POLITECNICO DI TORINO

Master degree course in Mechatronic Engineering

Master Degree Thesis

Design and development of the T0-R0 rover for the European Rover Challenge 2018

Management of Team DIANA

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To Team DIANA

Two possibilities exist: either we are alone in the Universe or we are not. Both are equally terrifying.

[Arthur C. Clarke]

Summary

During the future manned missions to Moon and/or Mars, astronauts will be assisted by mobile robotic systems capable of performing various tasks, which span from scientific research to maintenance tasks. International intervarsity competitions have been set up because of the need to investigate, test and validate, in analog mission operational scenarios, solutions that will be applied to the next generation of space rovers. Team DIANA, a student team from Politecnico di Torino, developed T0-R0, an engineering model of an analog astronaut assistance rover, designed for competing in European Rover Challenge 2018. After an brief introductory discussion of planetary space robotics the execution of the project from the preliminary design phase to the production of the latest version of the rover will be described, which presents innovative solutions such as modified rocker boogie suspension system with shock absorbers and a robotic arm with exchangeable tools. The strict requirements and constraints of the project posed numerous challenges both technical (mechanical, electronic, IT) and organizational which will be illustrated and discussed in detail. Team DIANA managed to compete in the European Rover Challenge in September 2018 coming 15th out of the 65 competing teams, a good final result considering that it was the first time that an Italian team had reached the final stages of the competition, proving that the project was correctly carried out and setting a solid starting point for future improvements and developments.

Acknowledgements

Firstly I would like to thank Prof. Giancarlo Genta, the Team's academic advisor, for the trust he has shown in the team, allowing us complete autonomy in the management and execution of the project and for his passionate and constant support.

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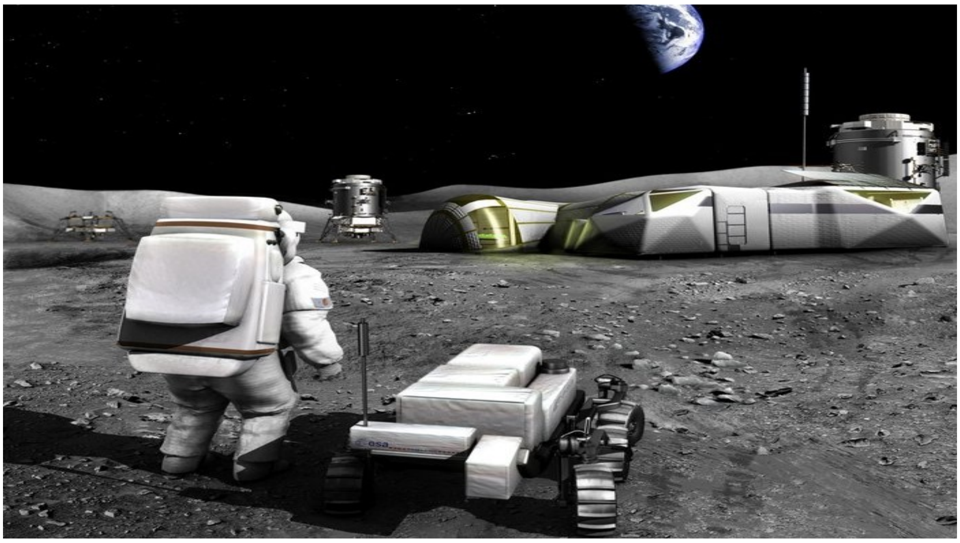


Figure 1.1: Artist concept human-robot collaboration in a future Lunar settlement.(Credit ESA)

In many respects, the ultimate "field" for robots is space. Creating robots for space is certainly one of the most ambitious engineering goals. Space applications present many challenges to robotic systems: from extremes of temperature, vacuum, shock, radiation, and gravity, to limitation on power, mass and communication; from the intricate complexity of system engineering, to requirements of reliability, robustness and efficiency.[1]

Robotic systems have been used for the exploration of our solar system while others have assisted astronauts in their activities on board the Space Shuttle and ISS. In the future in order to reduce human workload, costs and fatigue driven error and risk, intelligent robots will have to become an integral part of mission design (figure 1.1). [2]

In particular the use of astronaut assistance rovers will be of fundamental importance in the scenario of manned missions to the Moon and/or Mars. Up to now rovers, mobile robotic systems, have been used for the scientific exploration of the solid surfaces of celestial bodies of our solar system, however research is still necessary for the development of rovers that will one day work side by side with future space dwellers. In fact astronaut assistance rovers will have to carry out numerous tasks which span from maintenance and equipment servicing to scouting and sample collection.

The Rover Challenge Series is a series of competitions devised to promote the development of such rovers. Student teams from all over the world compete to produce multi-functional, low-cost, low-weight, remotely operated robots.

This dissertation will provide an overview of the design and development of the first version T0-R0 rover, an engineering model of astronaut assistance rover, which competed in the European Rover Challenge 2018th Edition. The project was carried out by Team DIANA in the period 2016-2018, during which the author was team leader and followed the project from the design phase, through its development and up to the participation in the competition.

In **Chapter 2** after a brief illustration of the space exploration rovers that have been sent to the Moon and Mars, an analysis of the characteristics of astronaut assistance rovers is carried out and the Rover Challenge Series is described.

Chapter 3 presents Team DIANA and it's projects, paying particular attention to the organizational aspects within a student team.

Chapter 4 describes every aspect of the T0-R0 project. It starts with an analysis of the competition rules and requirements which drove the design and successive development of the rover T0-R0 taking into consideration the available technologies, resources and time constraints which are also described. It goes on to discuss some of the problems that emerged and partially affected the outcome of the project but did not compromise the participation in the competition. After a break down of the funding and expenditure involved in the project the competition results are presented.

In **Chapter 5** a final consideration of the outcome of the project is made and possible future developments are discussed.

Chapter 2

Planetary space robotics

Since the dawn of the space era, the use of robotic system has been of fundamental importance for both assisting astronaut operations and for the exploration, from orbit or on the surface, of planets and other celestial bodies of our solar system and beyond.

Interplanetary rovers are a particular category of spaceprobes, designed for the exploration of the solid surfaces of planets and other celestial bodies, to do so these kinds of robots are equipped with some sort of locomotion system (generally wheels, but other kind of solutions have also been suggested such legs, skis, tracks, hopping systems [3]).

In the past decades rovers have been sent to the Moon and Mars in order to gather pictures and other scientific data for increasing our knowledge about our solar system and paving the way for future human missions. Because of the complexity of such missions only a small number have managed to land safely and successfully complete their missions.

2.1 Planetary exploration rovers: state of the art

Of all the successful space exploration missions effected so far only 11 have included the use of planetary rovers which operated on the Moon and Mars. In the following subsections these rovers will be briefly illustrated to give an idea of their main characteristics.

2.1.1 Lunokhod rovers

The Soviet Union's Lunokhod 1 (figure 2.1) was the first successful rover to explore an extra terrestial environment. It arrived on the Moon on Nov. 17, 1970, upon the Luna 17 lander. Driven by remote-control operators in the Soviet Union, it traveled more than 10 kilometers in 10 months. The rover was solar-powered by day

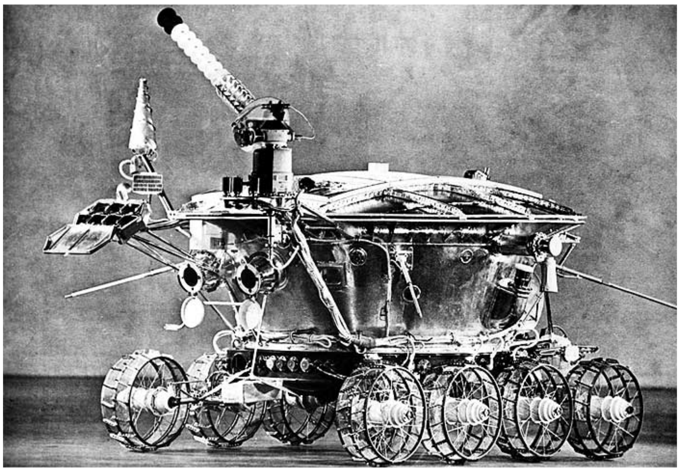


Figure 2.1: Lunokod 1 rover

and relied on thermal energy from a polonium-210 radioisotope heater to survive the nighttime cold, when temperatures reached minus 150 degrees Celsius. The rover was designed to last three lunar days. It exceeded its operational projection, lasting for eleven lunar days (approximately 10 months). The success of Lunokhod 1 was repeated with Lunokhod 2 in 1973, which eventually drove approximately 37 kilometers (22.9 miles) on the lunar surface in 4 months before facing break down, probably due to lunar dust that covered the radiators.[4] [5]

2.1.2 Luna roving vehicle

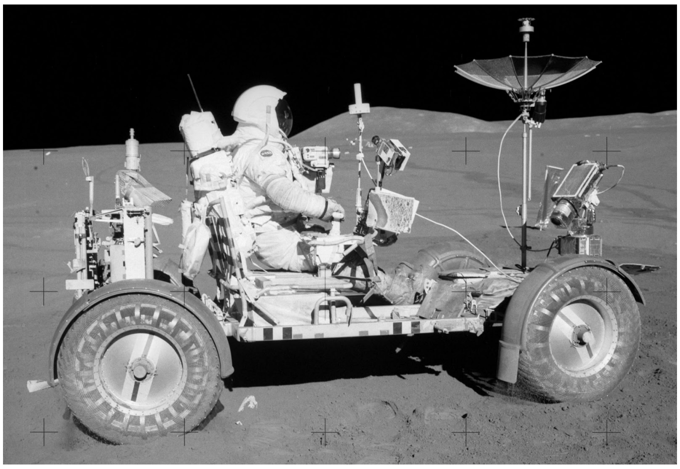


Figure 2.2: Luna roving vehicle driven by astronaut David Scott during the Apollo 15 mission. (NASA)

The Apollo 15, 16, and 17 lunar rover vehicles (LRV) driven by space-suited astronauts on the Moon in 1971–1972 were manned, four-wheeled vehicles but could be teleoperated from ground if necessary if the two-astronaut crew were incapacitated (Figure 2.2). Each rover was used on three traverses, one per day over the three day course of each mission. The longest traverse was 20.1 km and the greatest distance reached from the Lunar Module (LM) was 7.6 km, both on the Apollo 17 mission. The LRV had a mass of 210 kg and was designed to hold a payload of an additional 490 kg on the lunar surface. The frame was 3.1 meters long with a wheelbase of 2.3 meters. The frame was made of aluminum alloy 2219 tubing welded assemblies and consisted of a 3 part chassis which was hinged in the center so it could be folded up and hung in the Lunar Module quad 1 bay. The wheels consisted of a spun aluminum hub and an 81.8 cm diameter, 23 cm wide tire made of zinc coated woven steel strands. Titanium chevrons covered 50 percent of the contact area to provide traction. Each wheel had its own electric drive, a DC series wound 190 W motor capable of 10,000 rpm, attached to the wheel via an 80:1 harmonic drive, and a mechanical brake unit. Power was provided by two 36-volt silver-zinc potassium hydroxide nonrechargeable batteries with a capacity of 121 amp-hr. [6]

2.1.3 NASA's Mars rovers

Starting from 1997 NASA's Mars program followed a series of very successful missions which involved the use of rovers employing increasingly sophisticated technology every time. Figure 2.3 shows the models of the three generations of NASA's Mars rovers closely compared to each other.

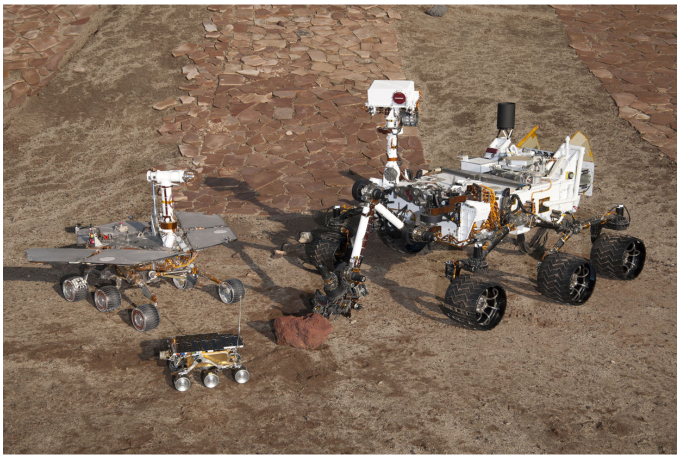


Figure 2.3: Photo of the models of NASA's Mars rovers. (NASA)

Mars Path Finder

Sojourner microrover was the very first rover to work on Mars. The rover landed in July 1997, at the Ares Vallis, on the Mars Path Finder (MPF) lander, designed for a mission lasting 7 sols[1], with possible extension to 30 sols. It was, in the end, active for 83 sols, traversing in total 106 m, all within 10m rage from the Pathfinder lander due to rover-lander radio link communication limits. Sojourner had a mass of 11.2 kg and dimensions of 63cm (length) x 28cm (height) x 48 cm (width). It used a six-wheeled rocker-bogie suspension system, Each wheel was powered by a tractive motor plus four additional motors on the outer wheels for steering. Sojourner carried three cameras: a forward-pointing monochrome stereo pair and a rear color camera for instrument pointing. However, its main navigation stereo panoramic camera pair resided on the Pathfinder lander on a telescopic mast. Sojourner had 16 x 0.127mm thick steel cleats per wheel which protruded 1 cm on each wheel. The vehicle could turn on the spot with a 37 cm turning radius and a top steering speed of 7°/s; steering angle feedback was provided by potentiometers. Sojourner traveled at speeds of 15 cm/s and stopped for hazard detection every 6.5 cm (one wheel radius). Sojourner drew 4W to drive the wheels, 1W for the microcontroller, and 1W for onboard navigation. Sojourner steered autonomously (dead reckoning) to avoid obstacles using its wheel odometry, potentiometers, gyroscopes, and accelerometers to generate steering requirements to reach commanded goal locations. Sojourner hazard detection was based on proximity sensors including a frontal stereo camera pair, five laser striping projectors, and frontal contact sensors.The rover had hybrid power supplies composed by non rechargeable battery (150 W/hr) in combination with solar panels (capable of producing max 16 W).[8][6]

Mars Exploration Rovers

In 2004 two twin rovers named Spirit and Opportunity landed on the two opposite sides of Mars, the rovers operated well beyond the nominal 90 sol missions: Spirit's mission finished in 2011 while Opportunity carried on until the 10th June 2018, when contact was lost due to a massive sand storm that obscured the sun for several months and probably covered the solar panels of the rover, the mission was declared officially concluded on the 13th February 2019.

Their mission was to characterize the geology of their local landing sites like "robotic geologists" in search of clues for aqueous processes contextual to Mars' astrobiology potential. Both rovers had a mass of 174 kg with a total vehicle length of 1.6m and wheel baseline width 1.22m and length 1.41m.

The chassis, like the Sojouner rover, was a six-wheeled rocker-bogie springless

[1] A Mars solar day has a mean period of 24 hours 39 minutes 35.244 seconds, and is customarily referred to a "sol" in order to distinguish this from the roughly 3% shorter solar day on Earth.[7]

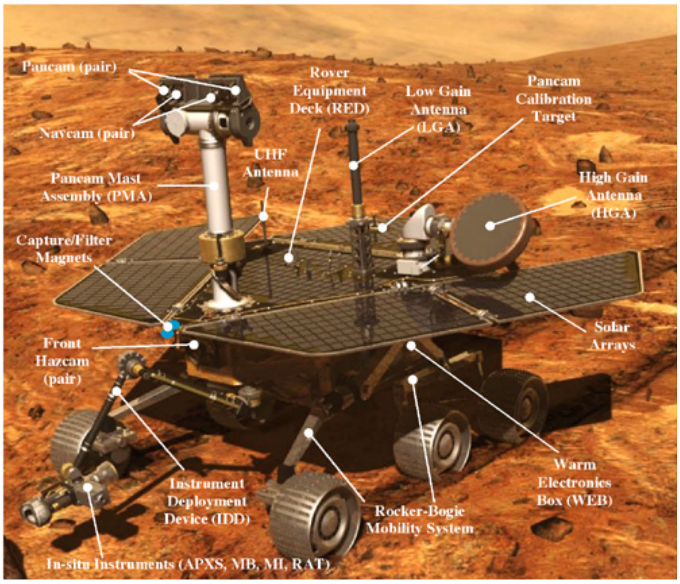


Figure 2.4: Render of the Mars Exploration Rover. (NASA)

suspension. The rovers structure was based on composite panels with titanium alloy fittings while the rocker suspension was constructed from titanium alloy mounting six aluminum alloy wheels. Each wheel had a diameter of 25 cm diameter with the six-wheel configuration defining a 1.4m length x 1.2m wide footprint. Each wheel was independently driven, the four corner wheels being steerable for on-the-spot turning (with turn radius of 1.9 m). Each wheel was cleated for increased traction. The design average traverse speed was 100 m/day including stops constrained by both energy consumption limitations and the risks inherent in target designation beyond 100 m. A 1.4m tall pan–tilt PanCam mast assembly mounted both navigation and science stereo camera platforms and thermal emission sensors. Hazard camera pairs were mounted onto the front and back of the rover. The mast mounted both the scientific stereoscopic PanCam and the traverse-supporting stereoscopic NavCams.

The maximum speed of the rover on flat ground was 4 cm/s but hazard avoidance would reduce this to 1 cm/s. The center of mass of the rover resided close to the rocker-bogie pivot giving it 45° lateral stability though software fault protection flagged any tilt exceeding 30° with an alarm condition. Each rover carried a Litton LN-200 inertial measurement unit incorporating three-axis tilt and rate data. MOLA (Mars Orbiter Laser Altimeter) data were used to localize the rover by triangulation from orbit initially. UHF Doppler tracking from orbit provides coarse navigation to within 100m accuracy supplemented by additional in situ techniques. Onboard self-localization error using onboard sensors was 10% and cumulative but the adoption of visual odometry reduced this error to 1%. The rover moved 30 cm traverse segments at 5 cm/s at a time separated by stops of 20 s for navigation functions with daily traverses usually limited to around 10m (though this constraint was relaxed later in the mission). Hazard detection was enabled through the hazard cameras (HazCam) the images from which were processed while static. As the terrain was imaged, they were collect incrementally into world model maps of 10 x 10 m. [6]

Mars Scientific Laboratory

Figure 2.5: Self portrait of Curiosity rover taken with the camera mounted on the robotic arm on Mars. (NASA)

Part of NASA's Mars Science Laboratory (MSL) mission, Curiosity is the latest, largest and most capable rover sent to Mars so far (figure 2.5). Touching down on the Martian surface on the 5th of August 2012 in the Gale crater, NASA successfully demonstrated the capability of landing with extraordinary precision within an ellipse 20 km long and 7 km wide, thanks to the innovative and complex entry and landing phase which included the use of a sky crane for the final rover touch down.[9]

Curiosity weights nearly 900kg , of which 80kg are of scientific instrumentations, and it is about the size of a small SUV: 3m long (not including the arm), 2,7 m width and 2,2m high.

The rover is powered by a "Multi-Mission Radioisotope Thermoelectric Generator" or MMRTG for short. The MMRTG converts heat from the natural radioactive decay of plutonium into electricity, providing 110W of electrical power necessary for powering the rover and it charges two lithium ion batteries rechargeable batteries to meet peak demands of rover activities when the demand temporarily exceeds the generator's steady electrical output levels. The heat from the MMRTG is also used to keep the rover's tools and systems at their correct operating temperatures.

Like for the previous NASA's Mars rovers, Curiosity presents a 6 wheeled rocker-bogie mobility system, the four external steering wheels allow the vehicle to turn in place and to perform arch shaped, with constant radius, turns. The structure is made out of titanium tubing while the wheels, which have a diameter of about 50cm, are made made of aluminum, with cleats for traction and curved titanium springs for springy support. The maximum speed of the rover on hard flat terrain is 4 cm/s but it is expected to have an average speed of less than than half of that.

The rover has two robotic arms:

- the mast, which has 2 DoF, it carries seven out of the seventeen on-board cameras and supports the Rover Environmental Monitoring Station (REMS).
- a 5 DoF, 2.1m long, robotic arm which carries on the hand 5 different tools and sensors.

The main mission objective is to identify if in the past Mars had the environment characteristics necessary for supporting microbial life. To do so the rover carries 10 different scientific instrumentations.[10]

2.1.4 Chang'e 3 and 4

Both the Chang'e 3 (2013) and Chang'e 4 (2019) missions, part of the China Lunar Exploration Program, successfully landed two similar rovers YuTu (shown in figure 2.6) and YuTu-2. In particular Chang'e 4 hold the primate of being the first lander and rover to land on the far side of the moon.

The rover's mass is approximately 120 kg, including 20 kg of payload. The rover has a rectangular cuboid body which supports solar panels. A turret supports cameras and antennas and a robotic arm is used to collect soil samples.

The mobility is a 6-wheeled rocker-bogie suspension system, with four external steering wheels. The wheels a powered by BLDC motors. The rover can climb up to 20° slopes and drive over 20cm obstacles.[11]

Figure 2.6: Photo of the Yutu rover taken by the Chang'e-3 lander (redit: BACC, CAS)

YuTu rover, was designed to operate 3 lunar days but after 6 weeks, covering 114.8m, it was subject to failure to the mobility system, the mission was ended ion august 2016. [12]

2.1.5 2020 scheduled missions

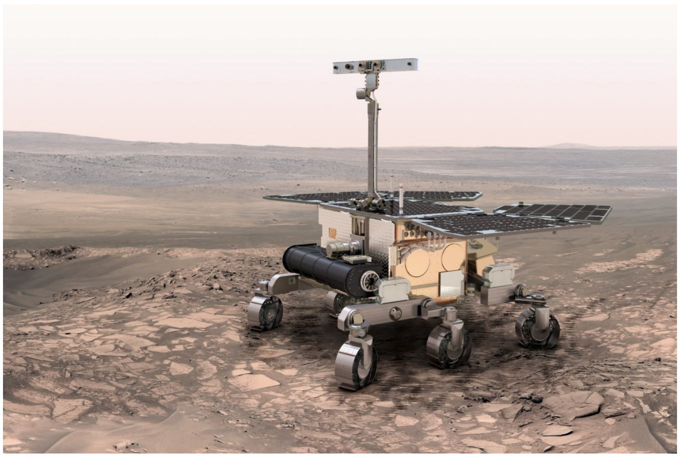


Figure 2.7: Rendering of ESA's Rosalind Franklin rover (credit: ESA)

Both NASA and ESA are planning to launch rovers rovers on Mars during the end of July 2020 launch window.

NASA's Mars 2020 rover is strongly based on the design of it's successful predecessor Curiosity rover. The mass is slightly higher 1050 kg (vs 900kg of Curiosity), carries 7 scientific instruments and 23 cameras. The rover will try to produce oxygen form the carbon dioxide present in the planet's atmosphere and it will collect and cache samples for a future sample return mission. In addition the rover will be accompanied by the very first Mars helicopter.[13]

Part of the ExoMars programme led by the European Space Agency and the Roscosmos State Corporation, Rosalind Franklin is a rover designed and developed by ESA that will have the objective to search for biomarkers, which are a direct sign of present or past life on the planet. To do so, the rover carries a drill capable of extracting samples form various depths, down to a maximum of two meters. The power system will comprise solar panels capable of producing 1200 Wh working in combination with Saft's 1142 Wh (nominal) battery system. The system will store the energy generated by the solar panels to ensure uninterrupted operation during the Martian night. The rover will provide highly autonomous functions for both navigation, traveling (in order to travel up to 100m per sol) and for scientific operations. The mobility systems consist of 6 wheels, which are in pairs suspended on independent pivoted bogies, each wheel can be independently steered and driven . The rover has also the possibility to move in a sort of walking mode. The total mass of the rover will be approximately of 300 kg.[14]

2.2 Future generation of space rovers

Up to now the main objective of the space probes has been the gathering of precious scientific data and, in parallel, validating and consolidating technologies used for space and planetary environments. But in the perspective of future manned missions to the Moon, Mars and the asteroid belt for both scientific and commercial means, the development of new robotic systems is necessary. In fact it is expected the use of robots will be fundamental for the preparation of base sites for future manned arrival, mining, astronaut transportation and in general for assisting astronaut operations on board space craft and during extra vehicular activities (EVA) in space or on the surface of space bodies.

