


Figure 13: assembly of rover's gripper

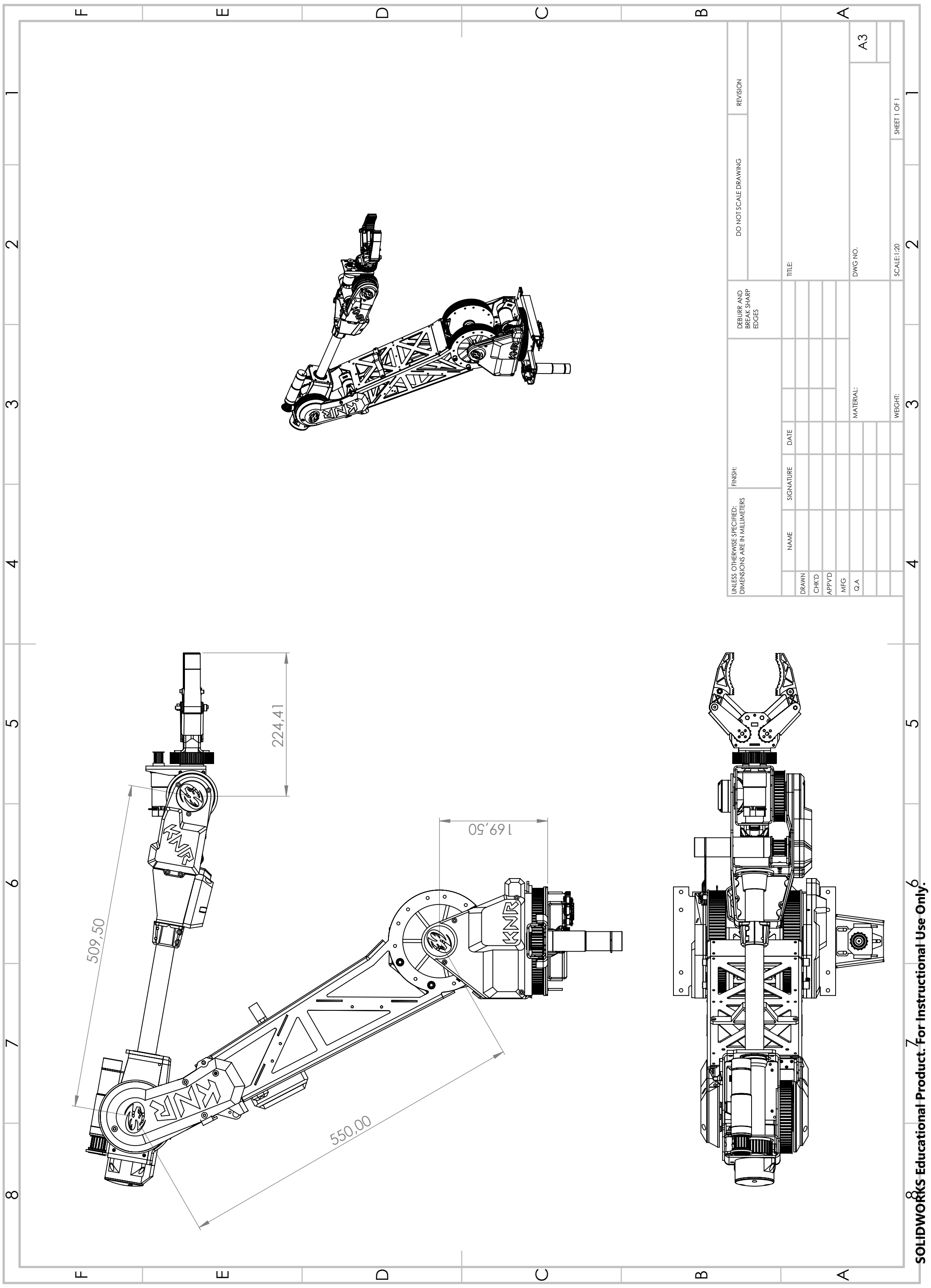


Figure 14: assembly of rover's gripper

Safety Systems

1. **Emergency stop button**
   Easily accessible and well visible characteristic red button. Our team have checked this very solution in practice and it proved to be compliant with ERC rules so the rover can be powered off in case of emergency. We provided robust mounting of the button so it could even withstand a hard blow. The button switches off the power for all motors and actuators, but logic and computers are still powered, that allows a fast diagnostic process or quick return to normal operation after the problem has been resolved and button switched back to its original position.