In particular robots designed for the assistance of astronauts on the surface of planets may be used for different operational scenarios briefly illustrated in the following paragraphs.

Preliminary surface exploration In order to save time or limit risks associated to EVAs, rovers could be used for a preliminary exploration of the surface of the planet for identifying the sites of interest for successive astronaut exploration. This kind of operation requires that the robot be equipped with instrumentation for preliminary scientific measurements and sample return containers. The rovers could perform these missions autonomously or be teleoperated by astronauts from a base placed on the planet surface or from orbit.

For these reasons astronauts need dexterous robotic systems, which can be operated by humans, to support extravehicular operations on the infrastructure The expectation of human-robot cross-operation on such infrastructures necessarily influences the design of future infrastructure elements in order to simplify operational aspects. Ideally it would be best to robustly automate tasks that require a high level of attention for long periods which is tiring for a human operator and increases the risk of error.

Assist astronauts during extravehicular operations During EVAs by astronauts, rovers could be used for the transportation of tools, scientific instruments, soil samples and life support systems. As in the previous scenarios the rovers could be teleoperated, autonomous or semi-autonomous or present some kind of vocal control by the astronauts.

The above mentioned tasks require multi-functional robotics systems similar in some respects to the current exploration rovers but different in others, in particular regarding their speed: the rovers used up to now on Mars and the Moon have very low maximum speeds (just a few meters per hour),due to power limits and safety reasons, while a rover for astronaut assistance must have a moving speed at least as fast as a walking man (3-5km/h). In addition these systems must be equipped with manipulators capable of working with different kinds of objects and materials for example loose soil, rocks, instruments and infrastructures intended for human use. Autonomy during the traverse and the operations would lighten the astronauts' work.

The possibility of maintenance work on the rovers by astronauts would allow the rovers to be reconfigured according to the task to be performed, and the possibility of repairing and upgrading the rovers during their life span impacts particuarly on the degree of reliability these systems present, reducing the rate of redundancy of current exploration rovers have in order to avoid mission failure caused by non repairable faults.

The costs and masses of these systems must also be limited given the enormous masses and costs of the other systems necessary for manned missions.

Exploration rovers are electrically powered by on board solar panels or RTGs (Radioisotope Thermal Generators) which directly power the rover and/or charge on board batteries, but mass and space constraints limit the maximum available power for these systems. For a manned mission a power plant will be necessary for sustaining all the systems of the settlement, and would also allow batteries used for the astronaut assistance rovers to be recharged, consequently simplifying the design and permitting higher power limits.

2.3 Rover challenge series

In space robotics as in space activities in general the term Technology Readiness Level indicates to the level of maturity of a specific technology with regard to the possibility of using it in a real space mission. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest. The following is the list of the various TRLs:

- **TRL 1** Basic principles observed and reported
- **TRL 2** Technology concept and/or application formulated
- **TRL 3** Analytical and experimental critical function and/or characteristic proof of concept
- **TRL 4** Component and/or breadboard validation in laboratory environment
- **TRL 5** Component and/or breadboard validation in relevant environment
- **TRL 6** System/sub-system model or prototype demonstration in an operational environment
- **TRL 7** System prototype demonstration in an operational environment.
- **TRL 8** Actual system completed and "flight qualified" through test and demonstration
- **TRL 9** Actual system flight proven through successful mission operations. [15]

For university science teams it is difficult to go beyond testing in a laboratory setup (TRL 4), going beyond this phase would require enormous resources which would only be spent if an actual mission were being planned. Another way to push the technology further is the so-called analog missions. These are missions that aim to simulate as much of the full functionality of the system in an ‘as close as it gets’ environment under terrestrial conditions. What analog missions bring to the table is the need to completely integrate all technologies (HW and SW) in the fully equipped system. From the ‘simple’ com link to the complex, autonomous path and manipulation trajectory planning all the way to mission control and operator interaction, everything has to be working in concert time of the ‘analog’ mission.

In fact, a fully integrated system is almost always more than the sum of its parts. There are cross-component effects that simply cannot be foreseen in the design and controlled environment testing phase. This is even more true for systems interacting with a dynamic, real world environment, possibly under harsh conditions.[16]

Analog missions and competitions are therefore fundamental for the successful development of real future space missions .

Many competitions, simulations and analog missions are organized in order to encourage research towards innovative solutions for currently unresolved problems in the space robotics sector, or to test possible operational scenarios that could be encountered in future space missions; one of these is the Rover Challenge Series.

The Rover Challenge Series is the most prestigious robotics challenge league, for university student teams, powered by the Mars Society[2] and its international affiliates. It consists of the following competitions (figure 2.8):

- University Rover Challenge - URC (first edition in 2007)
- European Rover Challenge - ERC (first edition in 2014)
- Canadian International Rover Challenge - CIRC (first edition in 2018)
- Indian Rover Challenge - IRC (first edition in 2018)
- UK University Rover Challenge - UKURC (first edition in 2016)

University Rover Challenge

(a)

ERC EUROPEAN ROVER CHALLENGE

(b)

CIRC CANADIAN INTERNATIONAL ROVER CHALLENGE

(c)

IRC INDIAN ROVER CHALLENGE

(d)

Figure 2.8: Logos of the Rover Challenge Series Competitions

The aim of these challenges is to get student teams to design and build a prototype of an astronaut assistance rover and compete in various task that simulate

[2]The Mars Society is the world's largest and most influential volunteer-driven space-advocacy non-profit organization dedicated to promoting human exploration on the planet Mars. http://www.marssociety.org/

the jobs that will one day be performed by the robots that will accompany the astronauts in the future manned missions to Mars[3]. These competitions also give the participants a chance to expand their knowledge of Martian exploration, provide valuable experience in different fields of engineering, project and team management, project documentation and presentation while also promoting STEM (Science, Technology, Engineering and Mathematics) and, especially, space exploration and robotics among the wider public.

All the above mentioned competitions present similar requirements:

- they must consist of stand alone platforms, remotely teleoperated with no direct view over the rover, no wiring is allowed for data or power transmission.
- configuration of the rovers can changed between one task and another
- total mass for each configuration must be inferior to 50/60Kg.
- use of COTS (off-the-shelf components) is allowed and encouraged.
- rovers must be built with a low budget; the total value of the rover must be inferior to approximately 20000€ (depending on the competition).

Regarding the last point of the previous list; limits to the overall cost of the rover are set, on the one hand, to induce the necessity to find low cost solutions for space projects and, on the other hand, to ensure a level playing field between teams that may have different economic resources available. The use of COTS is therefore encouraged because of their lower cost in comparison with custom components.

[3]Similar operations could also be performed in a manned mission to the Moon, but since the competitions are organized by the Mars Society they are presented in a Mars mission scenario.

Chapter 3

Team D.I.A.N.A.

Figure 3.1: Team DIANA original logo

Team DIANA is one of the Politecnico di Torino's oldest and most important student teams (logo in figure 3.1 and a photo in figure 3.2). The acronym DIANA stand for *"Ducti Ingenio Accipimus Naturam Astrorum"* which can be translated from Latin to *"guided by intelligence we can learn about the nature of the stars"*.

Team DIANA is a research group made up of students enrolled in degree courses (I,II and III level) at Politecnico di Torino and it was founded in 2008. The Team focuses on projects related to the field of robotics for space applications, and one of its purposes is to become a reference point in this field of studies within the University.

In October 2018 Professor S. Corpino took over as Accademic Coordinator of team DIANA succeeding Professor G. Genta who held the role from 2008 to 2018.

Team DIANA is officially registered as an affiliated team of the DIMEAS (Department of Mechanical and Aerospace Engineering) but, due to the interdisciplinary nature of the projects, it is also sustained by the DET (Department of Electronics and Telecommunication Engineering) and by DAUIN (Department of

Automation and Computer Science Engineering).

The Politecnico di Torino strongly promotes student teams, allowing the possibility to request conspicuous funding to support the teams' activities (section 3.1.4), in fact they are considered an important resource for both the students and the university itself for several reasons:

- **Strengthening the university didactics**: members of student teams get a unique opportunity to gain experience by:
  - working on real projects
  - putting into practice what is learned during courses
  - expanding and improving their knowledge about arguments not always strictly related to their study field
  - gaining experience in team work
  - dealing with problems encountered on real projects
  - collaborating with external companies
  - improving communication skill by writing technical reports and presenting projects to the public

  All of the above add important value to the students' CVs.

- **Promote university image and activities**: thanks to the participation in events such as competitions, meetings and presentations, the teams promote the University's activities and their innovative projects to the wider public.

- **Promote collaboration between university and companies**: Teams are encouraged to look for collaborations and sponsorships with external companies that may be interested in contributing to or collaborating with the student teams.

3.1 Management of a student team

The author had the honour of holding the position of team co-leader and project manager of Team DIANA, from October 2015 to October 2018. During this period the team faced radical changes due to the ending of the first project AMALIA (presented in section 3.2.1) and the start of the newer project named T0-R0 (presented in section 3.2.2), which is also the main focus of this thesis.

Organising and managing a sizeable group of people (in this case a broad-based group of young students), with an ambitious project to develop, is a complex and demanding task but it has certainly been an enriching and rewarding experience.

Figure 3.2: Photo taken after a general meeting in May 2018.

3.1.1 Team composition

To better understand how the work within the team is organized it is important to illustrate the composition of the team. The number of active members in the team each year ranges between 40 to 70 students, and over 350 students have contributed to the growth of the team since 2008. The team members come from both Bachelors and Master courses in many different areas of engineering: aerospace, mechanical, automotive, electronic, computer science, mechatronic, materials, communication and cinema, energy, telecommunications, biomedical, management and physics engineering

In addition to Bachelor and Master students the team is supported by a few PhD students (generally ex team members), professors and external experts that share their experience and give advice to the Team in case of need.

The Team can also claim a high cultural heterogeneity thanks to the presence of many foreign students.

The distribution of the team members between the various courses is shown in figure 3.3, it can be seen that the majority of the members come from aerospace and mechanical engineering courses with respect to the smaller number of students belonging to the electronics and computer science fields. While the high number of aerospace students can be justified by their natural attraction to the space sector in which the team operates, it would be extremely useful if more electronics and

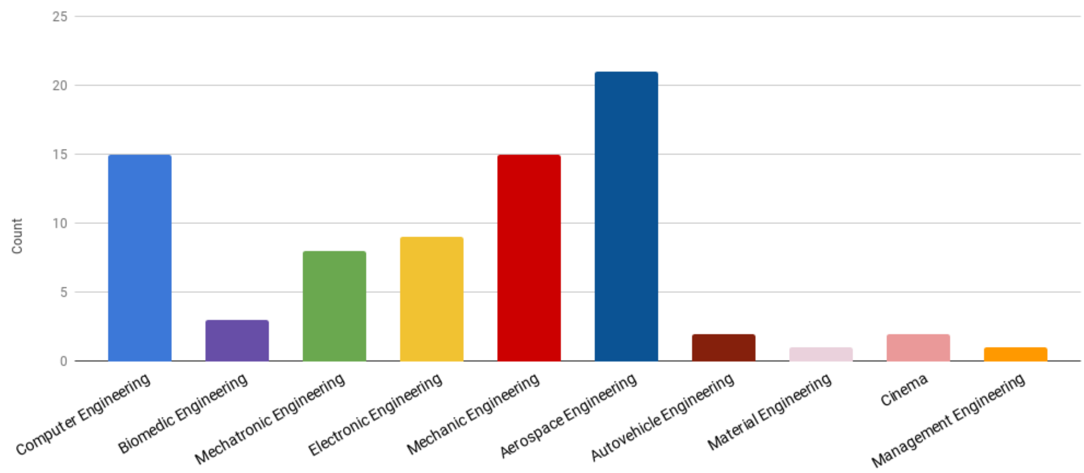


Figure 3.3: Distribution of team members between the various engineering courses in 2017/2018 a.y.

computer science students could be recruited onto the team as the project offers plenty of scope to put their skills into practice. Hopefully the future team leaders will find strategies to attract more students from the electronics and computer science courses, perhaps by encouraging the professors in these departments to help to motivate and incentivate their students' participation in the team projects.

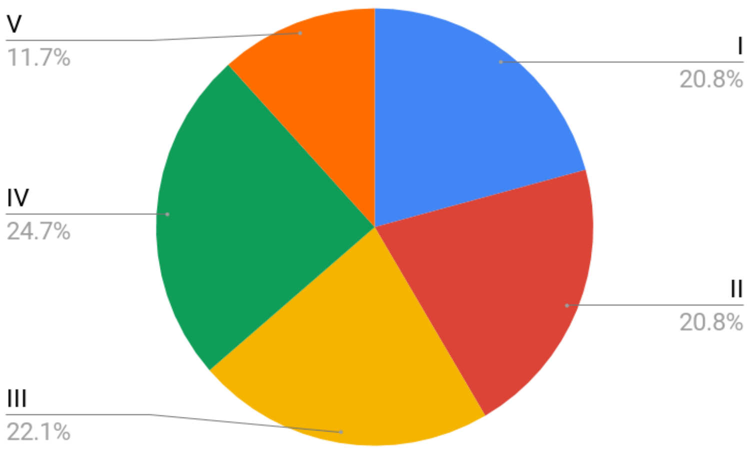


Figure 3.4: Distribution of team members between the various years in 2017/2018 a.y. IV and V indicate the master course years.

On average the team is made up of approximately 60% undergraduate students and 40% graduate students (figure 3.4); though undergraduates obviously do not have the same breadth of knowledge as the master's students, they do tend to have more time available to dedicate to the team.

Since most students spend only a few years in the team (rarely more than 3 or 4 years), the team has to face the high rate of turnover of its members; for this reason it is important to involve the particularly talented students from the first years of their studies, in order to allow them to spend as much time as possible within the team and gain enough experience and training for them to lead the team in the future.

The large variation in the number of team membersover the course of the year (between 40-70) is caused by a high drop out rate; in fact it's common that many students, no matter how willing and passionate about the project they are, cannot manage the work load required by the team in addition to their already demanding university commitments. To help reduce this problem, team members have the chance to request the substitution of a 6 CFU "free choice" exam with the recognition of the work carried out within the team, but this possibility is restricted to the most productive members in order discourage students who are only interested in avoiding an exam from entering the team. In addition, it is possible for members to use their work as the basis for a thesis project.

3.1.2 Team and work organization

The team's workflow tends to naturally follow the academic year, focusing the work during the course periods and pausing during the exam periods; the team activities begin after the September exam session, following the general structure presented below (and illustrated in figure 3.5):

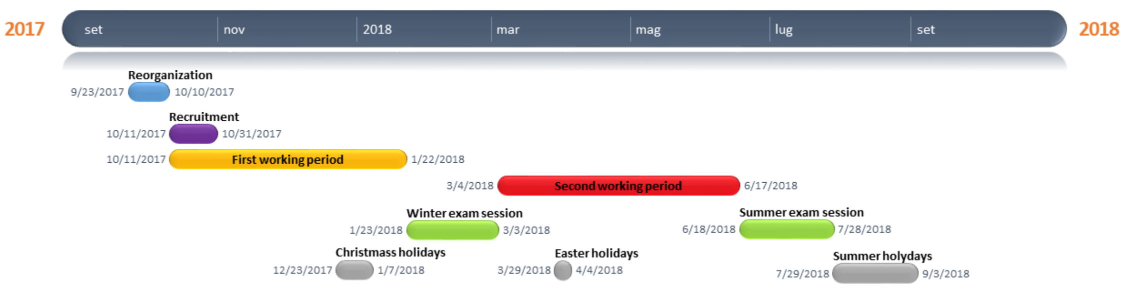


Figure 3.5: General timeline of the team's working periods during an academic year.

- **Team reorganization** *(End September - beginning of October)*: to ensure the continuous growth and improvement of the Team, at the beginning of each year a critical analysis of the previous year is carried out in order to identify strengths and weaknesses of the Team and find possible solutions to the latter.

In this period it is important to identify which members are going to continue in the team and how many new members need to be recruited and which fields they should ideally come from. New team leaders and subgroup leaders are nominated where necessary. The objectives for the year are identified and a preliminary time line and work schedule is created.

- **Firs period of work** *(Mid October - mid January)*: once the work has been organized and the recruitment period is over the members start to actively work on the project.
- **Winter exam session pause** *(End of January - beginning o March)*: in order to allow students to concentrate during the exam period the team activity stops, or in any case it slows down; in the last years, with the strict competition deadlines, it was not possible to completely stop the team's activities.
- **Second period of work** *(March - mid June)*: once the exams are over the team activities start again regularly until the summer exam period.
- **Summer exam period and holidays** *(Mid June - end of September)*: for years during this period the team activities used to stop, but during the summer of 2018 it was necessary to carry on with the team activities in order to manage to compete in the ERC, this lead to significant problems that will be illustrated in section 4.7.

The work is carried out in groups and sub-groups divided according to study field, tasks and duties such as:

- Mechanics group
- Electronics group
- Computer science group
- Media group
- Management group

Each group meets up, generally, on a weekly basis. Meetings are held in the evenings since it is usually the only time when all the students from the various course are available; during these meetings stock is taken of the current situation , decisions are made and work is carried out.

Because of the difficulty of gathering 70 people, all with different personal commitments, the team general meetings are organized just a few times per year; usually these meetings are also an occasion for team building activities (often a team dinner after the meeting, but other activities have been organised) which are fundamental to create a sense of unity and cohesion and to allow the members of different groups to get to know each other better.

The group leaders, nominated in a democratic way on the basis of their experience and availability, generally spend a great deal of time in the Team's laboratory (section 3.1.3), or in any case meet up frequently; this allows them to remain constantly updated on the progress of the various work groups, to coordinate with each other and ensures the successful integration between the various subsystems of the project.

Organizational chart

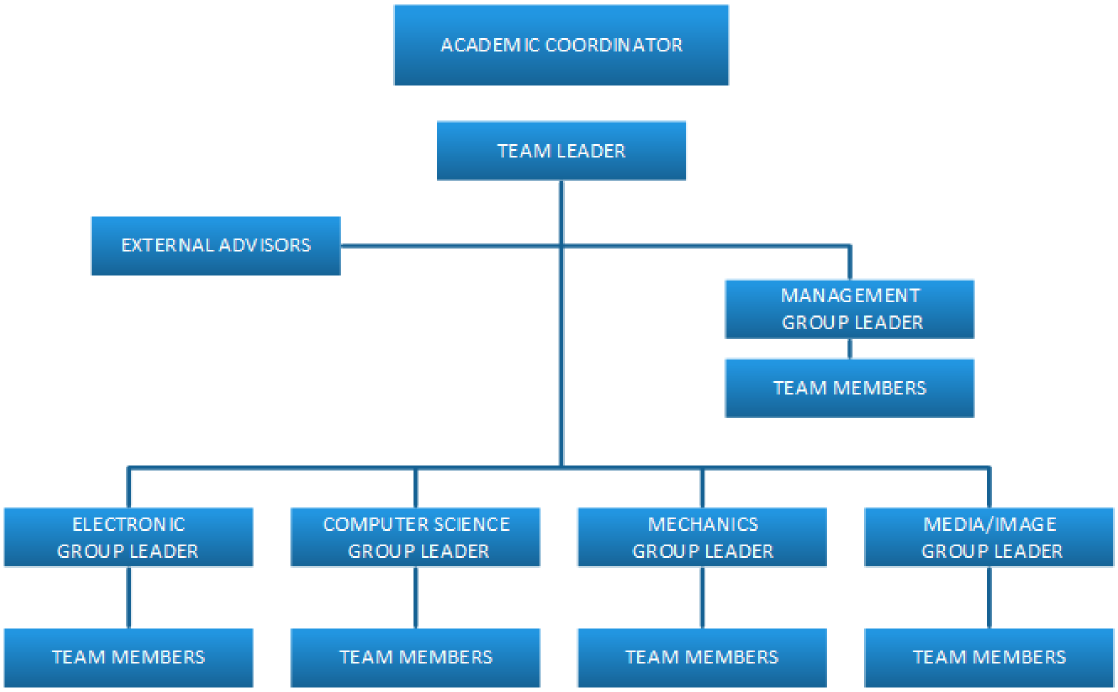


Figure 3.6: Organizational chart of team DIANA.

An organization chart is drawn up in order to show the structure of the team and the relationship between its parts (figure 3.6). A Project Team Organizational Chart is a detailed and document-based graphical representation of the team which outlines specific roles, duties and responsibilities of the team members and other stakeholders participating in the project, and formally represents exactly how they are expected to collaborate with each other throughout the course of the project.[17]

In the chart four different roles can be identified:

- **the Academic coordinator** is the founder of the team and has several responsibilities and duties:

  - Assumes responsibility for the management of funds.
  - Provides scientific and technical support to the design phase.
  - Provides guidance to students on academic goals and educational issues.
  - Assists students on course selection, study habits and career selection.
  - Assists in selecting the right student team leaders.

- **Team leader/group leaders**: a team/group leader provides leadership and guidance to the team and takes responsibility for the results of teamwork. The team/group leader role involves the development and encouragement of the team members through training, leading, motivation, recognition, rewarding and other activities that stimulate and drive team members to do the required tasks. Team leaders are also involved in managing the budget, bureaucracy (i.e. purchase offers, etc.), contacts with companies and finding sponsorship for activities and projects.

- **Team member**: a project team member is a student who is actually involved in doing assigned tasks. Team members directly access the project and actively evolve its processes.

- **Contributor**: a project team contributor is a PhD student or an ex-team member or professor e.g. a student who has completed the degree programs) who participates in teamwork but is not actually involved in performing tasks and carrying out project team responsibilities. Contributors help improve the project through giving valued suggestions, expert judgment and consultation. They are not responsible for the project results. Often project team contributors have an interest or concern in the project, so they facilitate successful completion.[17]

The organizational chart is a useful tool: for instance, team members use the chart to explore what roles and responsibilities they have been assigned to, who will share those roles, and who will manage and lead their efforts. A group of young students turns into a team when every person in the group is capable of meeting the following conditions [17]:

- Understanding the work to be done within the endeavor.
- Planning for completing the assigned activities.
- Performing tasks within the timeline and quality expectations.
- Reporting on issues, changes, risks, and quality concerns to the leader.
- Communicating status of tasks.
- Being a person who can work well in cooperation with others.

Recruitment

Up to 2015 no formal recruitment process was ever organized; students interested in entering the team were free to join at any point during the year; this was possible because of the non restrictive deadlines of the AMALIA project, also the team activities were not widely publicised which kept the arrival of new members at a reasonable rate. However, this kind of approach is not feasible in the case of a project with short deadlines: for example T0-R0 project presents yearly deadlines which correspond to the timing of the competition. In this case it is necessary to organize a precise recruitment campaign at the beginning of the year, in order to start working with a well-defined group of people as soon as possible. Thanks to the experience gained over the years, it has become possible to create a well structured recruiting phase which allows the best candidates to be enlisted in the shortest possible time. The recruitment phase can be broken down into the following steps:

- **Identification of the number and types of new members needed** : after defining the year's objectives and work schedule, the team and group leaders define the number and profiles of the new members they intend to recruit.

- **Publicising of the recruitment campaign**: the recruitment campaign is advertised through different communication channels such as the Team's social media pages, website, posters and thanks to the university mailing list system. During the recruitment campaign the team activities are briefly presented, the date of the public presentation is communicated and students are required to confirm their intention to attend to give an idea of the numbers expected. It is fundamental to try to reach the highest number of students possible in order not to miss any potentially valuable new members.

- **Team presentation**: a presentation meeting is organized to illustrate the Team's activities, share details about recruitment methodology and answer questions from the public. During the last presentation a live streaming was also organized.

- **Preliminary selection phase**: At the end of the presentation a link to an on-line questionnaire is shared. The questionnaire contains different kinds of questions regarding:

  - General information: name, field of studies, year of registration.
  - Technical skills, software knowledge, previous experience.
  - Motivation letter, time available per week, expected permanency, availability during summer.
  - A series of problems and exercises of varying difficulty to solve .

Candidates are given approximately 3-4 days to complete the questionnaire. This is used to make a preliminary selection of the members qualified for accessing the interview. Before the interview extra informative documents regarding team projects and competitions are given out.

- **Interviews and final selection**: selected students are called for an interview with the group leaders; during a 20 minute meeting, the questionnaire is discussed and the students' motivation and availability is evaluated.
- **Training phase**: once the recruitment is over a series of meetings are organized in order to instruct the new members in the team activities, working methods and software used.

The ideal candidate is a student with a strong background in his/her field of studies, with previous experience with projects, willing to learn and contribute to the growth of the Team. Flexibility, autonomy, independence, predisposition to team work and availability (indicatively the team requires at least 8 hours per week of work) are also important characteristics that must be kept in consideration. In my experience I have seen that these last qualities are particularly important for the success of the team and that high academic achievers do not always make the best team players.

The evaluation of students is not an easy task, especially considering that the time for this phase is be limited and the recruitment is done by other members of the team (students judging other students) with no real expertize or much experience in recruiting. Nevertheless, year after year, recruitment is becoming more and more efficient and successful. To give an idea, the latest recruiting numbers are presented in table 3.1.

Table 3.1: 2018 recruiting numbers

participants at the presentation	>250
questionnaires received	136
students interviewed (in four days)	70
new members selected	30

3.1.3 Workspaces and communication

In order to carry out the work physical spaces are needed and functional communication channels are of fundamental importance.

Workspaces

The availability of physical spaces is a critical issue within the Politecnico di Torino, the huge number of students, lessons and activities makes it hard for student teams to find laboratories and rooms where they can store material, organize meetings and in general carry out their activities. Team DIANA is fortunate in having the use of the micro-electronics software lab, located at the third floor of the DET (figure **??**). The laboratory has several electronic instruments: power supplies, oscilloscopes, signal generators and soldering stations. In addition, within the DET there is also a small workshop where simple mechanical jobs can be performed and a series of 3D printers are available. Other rooms and classes around the university can be booked for meetings if necessary.

Communication and file sharing

Information is passed within and through the team thanks to various communication channels:

- **Team-work on-line chats**: most of the information is shared thanks to free chat services specifically designed for team work, in particular the team uses Slack[1]; more informal than emails, it allows a fast, simple and effective means of communication and discussion. Channels can be created in order to reach precise receivers, reaction buttons allow fast and simple feedback and thanks to extra plug-ins it is easy to interface Slack with other applications and web services used by the team. The application can easily be used on both computers and smartphones.
- **Emails**:the most classic way for communicating since the Internet era, emails are generally used for general and complete information to all the members of the team.
- **Reports**: team member are required to write reports of the work done, these reports are important for tracking the team work and allow all members to be informed on the project's status and progress.
- **On-line notice board**: Trello[2] is an on-line collaboration tool used for the organization of projects, contains lists of task that must be done or their level of progress and who is responsible for them.
- **Orally**: traditional meetings are always an effective way of exchanging information and discussing any questions.

The team also relies on Internet cloud services for file sharing and storing. Google drive[3] is used for sharing files and documents while GitHub[4] is used for the codes.

[1] https://slack.com/

[2] https://trello.com/

[3] https://www.google.com/drive/

[4] https://github.com/

3.1.4 Funding and budget management

As previously mentioned, Politecnico di Torino supports student team activities thanks to funding. The funding can be requested from the "Commissione Contributi e progettualità studentesca" (Commission for contributions and student teams) by presenting a project plan and detaiedl budget estimate as explained in the Commission regulations [18].

Though the academic advisor resposible for the team's funds and signs the orders, it is the team leader's duty to manage the budget correctly and keep track of the team expenses. This task is carried out with the use of spreadsheets where all the incomes and outgoings are recorded, during this process it is fundamental to keep a careful record of the details of the various expenses in order to ease the process of final reporting at the end of the project.

3.2 Team's projects

Since 2008 team DIANA has worked on two main projects, both consisting in the design and building of engineering models of space rovers.

3.2.1 Project AMALIA

(a) (b)

Figure 3.7: Logos of the Google Lunar X Prize and of Team ITALIA

Team DIANA was founded in 2008, in order to represent the Politecnico di Torino in the national Team ITALIA[5] (logo in figure 3.7a), whose objective was to compete for the Google Lunar X Prize (logo in figure 3.7b), the mission was named AMALIA (Ascensio Machinae Ad Lunam Italica Arte).

The Google Lunar X Prize was a competition launched in 2007, offering a total of US$ 30 million in prizes to the first privately funded teams to land a robot on the Moon that successfully travelled more than 500 meters and transmitted back high-definition images and video. The first team to do so would have claimed the US$ 20

[5]http://www.amalia-teamitalia.it

million grand prize; while the second team to accomplish the same tasks would have been awarded a US$ 5 million second prize. Teams could also earn additional money by completing further tasks beyond the baseline requirements required to win the grand or second prize, such as traveling ten times the baseline requirements (greater than 5,000 meters), capturing images of the remains of Apollo program hardware or other man-made objects on the Moon, verifying from the lunar surface the recent detection of water ice on the Moon, or surviving a lunar night. Additionally, a US$ 1 million diversity award was to be given to teams that made significant strides in promoting ethnic diversity in STEM fields.

The competition ended in January 2018, with Google retiring as sponsor with no successful team managing to send their rover to the Moon. The X Prize foundation is currently searching for new sponsors in order to carry on the challenge, since there are a few teams which claim to be nearly ready to alunch their robots.

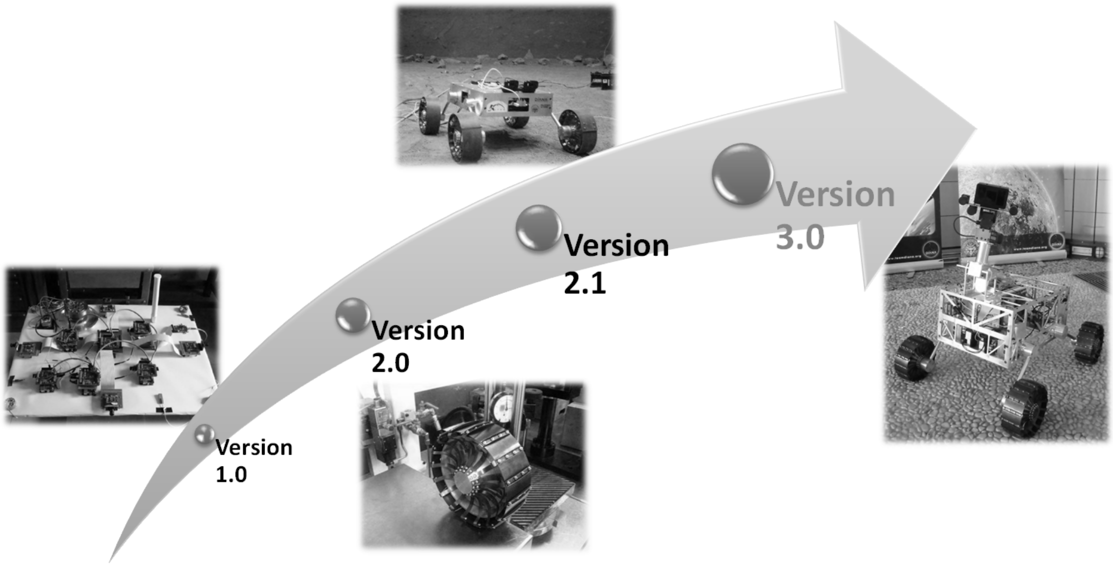


Figure 3.8: Rover AMALIA versions

Within this AMALIA mission Team DIANA was assigned the task of designing and building the engineering model of the lunar rover. From 2008 to 2015 the Team developed 3 versions of the rover (figure 3.8), with the last version (figure 3.9) presenting some innovative solutions such as: patented space graded elastic wheels (figure 3.10), an active suspension system developed in collaboration with the Centro Ricerche FIAT and SLAM (Simultaneous Localization And Mapping) algorithms.

Unfortunately Team ITALIA retired from the competition due to lack of funding since it was not possible to secure a launch contract within the competition deadlines. Nevertheless, team DIANA carried on working on the rover, using it as a research platform up to 2015.

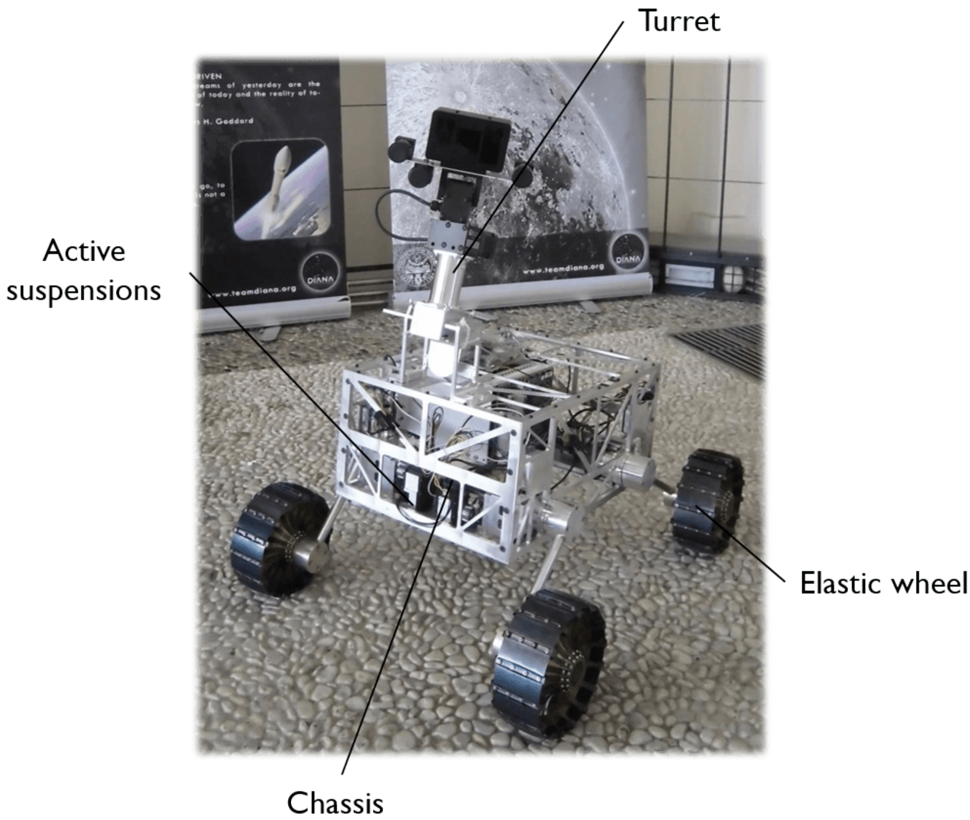


Figure 3.9: AMALIA rover version 3.1

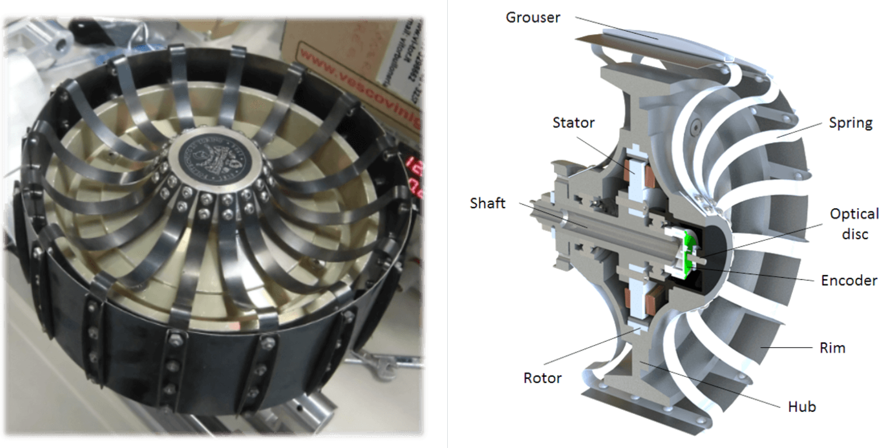


Figure 3.10: Detail of the custom elastic wheels

3.2.2 Project T0-R0

After the termination of the AMALIA project the Team decided to move towards more economically affordable projects and decided to try to compete in the Rover Challenge Series: a perfect competition for a team that historically deals with the development of rovers. Because of the completely different project requirements with respect to AMALIA, in 2015 (the year in which the author was nominated team co-leader), the Team began designing, from scratch, the first version of the engineering model of an astronaut assistance rover. The project is named T0-R0 (Torino Rover), a homage to both the city and the best known sci-fi films of all time. The objective is to compete in the European Rover Challenge in order to gain experience and to pave the way to the other rover challenges around the world. A detailed discussion of this project is presented in chapter 4.

Figure 3.11: Render of the T0-R0 rover

3.3 Outreach

Team DIANA not only focuses on the competitions but is also active in the divulgation of the work and results. This is done by taking part in conferences and expositions and by writing theses and articles.

3.3.1 Conferences and presentations

The team actively participates in many events, presenting the team and the university's activities and working to promote interest and enthusiasm for space exploration among the general public. For instance:

- Presentation at *"l'Italia,lo spazio e il futuro: studenti e ingegneri all'opera"* conference, Politecnico di Torino , Torino (Italy), 5 May 2015
- Television interview Rai 3 *"Speciale salone del libro"*, Torino (Italy), 10 May 2016.
- Exposition stand for *"100° Anniversario Aero Club"*, Torino (Italy), 2 and 3 June 2016.
- Exposition stand for *"Salone dell'auto"*, Torino (Italy), 9 to 12 of June 2016.
- Exposition stand for *"Notte dei ricercatori 2016"*, Torino (Italy), 30 September 2016.
- Exposition stand for *"Maker Faire Rome 2016"* , Rome (Italy), 14-16 October 2016.
- Speech for *"T0-R0 an Astronaut assistance rover"* for international student group, Politecnico di Torino , Torino (Italy), 8 May 2017.
- Exposition stand for *"Salone dell'orientamento 2017"*, Politecnico di Torino , Torino (Italy), 3-4 April 2017.
- Exposition stand for *"Bambini e bambine una giornata al Politecnico"*, Politecnico di Torino , Torino (Italy), 2-3-4-5 May 2017.
- Exposition stand for *"Bimbi al Poli con mamma e papá"*, Politecnico di Torino , Torino (Italy), 19 May 2017.
- Paper and presentation with video speech for *"3rd International conference on Artificial Intelligence & Robotics"*, San Diego (USA), 28-29 June 2017.
- Presentation for *"G7 oltre - idee dal futuro"* conference, Auditorium Giovanni Agnelli, Torino (Italy), 26 September 2017.
- Exposition stand for *"Notte dei ricercatori 2017"*, Torino (Italy), 29 September 2017.
- Exposition stand for *"Zero Robotics"*, Politecnico di Torino , Torino (Italy), 11 January 2018.

- Exposition stand for *"Salone dell'orientamento 2018"*, Politecnico di Torino , Torino (Italy), 16-17 April 2018. (Figure 3.12)

- Exposition stand for *"Bambini e bambine una giornata al Politecnico"*, Politecnico di Torino , Torino (Italy), 7-8-9-10-11 May 2018.

- Speech for *"Mars to Earth"* conference, Milan (Italy), 16-17 May 2018.

- Participation in the *"European Rover Challenge 2018"*, Starachowice (Poland), 14-15-16 September 2018.

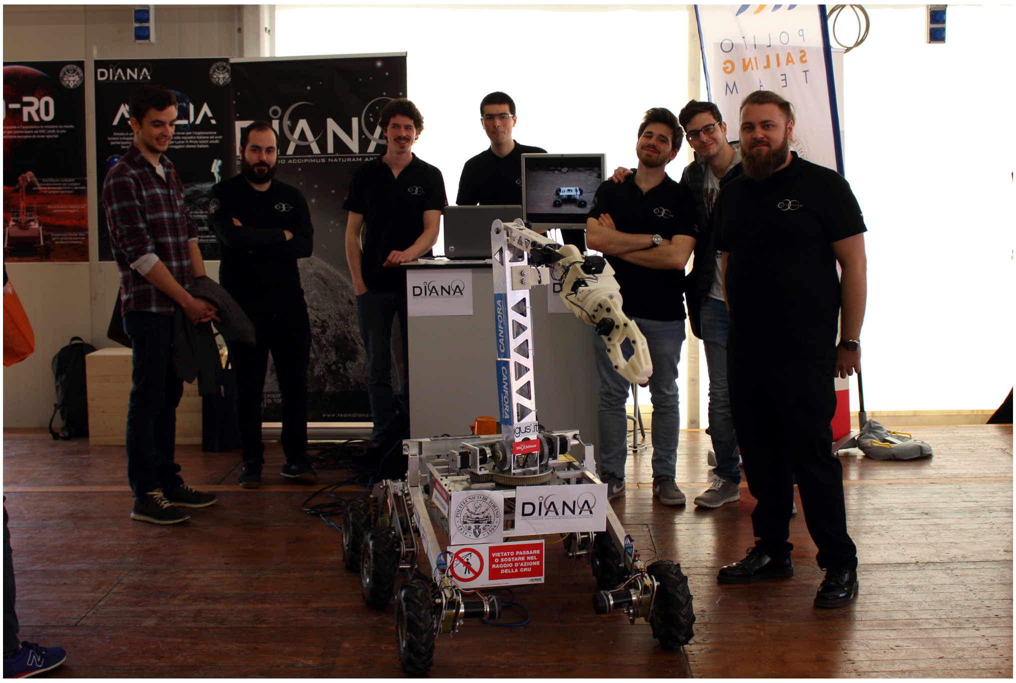


Figure 3.12: Photo taken during the "salone dell'orientamento 2018".

3.3.2 Theses and publications

As already mentioned, team members have the possibility of writing their theses on the work carried out in the team. Over 50 theses have been written since the team began here is a brief list of some of the most recent ones:

- *"Design of a wrist for a rover for ERC"*, J. Grasso, Bachelor's thesis;

- *"Structure analysis of a rod belonging to mechanical system for samples collection"*, L. Cordeschi, Bachelor's thesis;

- *"Preliminary study of the T0-R0 rover arm control system in ADAMS environment"*, M. Randine, Bachelor's thesis;
- *"Shock absorber for Space Rover characterization"*, M. Mazzetti, Bachelor's thesis;
- *"Running gear of the T0-R0 rover for the ERC"*, G. Binello, Bachelor's thesis.

Publication:

- C.Pizzamiglio, A.Andreoli, V.Comito, D.Lippi, G.Binello, S.Leveratto, D.Catelani, G.Genta, *"Simulazione dinamica multibody del rover T0-R0 per la European Rover Challenge"*, A&C. ANALISI E CALCOLO, vol. 76, Settembre/Ottobre 2016, pp. 38-45. - ISSN 1128-3874.

Chapter 4

T0-R0: engineering model of an astronaut assistance rover for the European Rover Challenge 2018

The T0-R0 rover presented at the European Rover Challege 2018 is the product of more than three years of work and over 150 students have contributed to the project. With the T0-R0 project, Team DIANA decided to enter the world of the Rover Challenge Series in order to make a contribution to the development of the future generation of space rovers, train future engineers and to compete against teams from all over the world. The idea of participating in the Rover Challenge Series was first discussed in 2013, but at the time only a small group of students from the mechanical department worked on it; at that time no funding was available for the project and the work was limited to the analysis of the URC rules, researching information, brainstorming ideas and developing the preliminary concepts of the rover.

The first attempt to compete was in the European Rover Challenge 2016 edition, but an underestimation of the time and financial resources necessary for carrying out such a project forced the team to retire from the competition. Nevertheless the experience was extremely useful: important lessons were learnt regarding the time requirements, a good preliminary design was produced (the team were among the highest scorers in the preliminary documents phase) and the first components of the rover where realized. The Challenge was not held in 2017 so the team finally managed to participate in 2018 obtaining satisfying results that will be presented in section 4.9. This chapter will illustrate how the project was managed, the final design of the rover and what was actually developed for the ERC2018. Failures and problems encountered over the years will be described in order to keep track of them for the future projects.

4.1 European Rover Challenge 2018

The European Rover Challenge (ERC) is an integrated program aimed at technological development specifically in the area of space exploration and utilization. The ultimate goal of ERC is to provide standardized test trials and a benchmark for planetary robotic activities while offering a strong professional career development platform. The ERC program is divided into two paths. ERC-Student delivers a career development platform with major focus on space engineering. It includes workshops, and year-round activities as well as mentoring regarding designing and building student planetary rovers. All the effort clminates in a yearly event where student teams compete on a specially landscaped area. The long term aim of ERC-Pro is to provide platform for monitoring and benchmarking the realization of robotics exploration roadmaps for strategic institutions and other interested agents. In this way, ERC-Pro intends to change the pattern of research into space robotics from one-off, single-mission projects and instead, following the best practices of terrestrial robotic development, to bring in iterative development and improvement by providing an arena for annual trials and demonstrations. Both paths form part of a single community network managed under ERC banner. Such a solution provides a unique opportunity to gather people at different stages of their career all focused on (robotic) space exploration. The Community works as a motor for continuous improvement in two directions allowing the transfer of expertise and feedback from professional teams to students and, at the same time facilitating the transfer of young talent to interested companies. It also connects universities, companies and other institutions promoting their strengths and identifying opportunities for collaboration. The European Rover Challenge is organized by the European Space Foundation in cooperation with a group of independent experts who make up the steering and jury board. Mars Society Polska is a partner of the program. [19]

Teams competing in the European Rover Challenge must design and build an engineering model of a rover that will then compete in a terrain similar to Mars terrain and must perform the tasks described in the competition rules in Appendix D and briefly illustrated in subsection 4.1.1. In order to compete in the final phases of the competition, teams must demonstrate their readiness by delivering a series of documents produced during the design and development phase:

- Proposal
- Preliminary report
- Promotional video

- Final report

The competition jury gives points for the preliminary documents which are added to those obtained for the tasks completed during the event to give the final score.

4.1.1 Competition tasks

During the competition days the teams must perform 4 tasks and present the projects to the judges. The tasks last 25 minutes each and simulate various operational scenarios that the future rovers will have to perform during their missions. The rover must be teleoperated remotely from a base station from which it's not possible to see the rover directly, so the operators must rely on the pictures and other information received via wireless communication. Though not obligatory, automation during the whole task or part of it is highly valued by the judges.

Scientific task

The scientific task simulates a preliminary exploration of the surface of Mars during which the following jobs must be performed:

- Reach 4 different locations and collect 4 soil samples which must be stored on board the rover:
  - 3 surface samples (50g to 200g)
  - 1 deep soil sample (below 15 cm from the surface)
- Dig a trench (5cm depth and 30cm long)
- Take photos of the samples and sampled areas
- Perform preliminary scientific measurements on the samples

Maintenance task

For the maintenance task teams are required to operate the rover in order to perform a series of jobs on electrical panels such as:

- Activate a series of switches
- Turn and regulate different kinds of knobs
- Measure voltage from a socket
- Pick up an industrial grade 3-phase plug and connect it correctly to a socket

Collection task

This task simulates a different kind of operational scenario with respect to a manned mission to Mars; during the collection task the rover must perform the task required by a Sample Fetching Rover (SFR) for a Mars Sample Return (MSR) mission which is currently under investigation by a collaboration between ESA and NASA. The rovers must reach 3 different locations to collect caches containing Mars soils samples left behind by a previous rover (Mars 2020). During the task the rover must follow the following steps:

- Reach the locationof the caches
- Find the caches (which may be partially buried or not in the exact indicated location)
- Collect the caches and store them on board
- Deliver the caches to a designated location

Navigation task

During this task rovers must reach four way-points, either autonomously or tele-operated, but the operators can only navigate the rover blindly, relying on basic information such as the rover's position, pose and speed and cannot receive pictures or videos from the rover.