2. **Activity indicator**
   On the mast of the rover a red indicator lamp is located. Blinking of the lamp informs about the status of the rover - active or inactive. The light starts to flash 5 seconds before the rover begins to be operable and continues to flash during the task. The flashing light is clearly visible from at least 20m.

3. **Power Management System and operating panel**
   A group of switches that could turn on and off different modules of the rover independently which significantly simplifies diagnostics. The operating panel also undoubtedly increases safety during tests. We can also determine the presence of modules thanks to diodes mounted on operating panel.

4. **Short circuit and overcurrent protection**
   The Rover's power source consists of six 100Wh lithium-polymer batteries which can safely generate 10kW of power. In case of any problems it may be dangerous not only to electronic circuits but also to structural elements - that's why we decided to use a large, 300-amp fuse located as close to the battery module as possible.

5. **Battery Management System (BMS)**
   Current control is not enough for safe operation of the battery module. The BMS additionally controls the voltage of all cells and balances cells between packages. It also controls the temperature of all batteries.

6. **Main driver**
   All communication data between the operator and the rover is sent independently from the computer for vision interpretation. Any failure of this computer does not impact the rovers movement. Furthermore, we decided to send command sets containing direction and speed of movement every 100 milliseconds. In case of loss of any two pieces of information from the data set, the control systems are set to automatically block all motors. To enable the rover's movement again sending another command is required.

7. **Motor drivers**
   The motor drivers and subsystems connected to the internal CAN bus inside the rover work in a similar manner. This guarantees that all motors stop even in case of damage inside the rover.

8. **Current limit regulator**
   All motor drivers contain three H-bridge modules calculated to withstand 100A of current. All modules have their own current sensor and are independently controlled to limit the current to a safe level even in dynamic state and sudden wheel lockup.

9. **Motor switch off**
   Motors drivers are driven by a PWM signal generated by the microcontroller and additionally two independent enable signals. The enable signal is used to switch off the motors when a communication error was detected. That ensures that motors don't start running when communication returns to a normal work state.

Final financial report

As it is the second time we are applying for the European Rover Challenge, we've focused on upgrading our previous construction. To achieve that, we were able to raise about 40 000 PLN from the following sources of funding:

- grant from The Ministry of Science and Higher Education - Najlepsi z najlepszych 3.0;
- dean's grants;
- Rector of the Warsaw University of Technology grants;

Funds breakdown is mentioned in table below:

Funding source	Budget
Ministry of Science and High Education	13 766.20 PLN
Dean	19 119.73 PLN
Rector of WUT	5 000.00 PLN
SUM	37 885.93 PLN

We were able to fully upgrade following elements of rovers structure:

- rovers body
- drives (motors with gearheads and motor drivers)
- wheels
- manipulator
- science task module
- electronics

Detailed list of expenditures and sources:

Elements		Costs	Funding source
Manipulator	Motors with gearheads for DOF 1,2	3 500 PLN	Ministry of Science and High Education
	Motors with gearheads for DOF 4,5	2 500 PLN	
	Mechanical parts and encoders	1 600 PLN	
	miscellaneous parts (gears, belts, shafts, bearings etc.)	6 150 PLN	
Electronics	Electronical parts	2 420.87 PLN	Dean
	Custom boards	1000 PLN	
	Wiring and connectors	1 538 PLN	
Drives	Motors with gearheads	4 370 PLN	Dean
	Motor drivers	2 250 PLN	
	Laser Cut Aluminium	750 PLN	
Wheels	Polyurethane foam	1 530 PLN	Dean
	Other materials and parts (coatings, ABS etc.)	1 210 PLN	
	Laser Cut Aluminium	850 PLN	
Science Task module	Laser Cut Aluminium	600 PLN	Dean
	motors with gearheads	420 PLN	
	miscellaneous parts (v-slot, bearings, auger screw)	1 015 PLN	
Platform	Laser Cut Aluminium	800 PLN	Dean
	miscellaneous parts (HIPS, mountings, air filters etc.)	290 PLN	
PC computer	Graphics processor	1 400 PLN	Rector of WUT
	other components	3 600 PLN	
SUM		37 793.87 PLN	