4.2 T0-R0 project overview

T0-R0 project represents the first attempt by Team DIANA to enter the world of the Rover Challenge Series competitions. Because of the strict time constraints induced by the competition time line it is of primary importance to correctly define realistic and achievable goals and consequently to identify the tasks to be prioritized in order to accomplish them. The primary objective of the project was to develop a working rover capable of satisfying the basic requirements for competing in the European Rover Challenge 2018, bearing in mind that this is the first step of a longer term program of entering the Rover Challenge Series. The competition rules are very demanding making it practically impossible to satisfy every single request, this is because they represent a longer term benchmark and it is in the spirit of the competition to let each team decide their strategy by identifying which requests to satisfy.

The following subsections illustrate the project requirements and how they were defined, the assumption the project is based on, technologies used for designing and developing the project as well as a risk analysis.

4.2.1 Project requirements and constraints

Precise identification and definition of the project's requirements and constraints was necessary to guide the design of the T0R0 project. The competition rules were analysed and the following subsections illustrate the requirements and constraints identified. Figure 4.1 illustrates a general panoramic of the functions and constraints of the project.

Project requirements

The functional requirements of the robotic system to be developed are defined on the basis of an accurate analysis of the competitions rules of the European Rover Challenge 2018 and of the previous competitions of the Rover Challenge Series. The final product and/or its subsystems must present the following requirements and characteristics in order to properly accomplish the tasks.

The very first requirement stated in the competition rules is the following:

The rover has to be a standalone, mobile platform. No cables or tethers are allowed for connection to external data links or power sources during its operation.

From the above statement it is possible to deduce that whole system will be composed of two main parts:

- **Rover**: the main robotic system to be developed. Rovers must respect the following limits:
  - The weight must be below 60 kg
  - the economic value must be below 20000€. The value of components provided by sponsors must be calculated in the rovers total value. In ERC2018 cost limits were abolished but with a view to competing in other competitions where cost limits exist it was decided to self impose a similar limit.
- **Control station**: necessary for the operators to remotely control the rover. This system shall be able to send/receive data to/from the rover such as pictures, videos, commands, the state o the rover's systems and information about rover position and pose.

The rover must present the following functions:

- **Provide mobility**: by definition rovers are mobile platforms, in this case the rover must be able to move on uneven terrain which could be sandy, compact or rocky and could present slopes up to 60°.
- **Provide communication**: rover must be able to communicate wirelessly with the Operation control station. The rover is not expecte to exceed a distance grater the 100m form the base station.

- **Provide power**: rover must be equipped with an onboard power source and guarantee sufficient autonomy to complete the tasks. Task last 25 minutes.
- **Maintain structural integrity**: rover must be able to sustain the mechanical stresses that are generated during operations.
- **Manipulate objects**: during competition tasks the rover must interact with different kinds of objects such as: rocks, loose soil, tools, electric plugs and switches.
- **Provide cargo capability**: rover must be able to store objects and materials on board.
- **Provide environmental protection**: rover must be able to operate in a dusty environment and could encounter light rain. In addition the temperature of critical components must be kept under control.
- **Provide images and video**: rover must produce videos and photographs for operations feedback and documentation production.
- **Provide situational awareness**: internal and external parameters must be monitored.
- **Provide safety systems**: dangerous situations must be prevented and if necessary the system must be easily shut down.
- **Provide data storage**: rover must record important data for future analysis.
- **Provide guidance and navigation**: rover must create a local map and provide information about location, altitude and speed.
- **Function autonomously**: it is desirable that the rover completes tasks or parts of tasks in a semi autonomous or autonomous manner.

Project constraints

The project is subject to the following limits and constraints:

- **Time constraints** The project deadline was set to the competition dates 14-16 September 2018. In addition intermediate deadlines were fixed for the submission of the following documents:
  - Proposal - deadline 31/03/2018
  - Preliminary report - deadline 10/05/2018
  - Promotional video - deadline 26/07/2018
  - Final report - deadline 23/08/2018

- **Constraints on resources** The resources can be identified as :
  - Workforce: the number of team members is limited and their availability differs from person to person and at different times of the year.
  - Available equipment: the Team has access to the use of a certain number of tools such as a mill, drills, soldering station, computers with specific software and 3D printers that must also be shared with other members of the university. The equipment available determines the kind of work that can be carried out on the university premises.
  - Facilities: The team's laboratories have limited workspace so it is important to organize each group's work periods carefully to avoid overcrowding.
  - Funds: In the period 2016-2018 the total budget available was 40000€. These funds have to cover all the project expenses such as the cost of the rover components, testing components, tools, traveling expenses and the cost of producing promotional material.
- **Purchasing constraints** The purchasing of components is subject to university regulations; in general, purchases can only be made after comparing quotations from different suppliers, purchasing from marketing web sites such as Amazon or ebay is not permitted, receipt refunds are limited to 150€ per receipt.

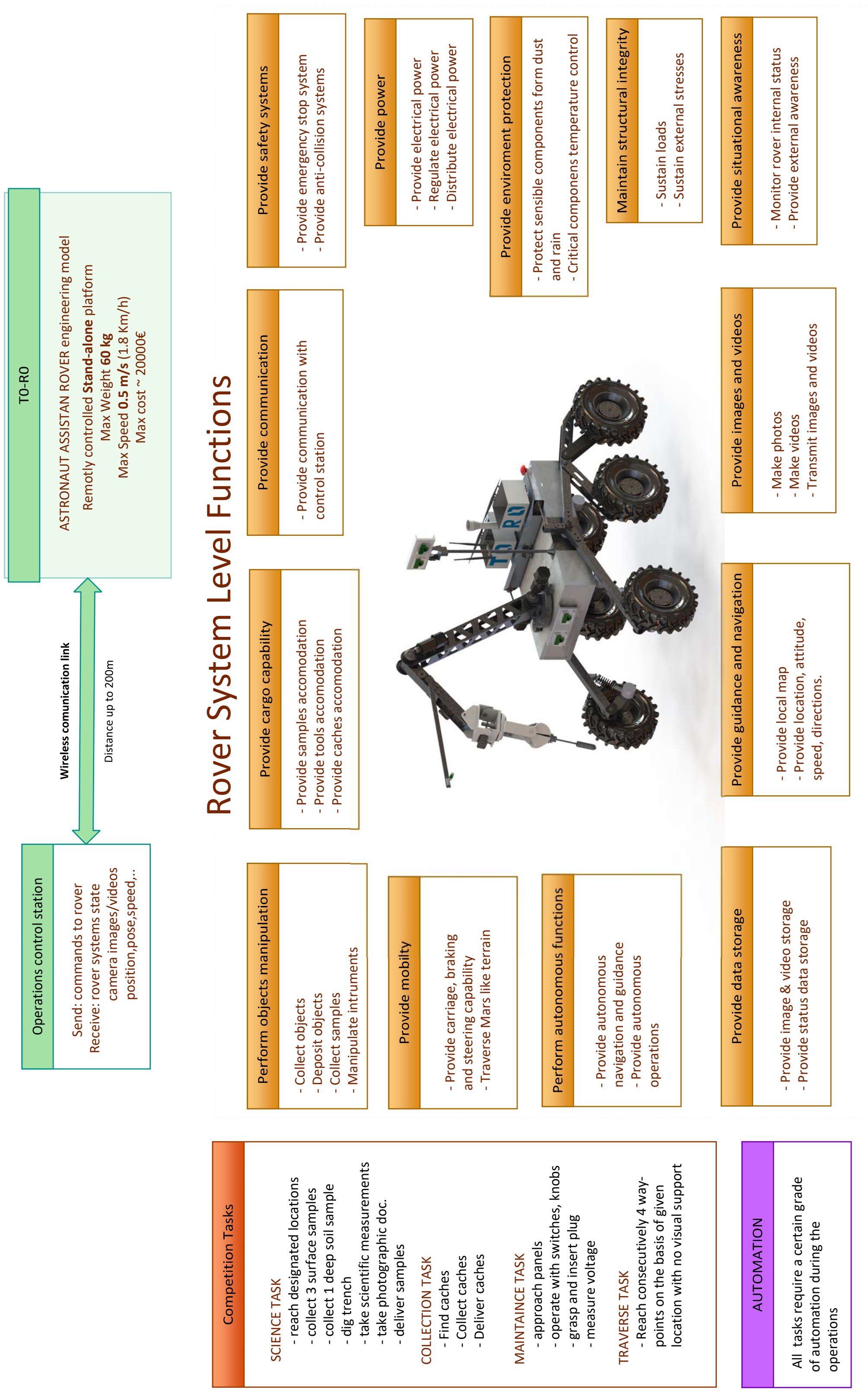


Figure 4.1: System functional requirements

4.2.2 Project assumptions

The rover designed for the European Rover Challenge 2018 edition is largely based on the first prototype designed during the 2016 edition of the competition and developed during 2017. This rover was designed taking into consideration the following assumptions which derive from the team's previous experience and projects, analysis of the competition rules (from current and previous editions) and the available video and photo documentation of the previous ERC competitions.

- Given the limited budget available and the heritage of the rover prototype, which was designed respecting cost constraints, T0-R0 was designed and built keeping a low budget profile. For this reason the use of standard "off the shelf" components was crucial in order to reduce the total cost of the rover.
- T0-R0 is an engineering model of a space rover: it is designed to work in the terrestrial environment of the competition and the possibility of operating in space or a planetary environment was not considered. This allows the use of materials and solutions that are not directly suitable for space applications, even though the general design resembles the nature of a real space rover as closely as possible.
- The design of the project is based on the need for solutions that can fulfill the primary tasks essential for participating in the competition. It has been our objective to verify the capabilities and performance of our solutions and gain experience in the development of these systems in order to create a strong foundation for future versions.

As far as the configuration of the rover is concerned, the following points derive from the first version of the project:

- Six-wheel rocker-bogie mobility system, based on URC requirements, since the ERC rules do not provide any detailed information about the characteristics of the terrain nor specific requirements for the mobility system except the speed limit. The rocker-bogie solution was chosen since it has been adopted on all the Martian rovers up to now.
- A robotic arm with at least 6 DoF, in order to move and orient the end effector without limitations within the robotic arm's work space.
- Manually exchangeable end effectors. The competition rules allow the rover's parts to be changed manually between one task and another: end effectors specifically designed for single tasks were judged to be a simpler and more efficient solution compared with designing a single universal end effector.
- Power supply based on battery packs. This solution has been adopted by all the teams in all the previous competitions.

- Research into the use of tools that can be grabbed by end effectors and used to perform additional operations when needed. This kind of approach could pave the way to the realization of an extremely versatile and flexible system that could be useful for a wide range of tasks that have not yet been considered.

4.2.3 Technologies used

The Team relied on different kinds of technologies for both the design phase and the development phase.

Design For the design, simulation and analysis, extensive use of CAE (Computer aided engineering) software was used for both the mechanical and electrical components.

In particular SolidWorks Student Edition was used for the CAD design of the mechanical components and assemblies. While Blender was used for renders and animations.

FEM analyses were used for studying and validating the structural proprieties of the mechanical components. ANSYS was adopted early on, later replaced by MSC Patran - Nastran. Iterative FEM analyses were performed in order to understand where the structure could be lightened. In addition SolidWorks, as a sponsor of the ERC 2018, distributed licenses that included a Simulation pack for simple and preliminary FEA (Finite Element Analysis).

MSC Adams has been used for multi-body dynamic analyses, this kind of software makes it possible to predict the behavior and aspect of the final product early on in the design phase. Thanks to this kind of analysis the Team was able to define the dimensions and simulate various components of the rover.

The electronic division adopted CAD software such as KiCAD and Eagle which were used to design PCBs for the rover subsystems, while LTspice was used for the simulation of circuit behavior.

Also MatLab was used for modeling for a series of iterative computations, plots and modeling the robotic arm's inverse kinematics.

Development The grates part of the mechanical design is based on the use of standard parts and semi-finished products. The machining process relies on laser cutting or CNC milling of simple cuts and perforations on metal plates and tubes in order to contain costs by avoiding the realization of complex shaped CNC custom made parts. These operations where assigned to external companies.

When possible, components subject to minor mechanical forces were produced with the FDM 3D printing of ABS plastics. This further reduced the costs and the dependence on suppliers in favor of implementing team-produced components.

Simple processing works were executed by the team members in the laboratory, using the tools available (drill, angle grinder, mill and manual tools).

The production of the circuits designed by the team was assigned to external professional manufacturers able to produce prototypes and small batches of PCBs, while the assembly process was carried out by members of the Team in the laboratory, using the soldering stations and the infra-red IC heaters.

4.3 Project timeline

Because the project has a defined non-postponable deadline, the competition days, the timeline of the various phases of the project was defined with a top-down approach; considering the time available from when the rules are published (1st January 2018) to the competition event (13-16 September 2018) the following phases had to be scheduled:

- Requirements definition phase
- Preliminary design phase
- Design phase
- Development phase
- Testing phase
- Preparation for the competition

The time necessary for the completion of each phase was scheduled based on the experience of the previous years of team activities.

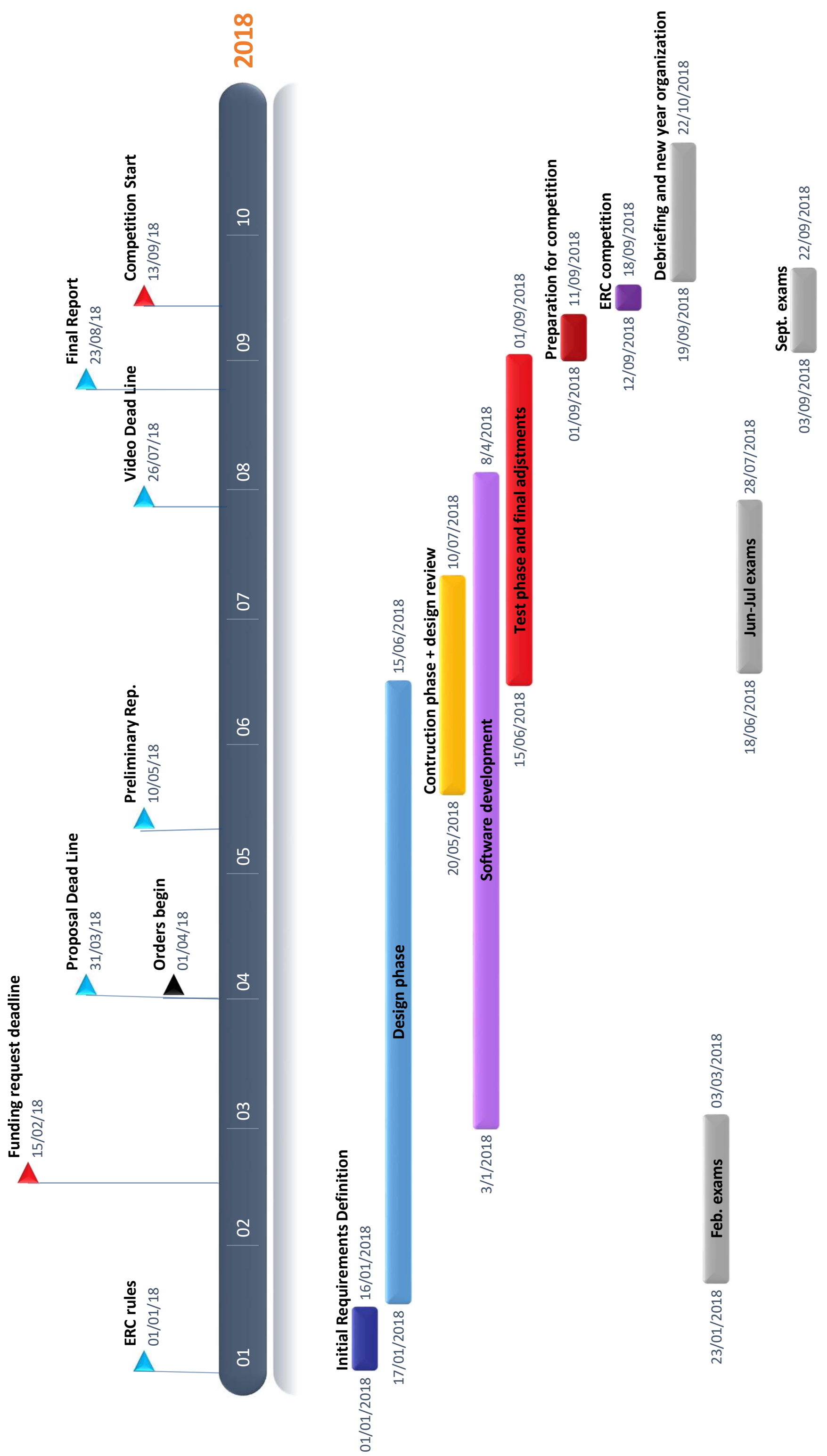


Figure 4.2: Planned project timeline from January 2018 to October 2018

4.4 Risk analysis

Due to the tight time constraints and given that the students are working on such a project for the first time, the T0-R0 project can be considered a high risk - low impact project since many things could go wrong but the worst case scenario would just mean withdrawing from the competition. The risks of the project have been evaluated for the project cost, time, quality and safety.

Risk related to variations in the costs of the project Since none of the members of the team is paid, the only variable that can affect the estimated cost is the price of purchasing and producing the components or unexpected expenses. In order to mitigate this risk, a detailed cost estimation was performed prior to presenting the funding request to the commission in charge of distributing funds to the university student teams. Careful preliminary research was done in order to be as precise as possible in estimating costs, correction factors were included based on possible variations from our estimates, and an extra budget was assigned for covering unexpected expenses. Including the cost of components that could potentially be provided free from our partner companies, gave us an extra safety margin.

Risks related to schedule variations Due to the high degree of uncertainty regarding availability of members and, in general, of problems emerging during the various phases, the risk of schedule variations and missing deadlines is considered high and hard to prevent. The best way to mitigate the risk of delays and limit their impact is to estimate the timing realistically and to prioritize the tasks that are most crucial for successful completion of the project. The time line was defined on the basis of the Team's previous experience and conservative deadlines were fixed.

Risk related to the overall functionality and quality of the rover and performances during competition tasks In order to minimize risks relating to errors during the design phase, extensive use of CAE tools for design, analysis and simulation were used during the project for the development of both the mechanical and electrical subsystems. Testing the various subsystems as soon as possible is also important in order to avoid unexpected malfunctioning. The modular configuration allows us to make changes to single systems without compromising the others. Various scenarios of events that could compromise success during the competition tasks were imagined and evaluated during the design phase to work out how to prevent or deal with them.

Risk related to safety Safety risk assessment for collaborative robots is a very important issue. During the competition tasks the T0-R0 rover does not work in direct collaboration with humans but does work in an open environment with people in the vicinity. The implementation of safety systems such as an emergency stop button and mounting a beacon light to indicate when the rover is in action are sufficient for the competition tasks. In addition, the low moving speeds of both the rover and the robotic arm make it unlikely to cause any serious damage to people or things. The rover can be considered safe and should not determine any risks.

4.5 T0-R0 rover design

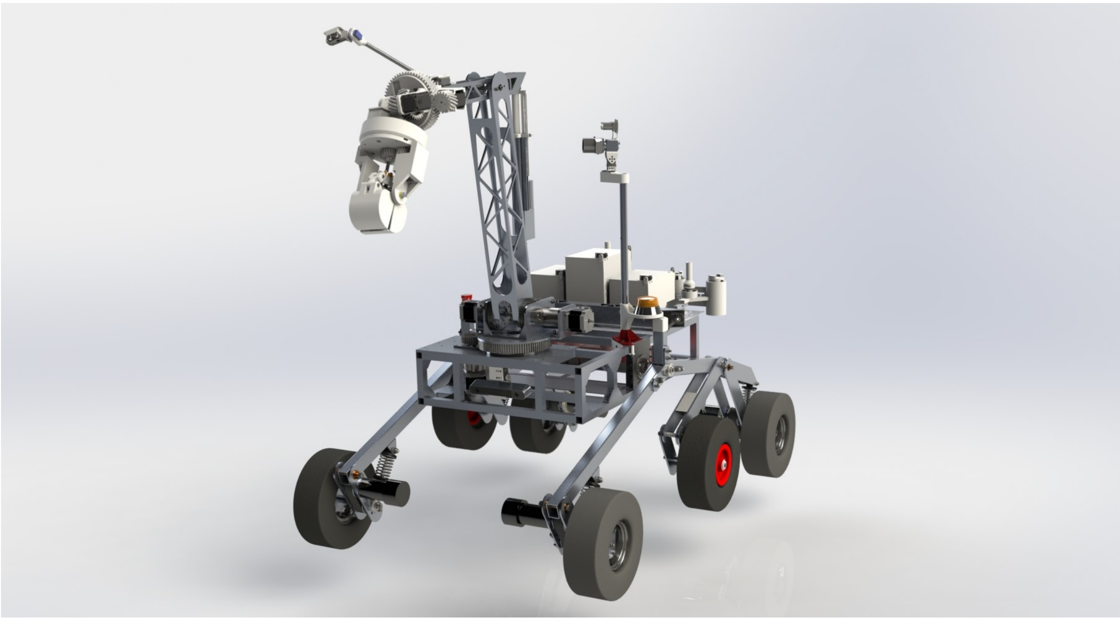


Figure 4.3: Render of T0-R0 rover in the scientific configuration

The rover T0-R0 (figure 4.3) is based on a strongly modular design. This kind of approach is often associated with higher costs, high power consumption and problems related to the communication between subsystems. However, from previous experience, the Team has learnt that a modular design dramatically reduces development and production times and makes it much easier to execute modifications on the existing platform for upgrades and repairs.

Some of the advantages of this design are:

- **Development is performed in a parallel manner**
  Small groups of students work on different sub-systems at the same time. The different subsystems can therefore be at different stages of advancement without causing delays

- **Easier testing and error reproducibility**

Most errors and bugs can be fixed by working solely on the single subsystem affected

- **Fault tolerance**
  If one subsystem fails, other subsystems can still work. It is also easier to restart or replace a single part if necessary

- **Easier upgrade capabilities**
  As stated earlier, we care about building a platform ready to be improved over time. Thanks to the software and hardware approach described earlier we can seamlessly add new features and devices or upgrade the existing ones

From the analysis of the competition rules, functional requirement and project constraints, during the preliminary design phase the following rover's system to be developed where identified:

- Mobility system
- Robotic arm
- Chassis
- Logic control
- Vision and navigation
- Communication system
- Specific task systems
- Power system
- Safety system
- Operators control station

In figure 4.4 a breakdown of the rover systems is presented and in the following subsections the chosen final for the various rover systems are described.

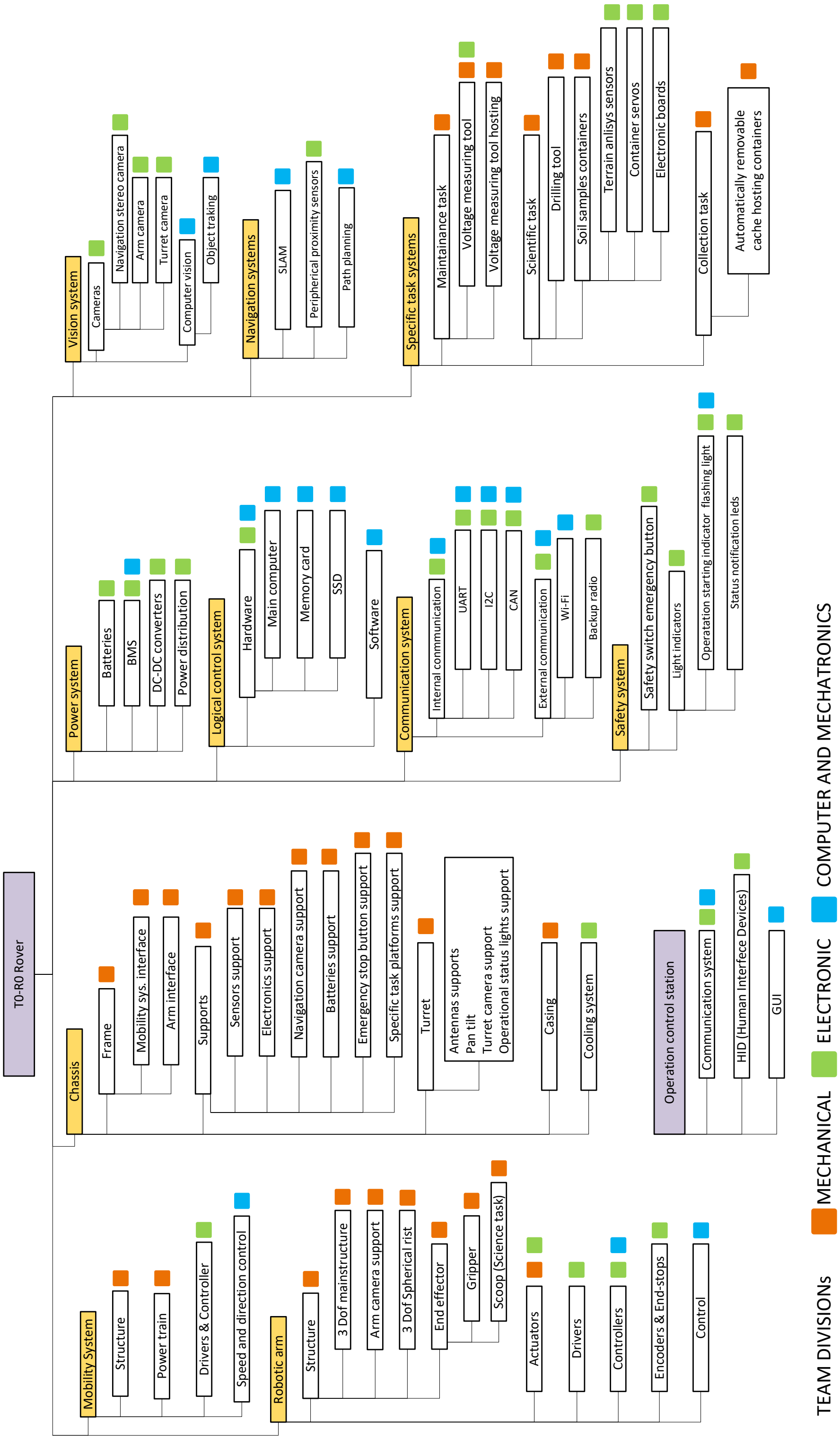


Figure 4.4: Rover systems breakdown structure

4.5.1 Logical Control System

The rover is equipped with a NVIDIA Jetson TX2 Developer Kit, an embedded system-on-module (SoM), which carries a Tegra processor from Nvidia that integrates an ARM architecture CPU (ARM A57/2) and a powerful 256-core Pascal GPU, capable of computer vision intensive computations. It will be called *main board* from now on. the main features of the TX2 are presented in table 4.1.

The main board works in a master position, acts as interface between the operators control station and the rover, it manages all the various subsystems of the rover by communicating with the other boards through different types of buses (UART, I2C, CAN) over which commands are sent and data is received. The main board receives the camera images and can perform high-level tasks such as trajectory planning and navigation.

Table 4.1: Nvidia Jetson TX2 main features

CPU	ARM Cortex-A57 (quad-core) @ 2GHz + NVIDIA Denver2 (dual-core) @ 2GHz
GPU	256-core Pascal @ 1300MHz
Memory	8GB 128-bit LPDDR4 @ 1866Mhz | 59.7 GB/s
Storage	32GB eMMC 5.1
Encoder	4Kp60, (3x) 4Kp30, (8x) 1080p30
Decoder	(2x) 4Kp60
Camera	12 lanes MIPI CSI-2 | 2.5 Gb/sec per lane | 1400 megapixels/sec ISP
Display	2x HDMI 2.0 / DP 1.2 / eDP 1.2 | 2x MIPI DSI
Wireless	802.11a/b/g/n/ac 2×2 867Mbps | Bluetooth 4.1
Ethernet	10/100/1000 BASE-T Ethernet
USB	USB 3.0 + USB 2.0
PCIe	Gen 2 | 1×4 + 1×1 or 2×1 + 1×2
CAN	Dual CAN bus controller
Misc I/O	UART, SPI, I2C, I2S, GPIOs
Socket	400-pin Samtec board-to-board connector, 50x87mm
Thermal	-25°C to 80°C
Power	7.5W

The whole software runs on the NVIDIA JetPack SDK, based on Ubuntu 16.04 LTS and Linux for Tegra (L4T), a modified version of the Linux Kernel providing all the required flexibility for our applications.

The TX2 is compatible with ROS (Robot Operating System, version Kinetic Kane), running on Ubuntu, is a framework for robotics application based on a decentralized, message-based paradigm which connects the nodes creating a modular system, granting the benefits stated earlier at the software level regarding the modular design. It is used to implement the computer vision and navigation systems on the rover. OpenCV, an open source software library, uses the CUDA architecture present on the main board. Though, because of delays and problems during the development phase, the rover presented at the competition did not implement the uppermentioned solution.

Furthermore, an SSD drive is used to store on board processed data for further analyses.

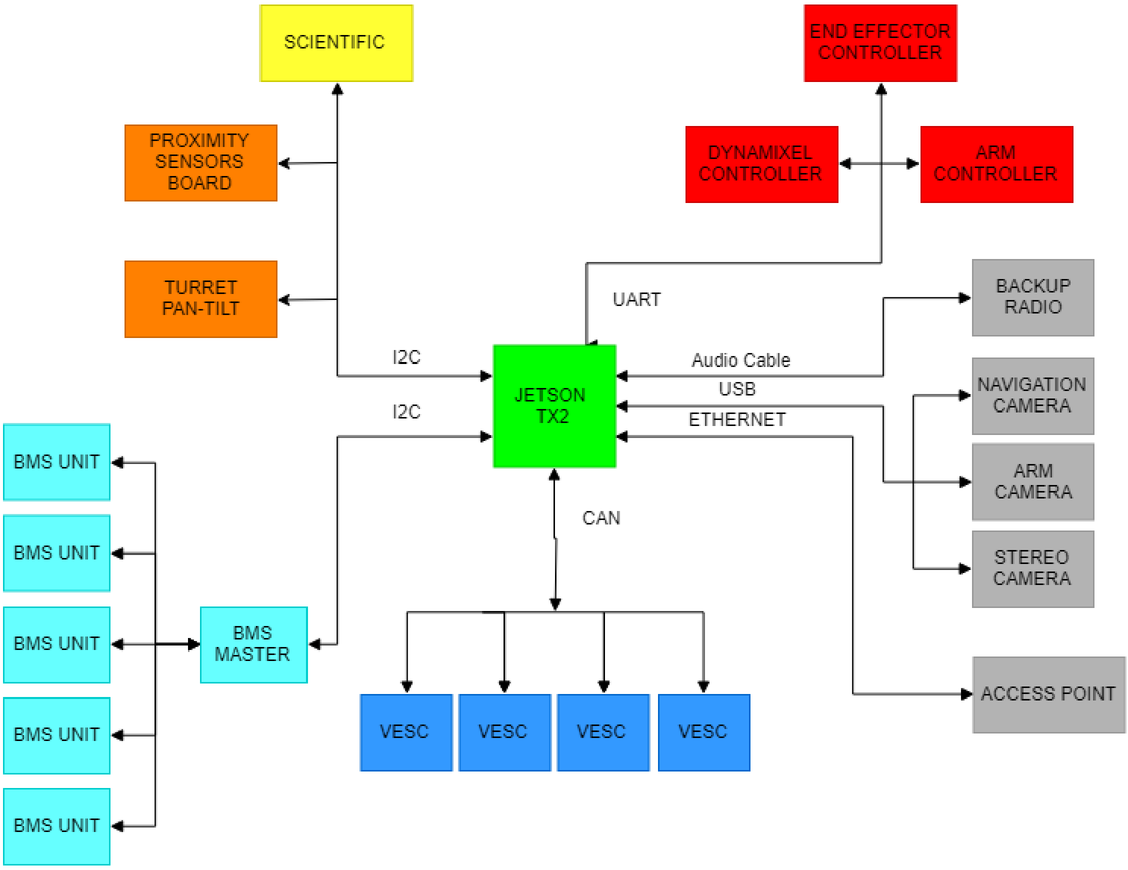


Figure 4.5: Overall connection schema of the rover electronics

4.5.2 Mobility system

The mobility system is one of the systems tha was developed first.

The **mechanical strucutre** of the mobility system is based on a rocker-bogie configuration. This configuration is inspired by the current state of the art of the Martian rovers, it has the particularity to guarantee wheel contact of the wheels on

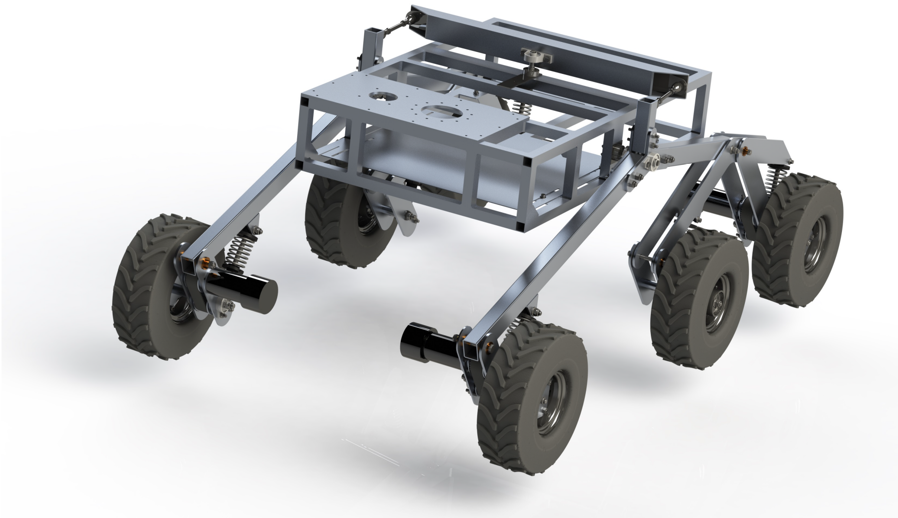


Figure 4.6: Render of the mobility system and chassis

uneven terrain and over obstacles while reducing the roll of the chassis, consequently stabilizing the rover, when overcoming obstacles present only on one side respect to the longitudinal axis (for example a rock).

In order to correctly dimension and optimize the system numerous multi-body dynamic simulations and FEM analysis where performed (example shown in figure **??**). Since the original rocker-bogie configuration is thought for low moving speeds (a few cm per second) it was necessary to modify such system in order to sustain T0-R0 rover speed (up to 3km/h) by adding shock absorbers on the wheels and flexural springs on the extremities of the differential bar in order to reduces the mechanical stresses on the rover structures generated by driving the rover at high speeds on uneven terrains.

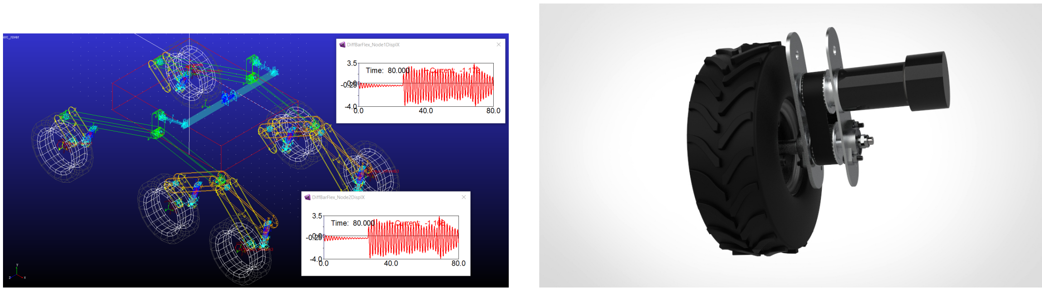
The mobility structure is mainly composed of aluminum tubes and suitably shaped plates, to reduce the weight and cost of the rover.

Including the wheels the rover is 1410mm long, 875mm witdh, and 570mm in order to allow the arm to be placed the base of the robotic arm initermediate position of the required workspace in ordet to reduce the lenght of the links.

The **power train** consists of 6 wheels, but only the four external wheels are driven by motors leaving the central wheels to be idle. This decision of such configuration was driven by cost and weight constraints but, turned out to be a bad choice since the idle wheels tend to get stuck when overcoming step-like obstacles, but the problem didn't emerge from the simulation performed and was discovered late within the project and it was decided to cope with it, for the future versions of the rover it will be necessary to motorize the wheels.

The motors chosen for driving the wheels are Maxon 24V BLDC motors with a 66:1 planetary gear reduction module capable of 15 Nm continuous output torque each. The motion is transmitted to the wheels thanks to a pulley-belt system (figure 4.7b) with a 1:1 transmission ratio which allow to uncouple the forces and misalignments acting on the wheel to be transfered directly to the motors shaft and places the motors in a slightly higher position reducing the chances of collision whist rocks.

During the implementation phase, one of the motors presented a failure to the windings for unknown reasons, and due to the unavailability of the same motors within a useful time it was necessary to find similar motors for powering the rear wheels, opting for similar Maxon motors with a 92.7:1 gear reduction ratio.



(a) (b)

Figure 4.7: Left: screen shot of a simulation performed on ADAMS. Right: detail of the pulley-belt transmission

The tires are an "off the shelf" solution, since the effort of developing custom wheels was not necessary at this stage of the project. The rover can be steered thanks to the differential speed of the wheels, also known as skid-steering, allowing the rover to steer in place with great precision. This solution has been chosen in order to keep down both the weight and the budget and reduce the complexity of the system.

For the motor **drivers** the VESC[1] (Vedder Electronic Speed Controller) ad been adopted, as an open source solution it drastically reduces cost respect to other commercial solutions.

The VESC can provide up to 240 A for a few seconds and 50 A continuously, enough for the 4.43 A nominal and 78.2 A stall current required by a single motor. They can also work in a wide voltage range which allows a certain flexibility for further implementations or modifications.

From a software point of view, the VESC uses ChibiOS (a Real-Time Operating System) running on a STM32 microcontroller.

[1] http://vedder.se/2015/01/vesc-open-source-esc/

Multiple control strategies (speed, current or duty-cycle) are available, consisting in sensorless, sensored or hybrid configurations. The latter will be used in combination with speed control. This allows a very precise drive of the motors at low speed thanks to the use of Hall sensors (integrated in the motors) and sensorless control at high speeds.

Another advantage provided by the VESC is that it can be configured according to the different applications, setting the maximum motor current (avoiding the risk of damage) and limiting the input current from the batteries. This allows better control in terms of power consumption.

The VESCs are also able to measure a wide number of parameters relative to the motors and the VESCs themselves (current, voltage, amp-hour and watt-hour consumed, motor temperature, power MOSFET temperature, etc.) which is crucial in an effort to monitor their state as well as the state of the motors during operations (this information is also shown in the GUI).

The mobility system communicates with the main board via the CAN Bus, a protocol based on the broadcast/multimaster concept. This solution has been chosen in order to provide an independent data bus from the other subsystems and a robust communication. CAN is interfaced with the main board through SocketCAN, an implementation of CAN for Linux, working in a similar manner to the TCP/IP protocols.

Since the main board only implements a CAN protocol controller, a transceiver (CJMCU-2551) is necessary in order to allow the communication using CAN.

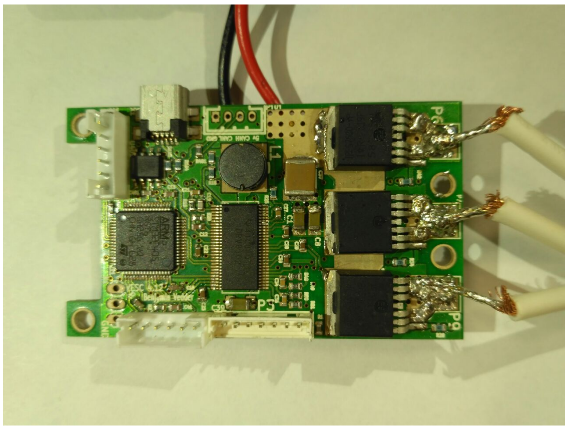


Figure 4.8: One of VESC drive

4.5.3 Chassis

The chassis of the rover is designed to minimize weight and costs while preserving the structural functions. Like the mobility system, the structure of the chassis is mainly composed of aluminum square section bars and suitably shaped plates . The cover casing is made of polycarbonate panels connected to the chassis with Velcro strips for fast removal in order to easily access the electronics. The mobility system is connected in three different points of the structure: two side hubs and the joint of the differential bar. Two bearing blocks for every hub support the shafts in order to minimize the stresses on the critical nodes of the structure.

The front side of the chassis supports all the forces coming from the robotic arm system. Inside the chassis is a mobile plate that hosts all the internal electronic components and the batteries. This plate has been designed for easy extraction of the electrical components for maintenance and for an even distribution of the weight when the robotic arm is not mounted on the rover. The proximity sensors and the navigation stereo camera are placed on the external perimeter of the chassis. Interchangeable plates are mounted on top of the chassis to host either the scientific platform, the cache container or the maintenance tools. An orange industrial grade safety button is placed on top of the rocker allowing easy access in case of the need for an emergency stop.

The turret is placed in the middle of the chassis. On the top of the turret a PointGrey IP camera is mounted on a pan-tilt system actuated by two Dynamixel servo-motors, providing vision all around the rover. The camera is combined with a lidar scanner sensor, granting correct positioning of the recognized objects. The turret also hosts a beacon light, the Wi-Fi antennas and the colored led that indicates the operational status of the rover (tele-operation, autonomous mode,...).

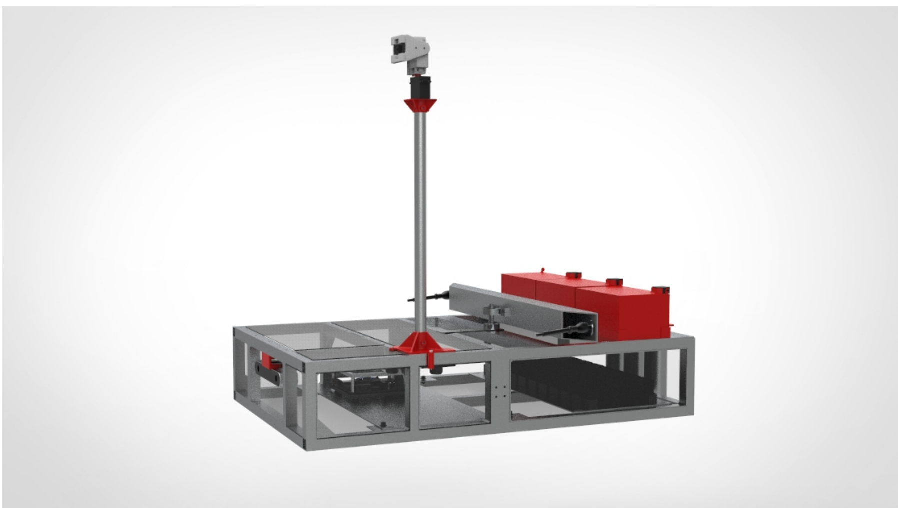


Figure 4.9: Detail of chassis, external view

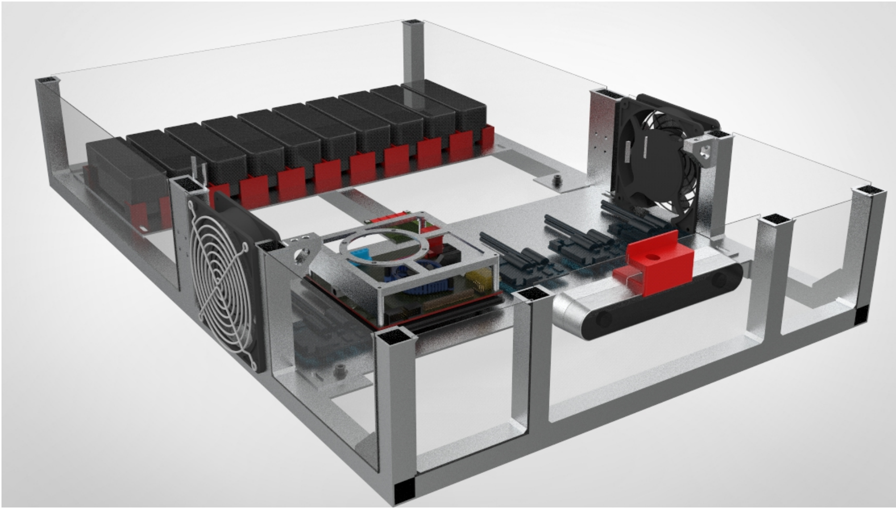


Figure 4.10: Detail of electronic placement

4.5.4 Robotic arm

The robotic arm is necessary for the successful execution of three of the four tasks required by the competition: the collection, maintenance and science tasks. During the navigation task the arm is removed in order to lighten the rover.

Main Structure The main structure of the arm is composed of the base, arm, forearm and wrist. Two degrees of freedom are given by the base, a third is located at the elbow and other three degrees of freedom are placed on the wrist. This brings us to a total of six degrees of freedom along the rover's arm.

This configuration allows all the operations required by each task to be easily accomplished, since the reaching capabilities of the arm have been optimized as shown in figure ??. The arm of the rover is able to operate at a height of up to 1.5 meters, cover a wide area on the ground, cache the samples and reach the tools on the back of the chassis.

Base The aim of our base design has been to obtain a light, compact and resistant structure.

Starting from the bottom, the base interfaces the rover's chassis through an aluminum plate that can easily be removed to fulfill the navigation task. The plate hosts the first motor and the slewing ring, that supports the upper plate of the base, creating a rotational joint.

Particular attention was paid to the bolted connections between these parts in order to distribute the stresses on the slewing ring, which is the most rigid component of the base, and to limit the deformation of the upper plate as much as

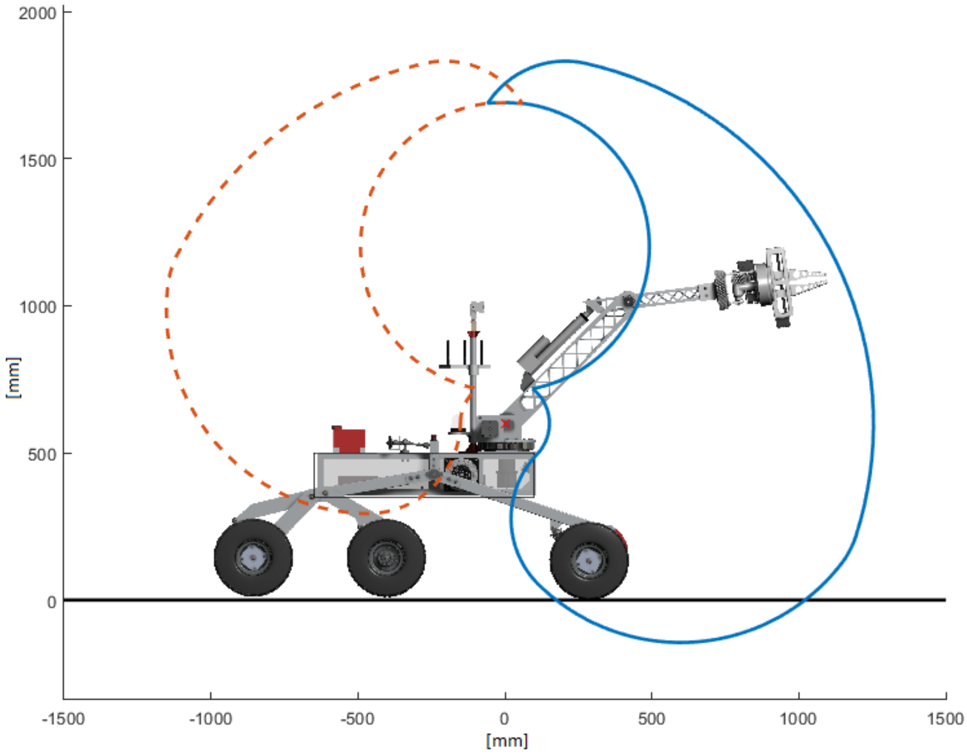


Figure 4.11: Workspace of the arm plotted in Matlab.

possible. The upper plate is a single monolithic support that holds the bearings of the shoulder and its two motors, further supported by plates for higher flexural resistance.