Risk Assessment

Limited time between URC and ERC proved to be a very serious risk again. Management techniques did improve in comparison to last year but we are still learning to make it more eective. We also did not manage to increase the number of students engaged in the project because of the summer period. This also did not allow us to progress in training new members. One of the most serious risk rovers being damaged during URC and it did happen - we burned half of our motors. But we did manage to buy new motors and create whole new drives modules. Currently our rover is fully functional but still can suer unexpected damages during tests. We continue to have spare parts ready for replacement if necessary. Another risk was the loss of control. During URC competition and all eld tests we have never lost control over the rover. Of course, we have lost communication multiple times but safety systems always stopped all movement. The same goes with LiPo batteries. They have never overheated, not to mention caused any re. We are satised with these behaviours and glad that our rover does not pose any threat to surrounding whatsoever, yet at the same time we still treat this risk seriously and do our best to assure safe operation of the rover.

Difficulties and Solutions Applied

Throughout the project's lifetime we have faced a lot of engineering problems, some of which we were able to foresee, but many of them surprised us and provided us with invaluable experience.

We had some serious errors in position and velocity readouts acquired from magnetic encoders mounted on motor shafts in the mobile platform's drives and in the joints of the robotic arm. It turned out that the reason for that was that motor shafts with magnets placed on them were not perpendicular to the encoder board. We have solved this issue by designing a new mounting that holds the encoder board and magnet always in alignment and is connected to the shaft via a special clutch. The magnet is placed inside a ball bearing to allow for its undisturbed rotation.

One of the intriguing issues we have encountered during previous motor drivers tests. They have performed just fine during load tests in winter, but during summer they were getting so hot, that the electronic components would unsolder. It turned out the difference of around 50 degrees was big enough to cause their failure. That's why the new design of chassis incorporates a cooling tunnel for transferring the heat away from the boards.

Previous design of the inner communication between the PCB boards of the rover used the CAN bus. The flaw of this design was, that in case of failure of one board all the other boards could be damaged as well, thus resulting in failure of entire system. The new design incorporates galvanically isolated CAN bus, which in case of one components failure won't kill all the other boards.

Previous design of the inner differential bar, comprised of two aluminium sheets and a 3D print turned out to be too fragile and it cracked during one of the tests, when manipulator was lifting up a heavy object. To keep its light weight the new differential bar was created by milling an aluminium block.

The initial concept of the gripper's drive unit consisting of two servomecha- nisms was flawed. We faced problems with connecting the output shafts of the servos to the rest of the gripper and ultimately decided to redesign the whole drive unit to consist of parts with simpler and more reliable assembly methods. From now on we will surely pay more attention to the reliability of connections used in precise mechanisms, because this problem cost us a lot of time, effort and money.

We've encountered a problem with a malfunctioning voltage converter. The converter had been giving an output of about 8V instead of 5V, which could've been dangerous for our electronic systems. The problem was that we produced our custom PCB with tending vias on it, which did not allow us to solder the bottom pad of converter. The makeshift solution was to rip the solder mask under the integrated circuit and solder it again, now with the bottom pad solder directly to ground. In future, we cannot allow for such mistakes and we have to pay more attention during PCB design.

While placing orders for parts to assemble the redesigned drives we found that certain inch screws required to mount the gearboxes were harder to obtain than previously anticipated. This caused a minor delay and led us to realise how important it is to check availability of required components.