The chosen motors are NEMA 23 stepper motors, equipped with a planetary gearbox with a reduction ratio of 77:1 that transmits the torque through the pinions and the gears directly connected to the arm. These gears are connected to the arm with a bolted connection, allowing the use of a very light shaft, since it only supports the weight of the arm.

Arm and Forearm design The project of the arm was driven by two fundamental requirements: the use of the available material provided by the sponsor and the need for a lightweight design.

For the design of the forearm the team followed the same path: starting from a similar aluminium square tube a lighter structure was obtained. The choice of the elbow joint was effectively the most difficult part in the construction of the forearm despite the lightening process.

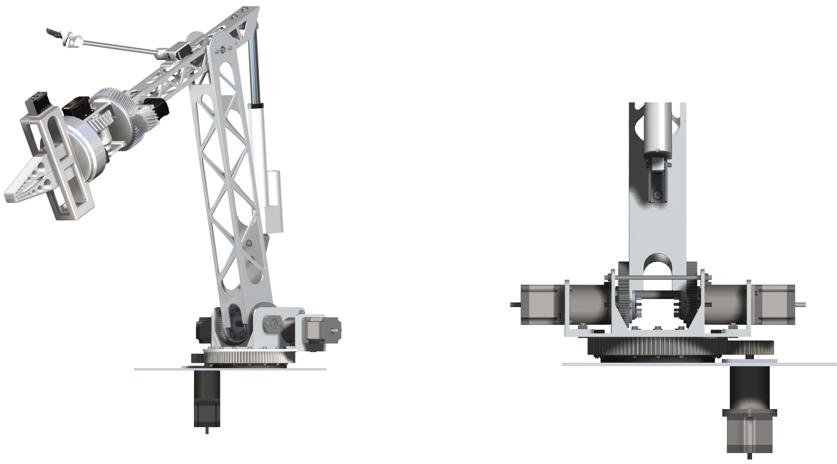


Figure 4.12: The new design of the robotic arm

Elbow Joint The development of the elbow joint represented a key point of the project. The first solution used a NEMA 23 stepper motor and a conical gear to transmit the torque at the forearm, but some structural issues appeared: the weight of the motor at the end of the arm generated great dynamical forces and the coupling between shaft and forearm underwent extensive backlash due to the tolerances on the key ways. Furthermore, the motor had to draw on the maximum amount of current to hold the forearm in place when still. This is the reason why, after tests on that kind of joint, a radically different configuration was chosen. The final elbow motor is a linear actuator. The linear actuator transmits the force directly to the forearm without any backlash and it is a non reversible mechanism. This means that when the forearm is still the motor does not draw any current. Moreover the bearings for the elbow joint were placed inside the arm, eliminating the need for any spacers. In addition, this allowed the reduction of the overall weight and an even weight distribution on the arm (CoG of the motor is closer to the base). The shaft used is very lightweight since it only supports the weight of the forearm and the incremental encoder which keeps track of the movements of the while the rest

Wrist The wrist has a spherical displacement and its concept was designed to satisfy both the requirements of the inverse kinematics control and the need for agile and precise movements during the tasks. It stands on a slewing ring that generates the first degree of freedom. A second degree of freedom, perpendicular to the first, stands on contact bearings made of a low friction plastic material from Igus, while a third is placed on the axis of a shaft, parallel to the first one. These degrees of freedom are obtained by helical gears controlled by Dynamixel servo-motors. The whole structure was 3D printed and the design of the gears was studied on the base of the use of ABSplus, which provides particularly elevated mechanical performance.

Slip Ring The Wrist is equipped with a slip ring in order to allow a continuous rotation of the last degree of freedom avoiding the twisting of the cables. The slip ring can deliver enough current to the end effector and carry the signals from a distance.

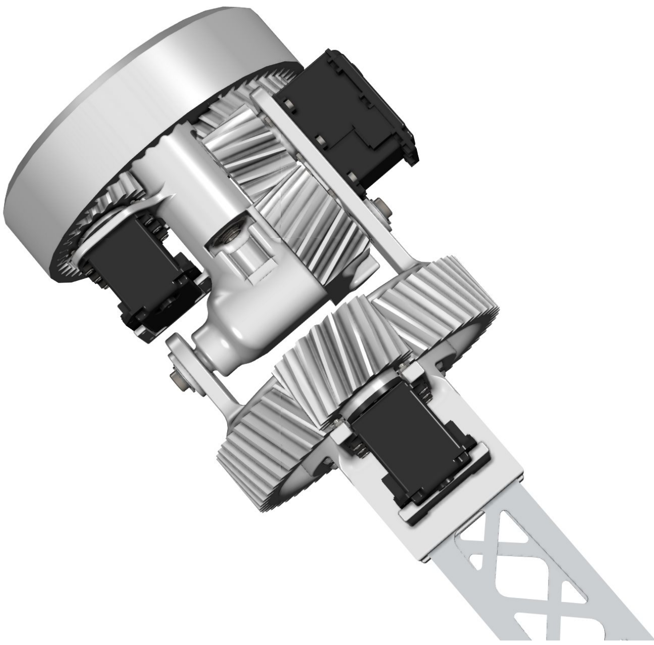


Figure 4.13: The wrist with three DOF and helical gears

End Effectors The robotic arm's wrist can be connected to several end effectors in order to adapt the kinematic abilities of the arm to each specific task. This kind of solution highlights the advantages of a modular construction. The end effectors are mainly 3D printed using an FDM technology.

Arm Camera The arm camera system is attached to the forearm. The arm camera is composed of a lightweight USB web cam, positioned by two servo motors that allow it to follow and give a close-up view of the end effector.

Gripper The first end effector developed was the gripper hand, used for the maintenance and the collecting task. It relies on a screw mechanism composed of a left handed and a right handed screw each of which converts the rotational motion of the actuator to linear motion for the two fingers. This solution allows high gripping force without wasting the energy provided by the actuator due to the non reversibility of the mechanism. The amount of force applied on the fingers can be monitored by the torque on the screw measured by the Dynamixel servo motors' PID control. The gripper is also modular: the fingers can be replaced in order to adapt the gripper to any kind of surface and shape. Other tools can be electrically connected to the hand gripper for tasks such as measuring the voltage in the socket. In the future, other tools can be developed using the same modular electrical connections.

Figure 4.14: The gripper with screw mechanism

Scoop The second end effector to be developed was the scoop, crucial for the scientific task. It relies on a screw mechanism that converts the rotational motion delivered by the Dynamixel actuator to the linear motion of the central part of the scoop. The central part is connected to two rods, each of which is connected to a shell of the scoop which applies shear force to cut into the soil. The scoop is also modular and can pick up the core drills from the sample containing area of the chassis. The drilling is performed thanks to the rotation of the last DOF of the arm's wrist.

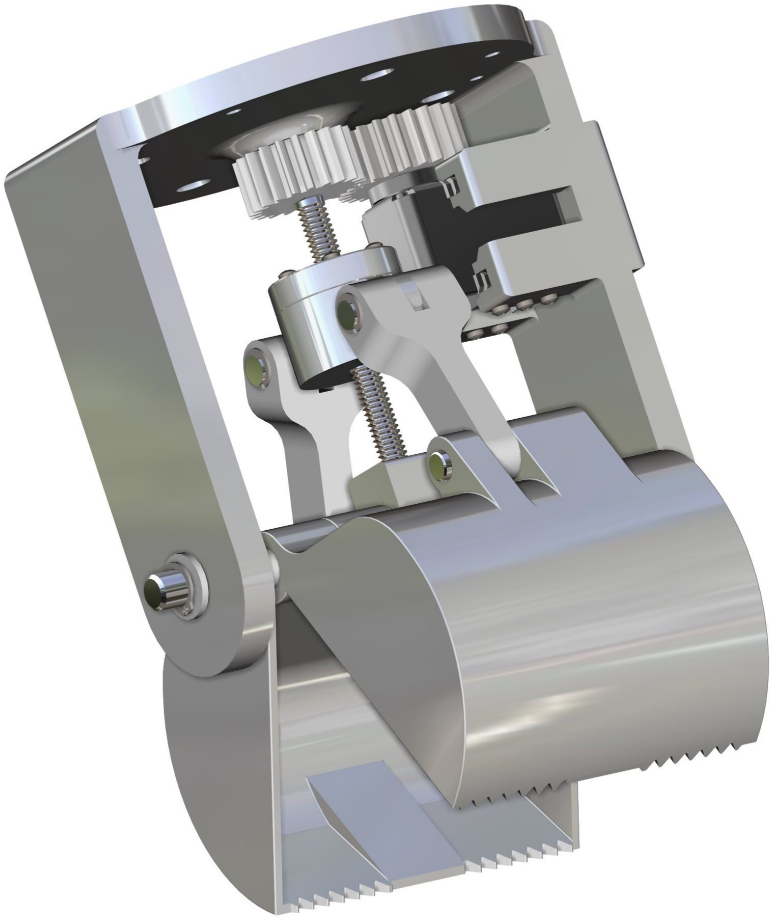


Figure 4.15: The scoop opened

Electronics The *Nema-23* bipolar stepper motors and the *linear actuator* require a driver with enough output current. We chose the *L298N*, which provides 2.5 A_{rms} output current. Each driver is controlled by an ATMega328P-PU micro controller.

The kinematic control of the arm relies on incremental encoders and end-stop switches to detect the angular position of the joints. The ATMega microcontroller tracks the motion of the stepper motors thanks to a rectangular profile function. Each stepper is equipped with an HKT22 optical encoder in order to keep count of motor stalls and transmit feedback for each phase of movement to the microcontroller.

For the linear actuator, we designed a custom encoder made with 3D printing

FDM technology that fits on the elbow joint This incremental encoder ensures an accuracy of 0.5° of angle and combined with the end stop switches gives complete control over the positioning of the elbow joint. The current drawn by the DC motor of the actuator is provided by the L298N, driven by PWM, in order to control the mechanical power output and the speed of movements.

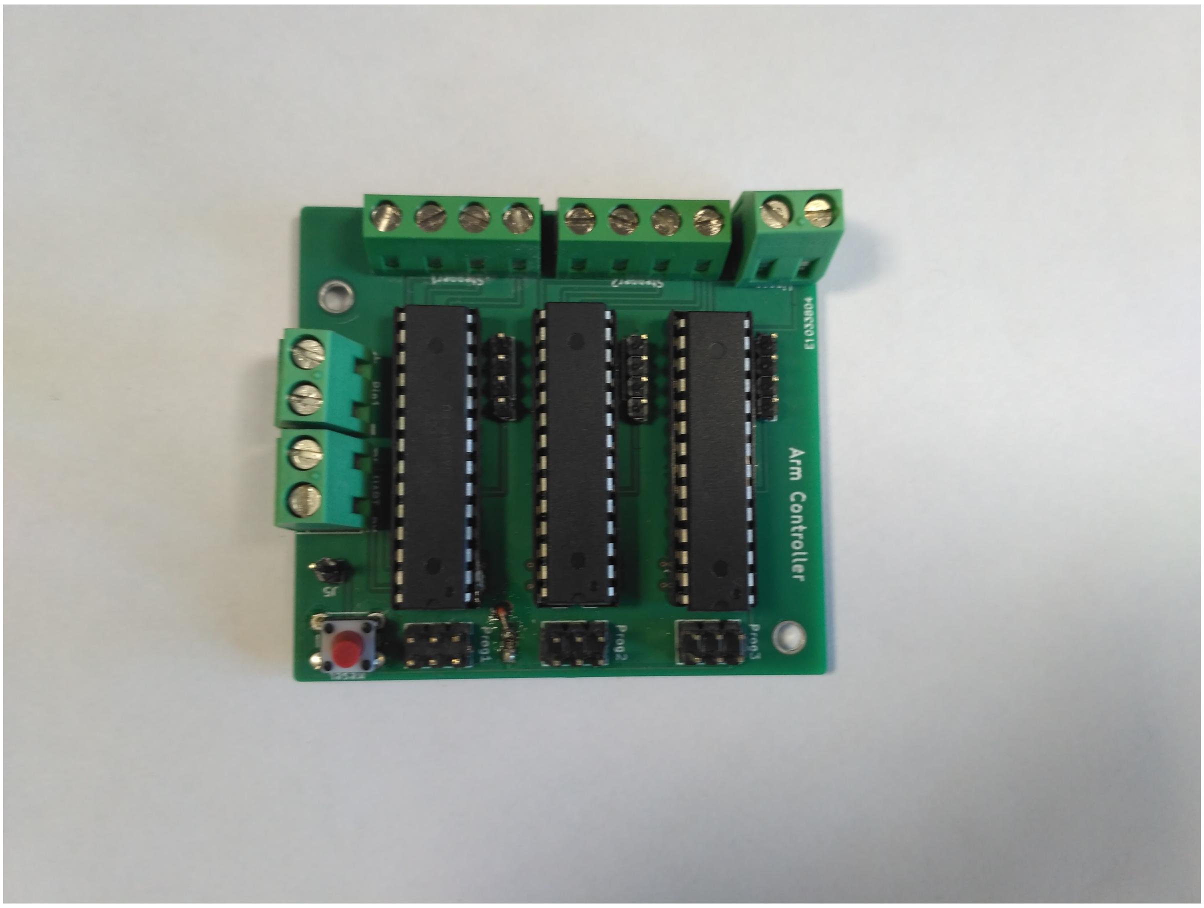


Figure 4.16: The Arm Controller PCB

The *Dynamixel* servos, on the other hand, do not require an external driver: they integrate a PID control and receive commands from a TTL Multi Drop bus mastered by an *ATMega328P-PU* microcontroller.

The *Jetson TX2* computer controls the arm at a higher level with an inverse kinematics algorithm requiring strong computational power to allow the arm to follow trajectories at higher speed.

The main board computes a final target pose or a path to be followed by the end effector provided by computer vision or manual control, the processor will compute the target angle of the joints and the micro controllers will drive the motors to the targeted position.

It is also possible for the human operator to bring one or more motors into position directly, skipping the IK algorithms. This functionality works as a backup. The end effectors are often operated manually, controlling speed and direction. Stall control helps to identify when a certain object is grabbed or when the scoop reaches the ground.

The human operator can ask the system to place the end effector in a certain pose in space or move it by steps, always in Cartesian space. This is useful when the operator wants to place the grabber over an object using incremental position updates.

Control The arm can be controlled using both joint angle and pose (X,Y,Z,R,P,Y). This is permitted by implementing an inverse kinematics block which, thanks to a kinematics decoupling algorithm, This is effected by finding the the intersection of the wrist axes and, successively, the orientation of the wrist itself. A rototraslation from the w-center to the base completes the algorithm. A complex path can be used to perform an arbitrary movement of the arm in space. This is used to place samples or caches safely and smoothly inside the boxes placed behind the rover without risking over- or undershooting the containers. It is also be used to perform drilling perpendicular to the ground moving all the motors together. The torques on the wrist are measured to have feedback regarding the force used against panels or switches. To minimize mechanical stress at the start-up of the motors, a trapezoidal velocity profile is actuated autonomously by the ROS node that manages the arm.

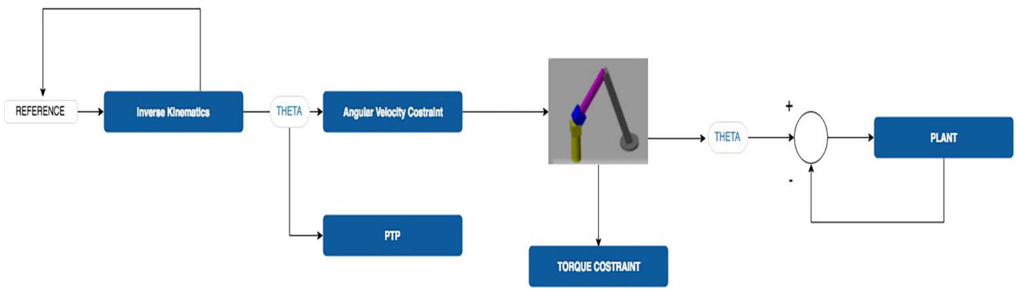


Figure 4.17: The block scheme of the inverse kinematic control

4.5.5 Power system

The rover is powered by 10 4-cell Li-Po battery packs, connected in a hybrid configuration (5 parallels of 2 battery packs connected in series) managed by a BMS (Battery Management System) designed by members of the team.

The number of the batteries and the configuration was chosen after evaluating the voltage required by the different devices and the maximum current they could absorb. Estimations of the power consumption of the different subsystems were made considering typical operating situations the rover would face. Worst case scenarios were taken into account as well.

The actual power consumption was then verified, testing the rover in the configurations of the different tasks. Power consumption often turned out to be actually lower than predicted

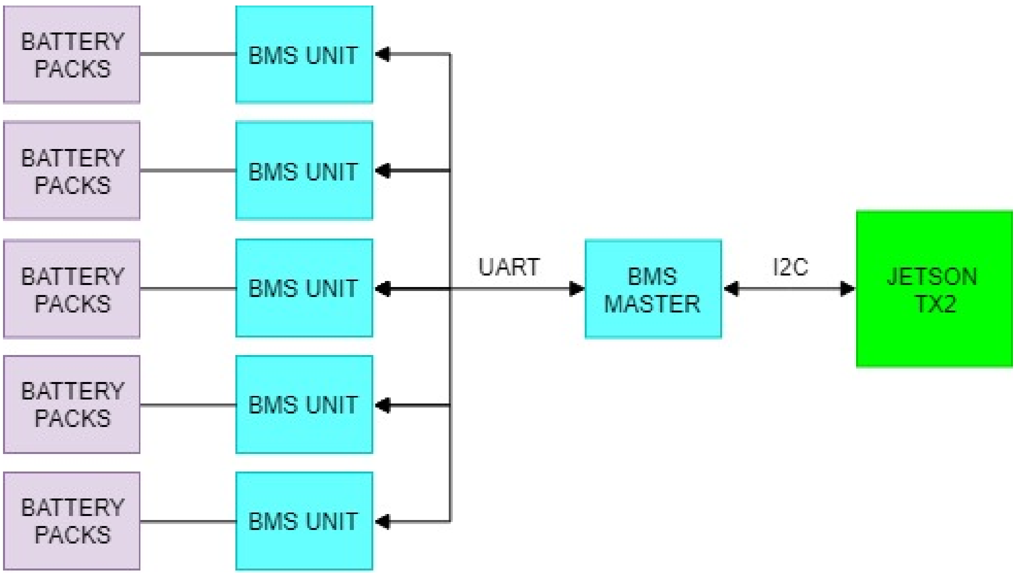


Figure 4.18: BMS Schema

The BMS was designed to monitor the current, voltage and temperature of each battery unit.

However, even though investigated, several problems affect the BMS Units, hence it was decided not to implement them in the version presented for the ERC 2018.

A complex and articulated system such as T0-R0 rover requires a regulated and filtered power supply in order to avoid interference and damage to the electronic components. For this reason a power converter board with three isolated switching converters made by Traco Power was designed by members of the team. The most powerful one, capable of 13A output, is used to power the Dynamixel servo motors of the wrist. A second one, capable of 8A output, is used to power the stepper motors of the arm and the linear actuator. The last one powers all the logic components, keeping them isolated from the EMI generated by the motors.

The board is also equipped with smoothing capacitors to lower the EMI and limit peak currents.

The output voltage of the DC-DC converters is independent from the load applied thanks to the internal sensing and can be adjusted with an external trimmer circuit. Hall effect current sensors are used to measure and keep track of the current drawn from the converters, since the current absorbed is internally limited by the

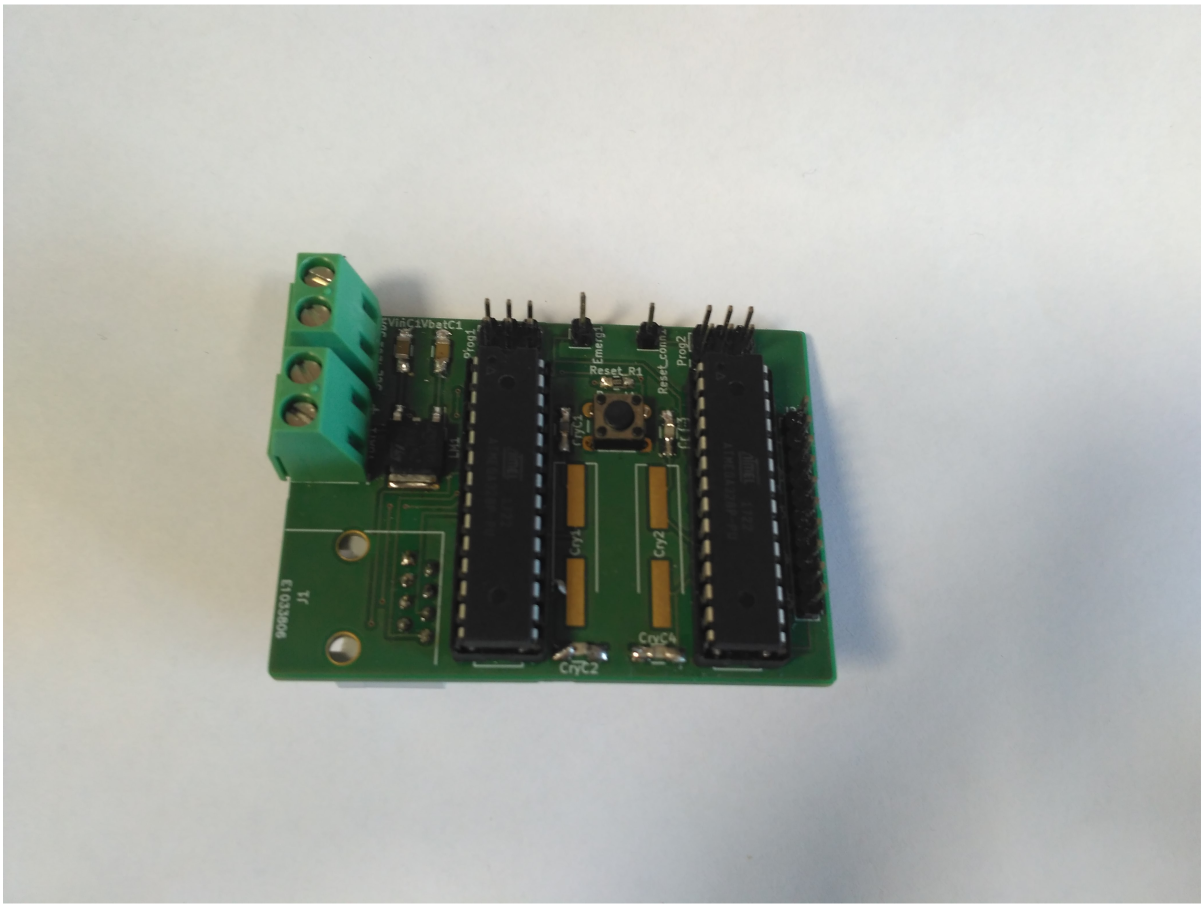


Figure 4.19: BMS Master

converter itself. This feature can avoid severe electrical damage, overheating and fire in case of damage to the cables or batteries.

The VESC boards are powered directly at battery voltage and turned on and off by four Smart Highside Power Switches granting load dump and reverse battery protection, short-circuit protection, current limitation, thermal shutdown and diagnostic feedback.

The CMOS compatible input logic receives the signal to turn on the mobility system of the rover from the BMS Master. The system is otherwise kept switched off by default for safety.

4.5.6 Communication system

The T0-R0 network consists of two segments: the rover and the base station. The connection between the two segments is supplied by Wi-Fi Technology: two Wi-Fi access points are accordingly set up to do the job. We decided to use the IEEE

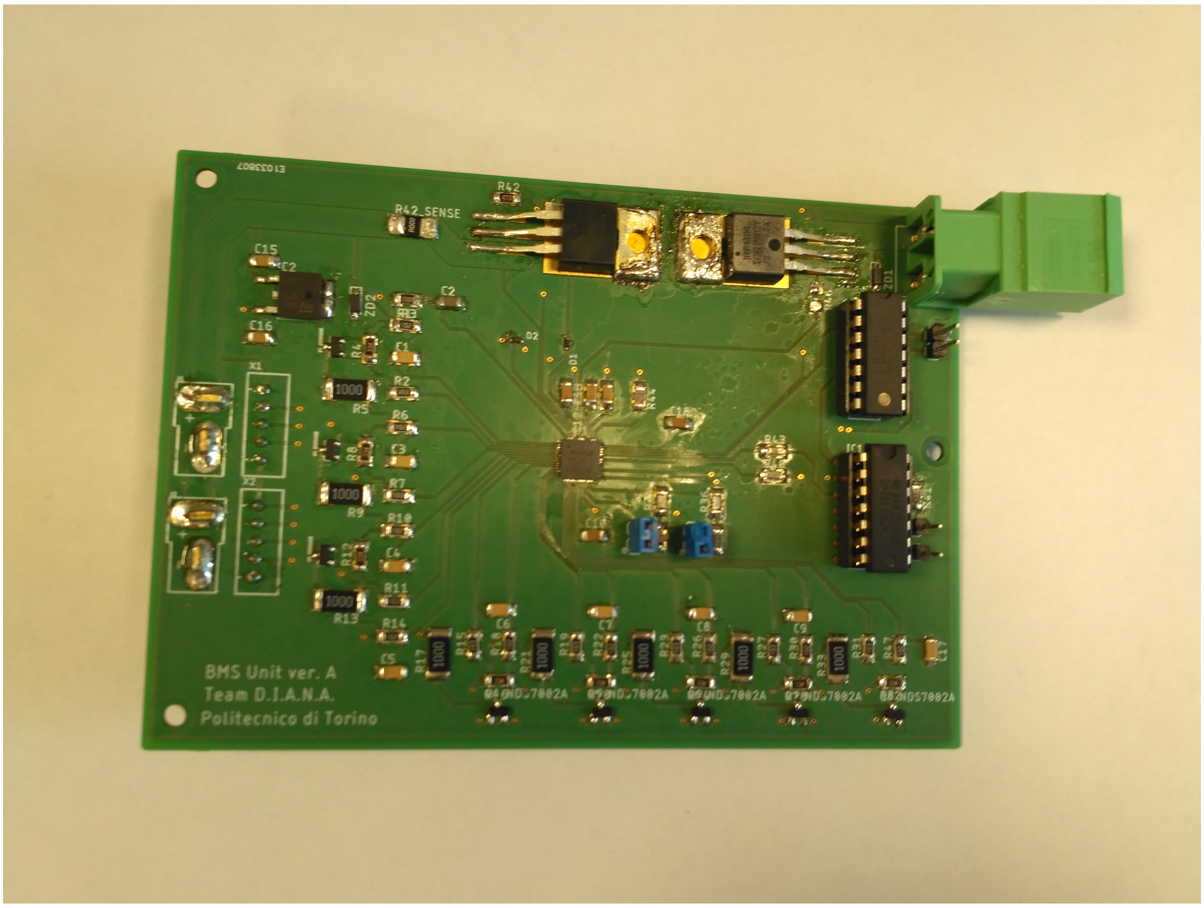


Figure 4.20: BMS Unit

Table 4.2: DC-DC converters power budget

Power Budget	Power in[W]	Power Out[W]	Power Lost[W]
DC-DC 12A (Wrist)	175	154	20
DC-DC 8A (Arm)	103	91	55
DC-DC 8A (Logic)	71	63	9
Total:	350		85

802.11 b/g standard on 2.4 GHz frequency, as it performs better over a distance. The access points use three 9 dBi antennas to output a signal lower than 100mW EIRP.

The base station segments connect several computers via an Ethernet switch. These computers are used to monitor, control and diagnose all mission-vital parameters.

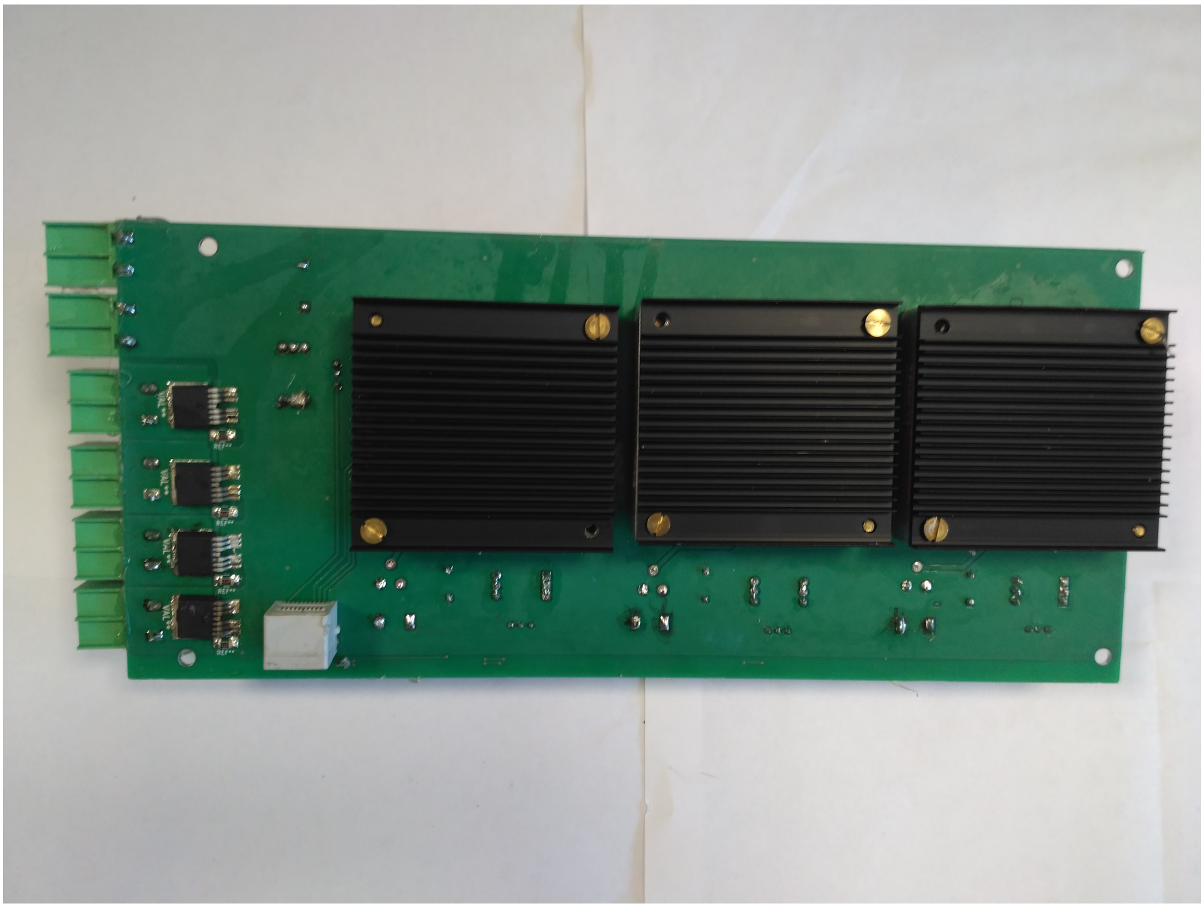


Figure 4.21: BMS DC/DC Converters Board

Video feedback is sent through the network from the rover to the base station (Driving Station) with an UDP protocol. GStreamer open source framework supplies these features.

TCP protocol provides a reliable connection for the main controls of the rover.

Telemetry, status parameters and other non-vital data are sent with the MQTT protocol. Eclipse Mosquitto (open source) has been adopted as MQTT broker and runs on a computer on the base station .

In order to contact the rover in more challenging situations we opted for a radio backup system composed by a VHF radio bridge which transmits over the 2 meter band. In particular, the radio system is composed of two Baofeng UV5RA.

The backup system will take advantage of the transceiver and a program (which uses AFSK) which sends basic commands to the rover.

More information is available in the attached RF form.

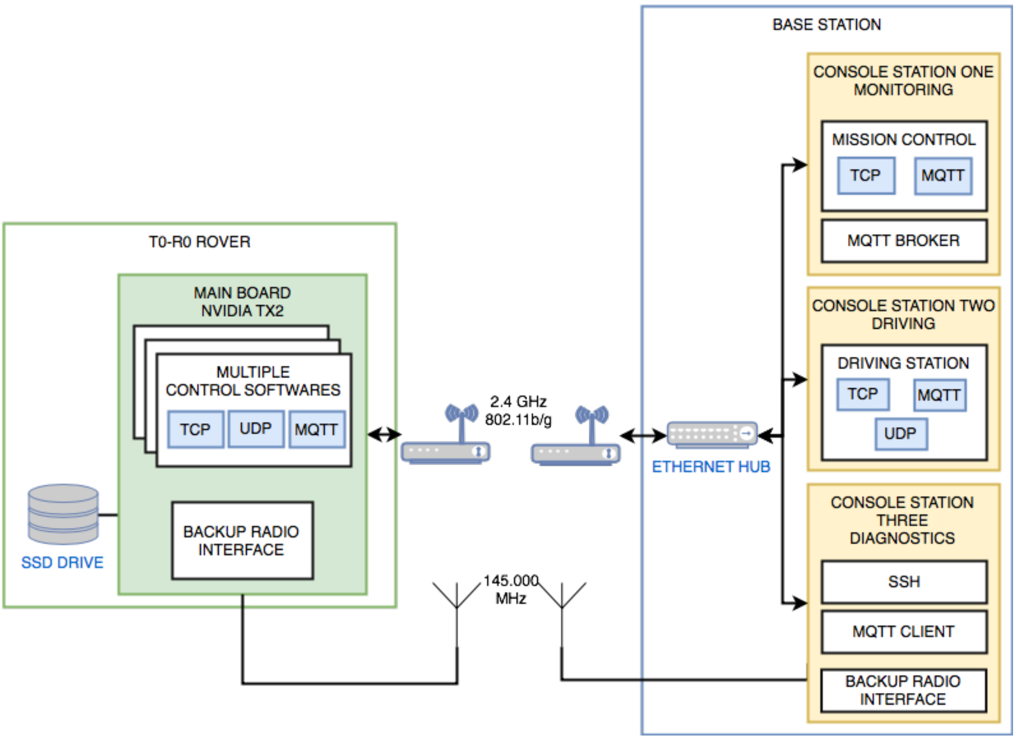


Figure 4.22: Overall network schema of the rover

4.5.7 Vision & Navigation systems

The vision system is based on a **stereo camera** (ZED camera) mounted in front of the chassis. This camera provides synchronized recordings processed by a SLAM algorithm that computes a three-dimensional reconstruction of the environment around the rover. Once the three-dimensional map is computed, a path planning algorithm can find the best way to reach the desired location.

The arm camera guides the arm during precise manipulation tasks and can capture photos of samples and locations. A third camera is placed on the turret, giving the operator a broad field of vision in all directions thanks to a pan-tilt system. The images captured from these last two cameras are elaborated by a computer vision algorithm based on an artificial intelligence able to identify the location of objects on the surface of the ground or on a panel, depending on the task in progress.

Rover and human safety is granted thanks to an ultrasonic sensor system able to detect obstacles close to the rover and notify their presence to the operator.

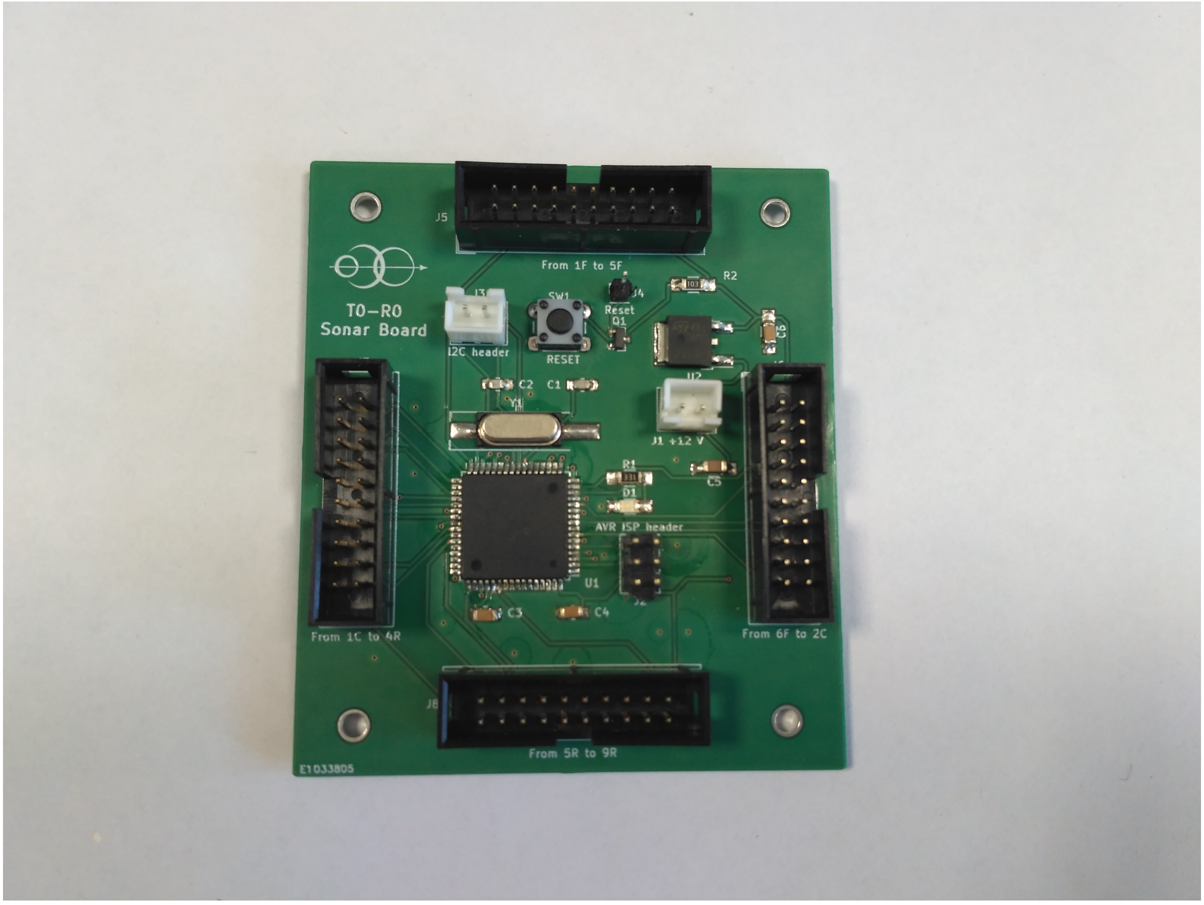


Figure 4.23: Sonar Board

4.5.8 Specific task system

Maintenance task

The maintenance task is mainly performed by the robotic arm which can carry out the operation requested using the gripper end effector. Guided by the computer vision system, the rover is able to recognize the points of interest where the operations will be performed, recognize the shape and color of the objects on the panel and place the gripper thanks to the inverse kinematics calculations. Once the end effector is placed over the required point, pre-recorded tool paths will perform the operation necessary. Proximity sensors around the chassis are fundamental for positioning the rover at the right distance from the panel and the proximity sensor placed on the gripper avoids the risk of damaging the electrical panel. Voltage measurements on the electrical socket will be performed by an additional tool picked up by the gripper that contains the electronic circuit which performs the measurement and sends the data to the main board by I2C bus. The computer vision system is trained on a real model of a similar panel, built to simulate the task in our laboratory.

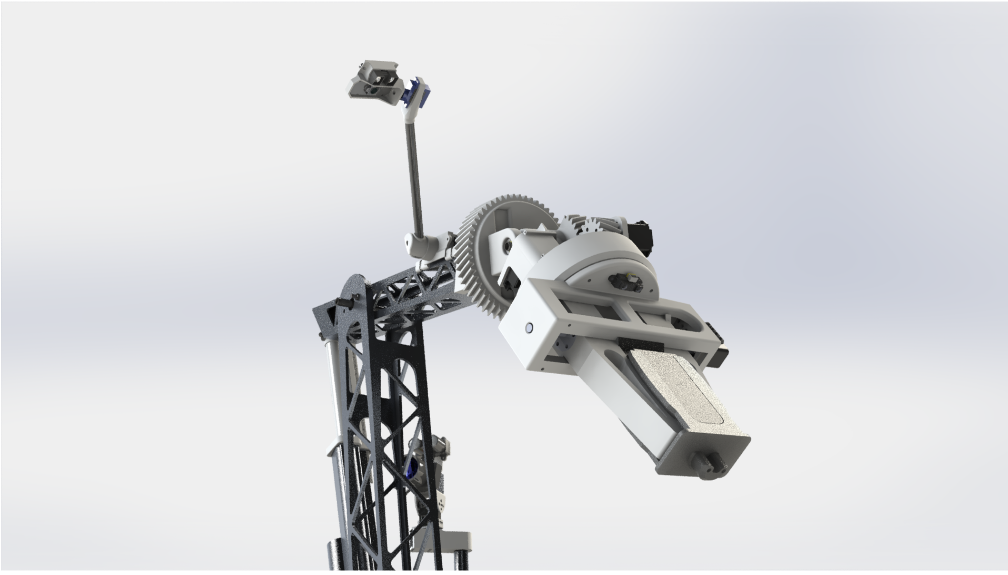


Figure 4.24: Gripper with voltage measurement tool

Scientific task

The scientific task demands the most complex operations of the ERC 2018 competition with strict constraints deriving both from the competition requirements and from our assumptions. Initial research showed how many variables and unpredictable situations the rover may encounter and deal with. Even if the quality of the surface layer of the terrain matches expectations, the nature of the material present below the surface is unpredictable, resulting in the need for a versatile drilling system, able to work in a wide range of conditions. The system is able to drill in both soft and hard materials, even though the strongest material likely to be encountered in the competition is gypsum (Mohs scale of mineral hardness 2). The tests for the drilling system included a wide range of soil types, including the specific soil made available by ALTEC facilities at the Mars Terrain Demonstrator.

The scoop end-effector with an integrable core drill and a collecting system were designed to perform this task. This solution is compatible with the choice of using interchangeable end-effectors and additional tools to perform the tasks.

The scooping system can apply enough shear force to cut and collect superficial soil inside the scoop. The inverse kinematic control, addressed by the recognizing algorithm of the computer vision, drives the scoop to the exact point marked on the ground. Once scooped, the payload will be carried inside the collecting boxes by the robotic arm and unloaded. In the meantime the arm camera will take pictures of the area. The collecting boxes are provided with a group of sensors that can measure weight, temperature and humidity of the sample. Volume measurements will be performed thanks to a reference grid printed inside the box. Storing boxes have an automated lid that seals the samples.

The same routine will be followed to excavate the trench and the arm camera will perform measurements and acquire photographic documentation. This subsystem is able to perform the task in accordance with the rules requirements.

In case of deep sample collecting the drilling is performed by a core drill tool grabbed by the scoop and stored inside the sample container area.

This solution is not exactly in line with the rules requirements but has been chosen for consistency with our research on interchangeable tools and end effectors. This core drill is operated directly by the arm and does not require any other actuator or support structure except the robotic arm itself and its own motors.

Due to the limited power of the wrist actuators and to the risk of causing excessive vibration and stresses on the arm structure, the drill cannot reach high rotational speeds.

Since at the moment this solution doesn't completely comply with the rules requirements correctly in uncoupling the stresses caused by the drilling and in the maximum drill depth , we assume the need to develop a new flexible and light weight drilling solution. In comparison with more traditional drilling solutions placed on the rover chassis, the advantage of the robotic arm is that it provides great reaching capabilities and permits drilling in sites located on slopes, vertical walls or craters as well as on the ground. There is also the possibility of carrying more than one drill, allowing sampling on a wide array of soils. The core drill body functions as a sample container and allows samples to be stored and insulated from the environment. The sample can then be extracted from the driller body and analyzed in a laboratory.

Although we are aware that our solutions do not fully satisfy all the requested performances at this stage, our work embodies the results of the intensive research the team has undertaken and we confirm our intention to develop efficient and innovative solutions in the near future.

Collection task

The caching task is performed with the gripper end effector mounted on the arm wrist. The computer vision uses OpenCV in order to recognize the cache shape and colour from the navigation camera image and registers the location on the map. The path finding algorithm drives the rover to the cache location and then the arm picks up the cache guided by the inverse kinematics. A specific storage zone on the chassis is designed to protect the caches from damage during transport and re-entry of the samples. Once the unloading site is reached, the gripper grabs the handle of the container, unlocking the retaining mechanism, and leaves the container on the

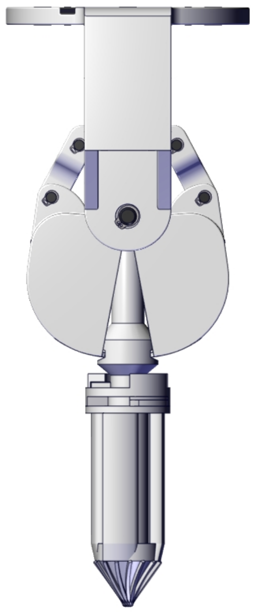


Figure 4.25: Scoop and core drill joining

required point on the ground.

Navigation task

During the navigation task the robotic arm will be removed in order to lighten the rover and reduce stresses on the chassis when the rover is driving on bumpy terrain and steep slopes. In this task the capabilities of the mobility system are exploited in full. The mobility system is designed to overcome unexpected obstacles and significant slopes. The absence of motors on the two central wheels are not a limit since the traction of the motorized wheels is constantly monitored by the control software of our VESC drivers board.

Autonomously driven by the computer vision system the rover reaches the points received by coordinates on the map using the SLAM algorithm.

4.5.9 Operation control station

Human-computer interaction is implemented by using several HID (Human Interface Devices). The operator can send commands through different input peripherals: a joystick is used to control the arm and a joypad to control the motion of the rover (a mouse and keyboard are also used) and monitor current rover status with

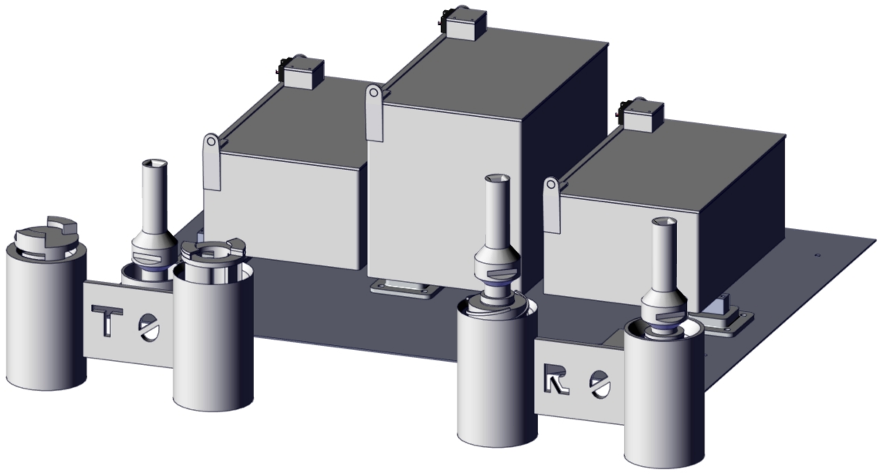


Figure 4.26: Scientific Platform

output devices (GUI on computer display). The Operation Control Station (OCS) transmits and receives data through a radio data link.

4.5.10 Safety system

Due to the previously mentioned problems in the Power System section, the new implementation of the safety system is composed of the BMS Master interfaced with the DC/DC Converters Board.

When the emergency button is pressed, an interrupt is generated on the ATMega present on the BMS Master Board. This will polarize the transistors on the DC/DC Board (one for each converter) which pulls down the DC/DCs' control pin (which is normally floating). This will immediately disable the power supply and stop the rover.

As well as the emergency button, it is also possible to deactivate the rover from the base station by means of a control input from the operator. To avoid unintended deactivation, a two-hand key combination is required.

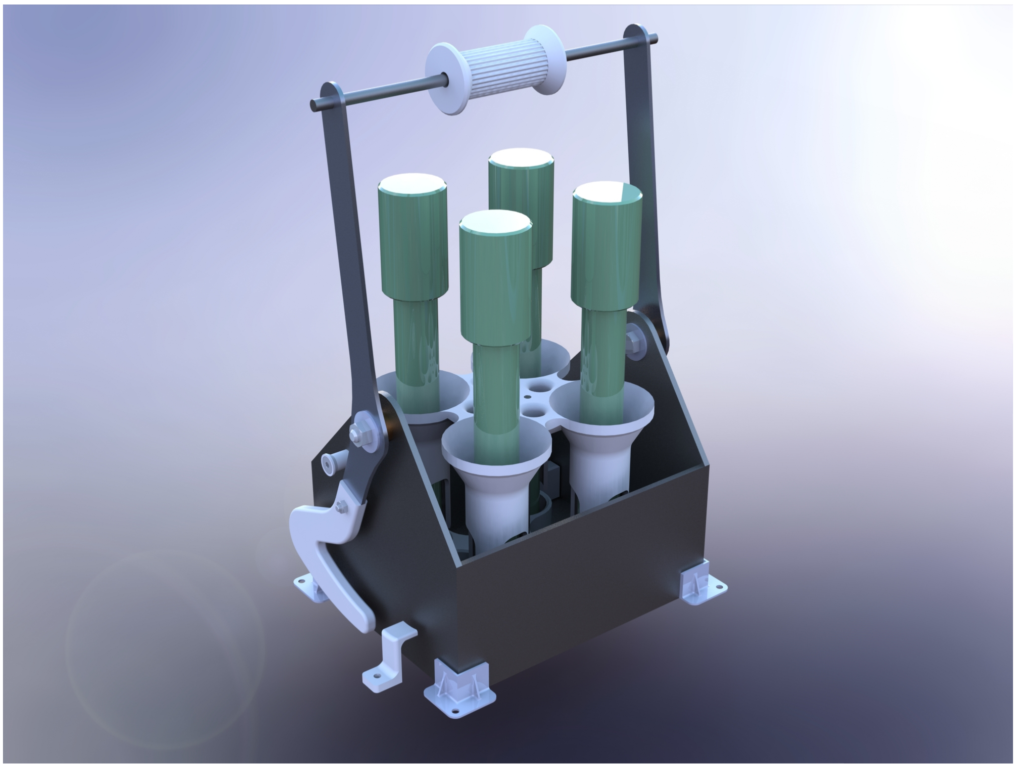


Figure 4.27: Caches box operation

4.6 Testing phase

Tests are fundamental for the validation of the project and for the identification of the limits of the systems. Testing early in the system life cycle reduces risks such as schedule delays or cost overruns due to incomplete or unacceptable components. However it is not possible to fully validate the outcome of the project until the final product is tested with all the systems integrated.

In the case of the T0-R0 project, the test phase was also important for training the operators of the rover. It was necessary in this phase to practice and gain confidence in manouevering the robot in order to optimize performance during the competition.

Tests were regularly performed on the subsystems and on parts during the development phase in order to verify their functionality. Unfortunately because of the long delays that occurred during the project caused by problems illustrated in section 4.7 the team had a very limited amount of time to perform tests on the completed rover.

Nevertheless a minimum number of tests with a semi-complete rover were performed to confirm the correct functioning of the systems:

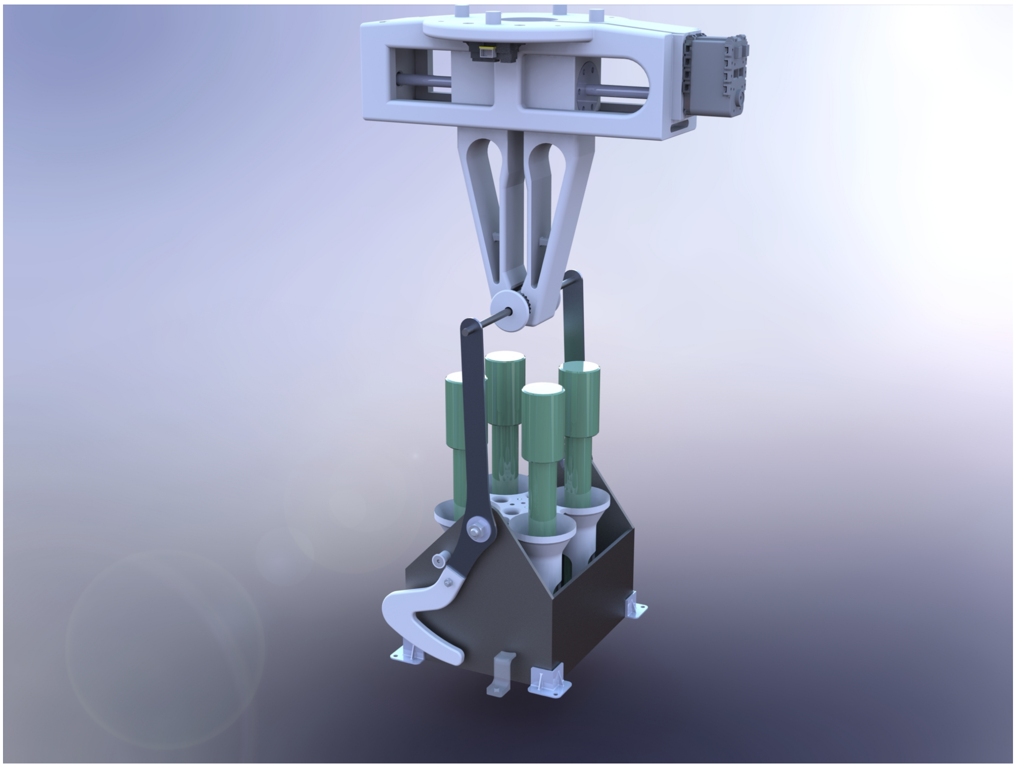


Figure 4.28: Caches box operation, acquisition of the box

- The rover mobility system and remote control through Wi-Fi connection was tested in the laboratory corridors, in the university courtyard and on the sinusoidal structures of the OGR (Officine Grandi Riparazioni), demonstrating the smooth and precise control of the rover and the correct functioning of the rocker-bogie system. The anticipated problems with overcoming step-type obstacles due to the idle middle wheels were confirmed and a problem with the transmission belt tension emerged but this was corrected with a rudimentary but effective tensioner system.

- The various competition task operations where reproduced in the laboratory in order to test performance of the robotic arm, these tests confirmed the precise, smooth movement of the robotic arm and were vital for training the operators to drive it in the direct kinematic mode. The test also confirmed the validity of the various subsystems for the completion of the specific tasks. The robustness of the 3D printed parts of the wrist and end effectors was also confirmed.

- Other tests were conducted on the rover's communication and video streaming capabilities.

Figure 4.29: The base station during competition

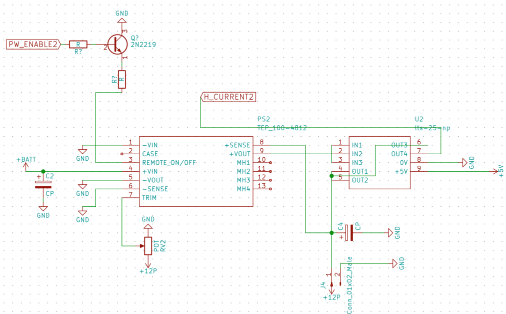


Figure 4.30: DC/DC Board schematic

Some moments from the test phase are shown in figures 4.32, 4.36 and 4.34.

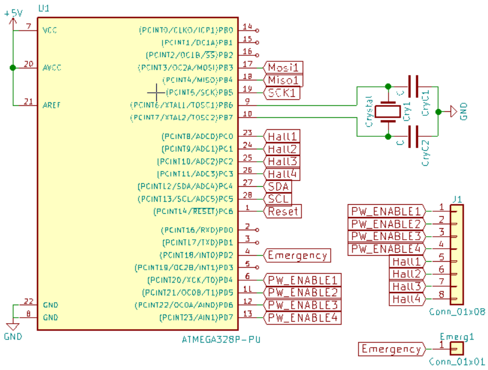


Figure 4.31: BMS Master schematic

Figure 4.32: Simulation of the maintenance task

4.7 Problems encountered

During the course of the project the team had to face numerous problems and difficulties which emerged causing delays and impacting on the overall outcome of the project.

First of all, at the beginning of June, with the exam period getting closer, there was a dramatic reduction in the time many team members were able to dedicate to the project. The team was effectively reduced to 10/15 members over the whole of the summer period (even fewer during August) leaving work unaccomplished.

In addition, the design of some subsystems, especially regarding the PCBs, proved to be extremely problematic and required more time than estimated. One of the most time-consuming aspects from the administrative/bureaucratic point of

Figure 4.33: Testing the science task

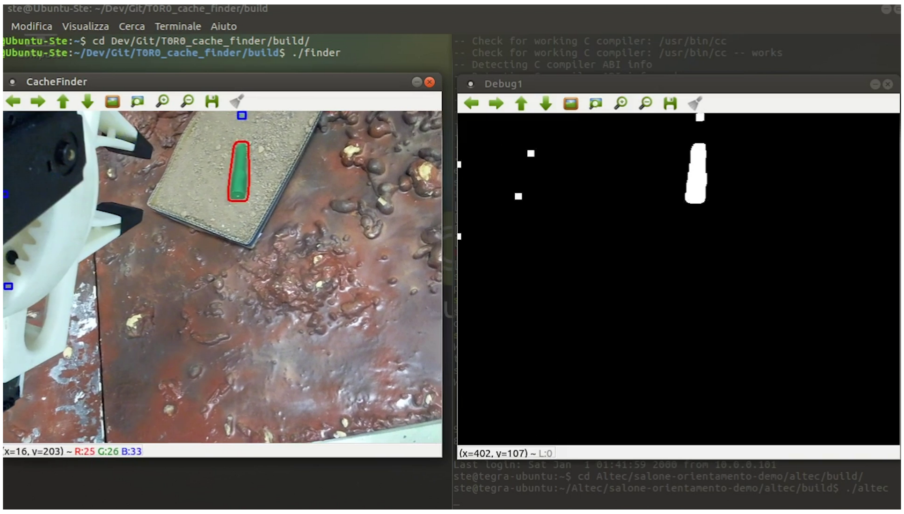


Figure 4.34: Testing of the cache collection task and of the computer vision cache recognition

view was the length and complexity of the purchasing process. This led to the necessity to aggregate orders which resulted in delays affecting the production of other subsystems.

Also the soldering of the most complex PCBs turned out to be more difficult than expected and, in the case of the BMS cells, it was not possible to make them work forcing the team to forego their use.

During the implementation phase various components suffered failures in particular:

Figure 4.35: Testing of the cache collection task

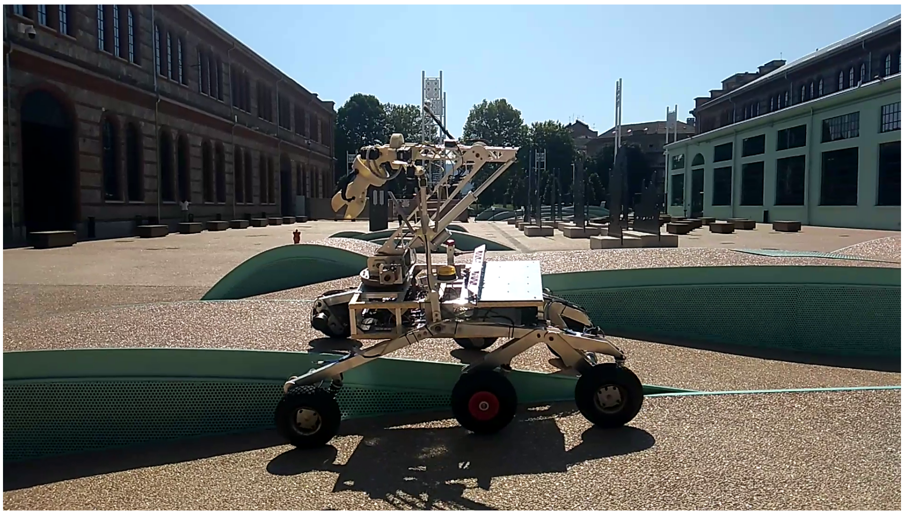


Figure 4.36: Testing the mobility system at the OGR

- The Dynamixel MX-64T motors that should have been mounted on the wrist were sent to be repaired after a first failure, but returned with a different type of connection (RS-485 instead of TTL) which was incompatible with the pre-existing controller software and hardware. The problem was solved by substituting the Dynamixel MX-64T with MX-106T but this change required adjustments to the location of the motors.

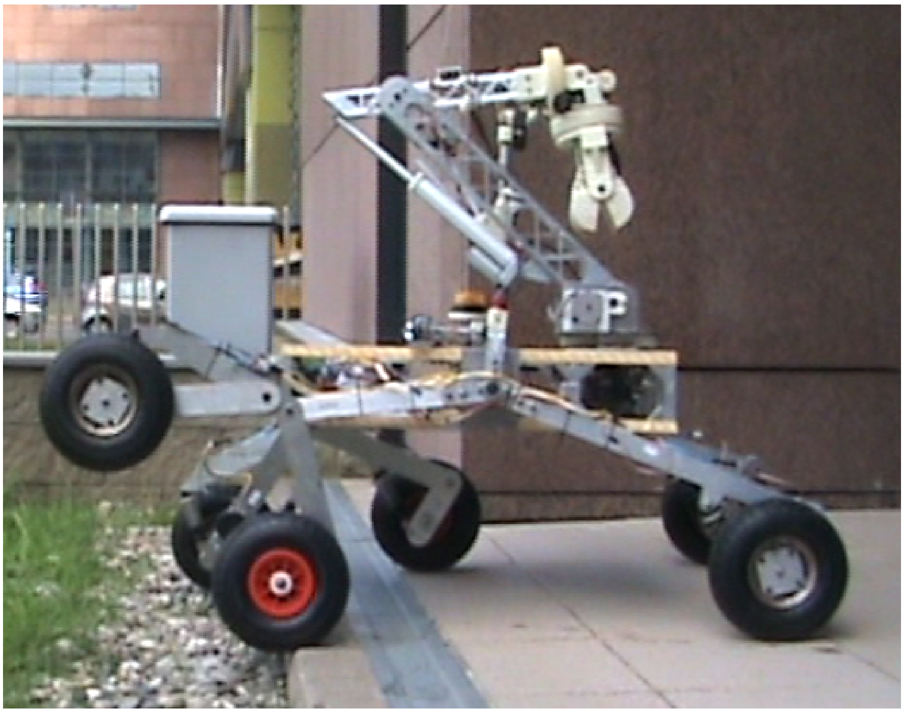


Figure 4.37: Testing the mobility system in the Polytechnic courtyard. As expected, the bogie can get stuck when overcoming step-like obstacles

- During the testing phase, one of the Maxon motors of the mobility system exhibited a severe failure on the windings, for reasons which could not be explained, and could not be replaced with an identical one due to the unavailability of a replacement part. The team coped with this problem by adapting a motor which was similar but not identical in size and mechanical performance. This meant that it was necessary to design an adapter with 3d print and manufacture an extend shaft.
- During an integration test of the control and power electronics via CAN bus, the main computer was subjected to an over voltage and was irreversibly damaged. The team had to wait for a replacement part in order to continue testing and had to redesign part of the electronic power system, delaying the progress of the work by several weeks.

4.8 Project cost reporting

The first funding request was made in February 2016 and the team obtained 20000€ of which 11383,07€ was spent during the 2016-2017 period when the first prototype of the rover was built.

- improvement and completion of the rover prototype built in the previous period (2016-2017)
- travelling expenses to attend the competition
- production of the team's promotional/image materials
- purchase of materials necessary for carrying out the project
- minor adjustment to the previous AMALIA rover

Total expenditure from March - September 2018 came to 19.750,73€, well within the initial forecast; despite some unforeseen expenses (detailed under the heading 'Margin for unexpected costs' in the table 4.4) and the higher than expected cost of the 3D printing material, it was possible to keep the total expenditure much lower than estimated and at the moment the budget has a surplus of 9513,64€. The savings were possible thanks to the use of components and materials already present in the laboratory, particularly favourable prices obtained from some suppliers (e.g. for the cost of the batteries, producing the arm structure, components for the scientific task), travel costs kept lower than predicted and changes to the choices regarding the Amalia Rover project.

A summary of the economic situation is shown in table 4.3, while a detailed reporting of the actual spending in comparison with estimated costs is presented in table 4.4. On closing the Diana 2016 account, the residual sum of 659,62€ (resulting from money set aside for orders that, for various reasons, were never concluded) was transferred to the new Diana 2018 account.

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Table 4.3: Synthesis of Team DIANA's economic situation

Budget	
2018 obtained funds 2018	20000,00
2016 residual budget	8616,93
Residue remaining on the Diana 2016 account	659,62
Total budget	**29276,55**
Expenses	
Total expenses	**19751,41**
Residual budget	
Residual budget (Total budget - Total expenses)	**9525,14**

Table 4.4: List of Team DIANA expenses in comparison to the estimates

Team DIANA 2018 expenses		
	Estimate	Actual expenditure
Rover T0-R0	**10548,00**	**6879.39**
Electronic components	*(4733,00)*	*(3310,93)*
DC-DC converters	350,00	224,99
Stepper controllers	60,00	113,16
Dynamixel controllers	20,00	0,00
BMS cell	600,00	464,85
Batteries	2000,00	1078,21
Battery container	300,00	55,63
Scientific Task sensors	220,00	212,06
Scientific task actuators	150,00	89,26
Radio link	300,00	10,07
Cables and connectors	350,00	386,30
Arm sensors	50,00	137,20
Arm camera	71,00	65,55
Arm camera tilt	30,00	38,01
Chassis sensors	35,00	99,13
Wi-Fi system	96,00	130,34
Turret camera	71,00	64,05
Pan-tilt turret	30,00	112,12
Mechanical components	*(5815,00)*	*(3568,46)*
Robotic Arm Structure	2500,00	1406,42
Robotic Arm bolting and bearings	300,00	596,51
Rover covering	300,00	157,16
Scientific Task mechanics	1500,00	506,34
Mobility system structure	500,00	462,99
Rover wheels	400,00	54,00
Suspension springs	165,00	268,40
Bearings Mobility systems	100,00	112,91
Differential bar springs + pad	50,00	4,40
Other	**2690,00**	**2815,37**
Instrumentation and accessories		
Operators controls (joysticks)	300,00	308,42
Toolboxes and tools	350,00	51,93
Battery chargers	120,00	105,21
Test platform	350,00	40,84
Trolley + crick	100,00	58,78

Consumables		
3D printing material	1320,00	2159,40
Soldering Paste	100,00	38,00
Grease for bearings and cog wheel	50,00	52,79
ERC Jurney costs	**10100,00**	**6404,79**
Plane and train tickets for 9 people	2500,00	1339,63
Van hiring + petrol + motor way	1400,00	1502,81
Hotel	2600,00	2193,91
Food expenses	3600,00	1368,44
Team Immage	**1495,00**	**1139,79**
T-Shirts	1125,00	999,79
Roll up	140,00	55,00
Stand exposers	30,00	0,00
Stickers	200,00	85,00
Rover AMALIA	**2170,00**	**601,28**
Microcontrollers for active suspension	50,00	0,00
Vesc (4x)	320,00	385,09
Bearings for suspension	200,00	0,00
New active suspension system	1000,00	0,00
New control board	200,00	0,00
BMS	300,00	216,19
Sensors and controller	100,00	0,00
Margin for unexpected costs	**2000,00**	**1910,12**
New BLDC motorreductors		*1260,31*
Dynamixel repair		*126,77*
MarsToEarth conference costs		*124,50*
Upgrade on-board computer		*398,54*
Total	**29003,00**	**19751,40**

Thanks to the detailed Bill of Materials (BOM - Appendix **??**), it was possible to estimate the net value of the rover at 17417,63€ .This value was calculated by adding up the known cost of the components that the team bought and estimating the value of hard to track components (bolting, cables, 3D printed components, manufacturing done by partners) in a conservative manner (real value may be lower). The team also reused many components already in the team's possession from previous projects and other parts which were donated by partner companies. The estimated value of these components is equal to 7195,39€. In Table 4.5 the value of the rover is presented divided into the certain value and the estimated value (conservative),

Table 4.5: Breakdown of the T0-R0 rover value

True value VS estimated value	
True components value	11189,43€
Estimated components value	6228,19 €
Total	**17417,63 €**

Paid VS sponsored/reused	
Paid	10222,23 €
(Paid including VAT)	*(12471,22€)*
Nor paid	7195,39 €
Total	**17417,63 €**

4.9 Competition results

Despite the problems encountered during the project the Team managed to take part in the competition (figure 4.41). Ten members of the Team were selected to go to the competition which was held at the Museum of Technology in Starachowice (Poland) from the 14th to the 16th of September 2018. The journey was organized in the following way:

- Three members left on the 11th of September in a hired van, carrying the rover and equipment necessary for executing maintenance, for a two day journey covering over 1600km.
- Six members left on the 12th of September and reached the competition location by plane and public transport.

The alternative to travelling by van would have been to have the rover shipped, but this solution posed several problems such as the need to send the rover a week before the competition thus reducing the time for final adjustments, and it would also have limited the quantity of material and tools that could be taken to the competition - tools and material which actually turned out in the end to be very useful.

Unfortunately, the rover presented at the competition was far from being completed; in fact, due to the limited time available, caused by the problems illustrated in the previous chapters it was not possible to complete the implementation and testing of all the subsystems, but only those strictly necessary for executing the basic points of the tasks.

Nevertheless, the team managed to compete in three out of the four tasks, the navigation task was not performed because problems emerged in transmitting the data produced by the ZED camera regarding rover position and obstacle presence to the base station making it impossible to drive the rover blindly.

The cache collection task, science task and maintenance task were performed with discreet results.

During both the science task and maintenance task a problem occurred to the actuator of the end effector: lack of feedback to the operators regarding the torque applied by the motor delayed the switching off of the motor causing it to go into protection mode from which it could be recovered only by turning off the system, which was not allowed during the competition. However it was still possible to continue performing the task with the end effector blocked which allowed the team to gain some points.

The cache collection task was less successful: just before the execution of the task, a failure of one of the battery packs exhausted all the batteries necessitating an impromptu battery change which used up some of the time allotted to performing the task. A cache was successfully picked up but wasn't placed on the rover in time, leading to no points for that task.

Despite the problems encountered prior to and during the performance of the tasks, **Team DIANA managed to come 15th out of the 65 teams competing from over 13 countries**. Considering that it was the first time Team DIANA had taken part in the the competition, and, indeed, that they were the first and only team to represent Italy in the ERC, it can be considered a very successful result, demonstrating that the Team is capable of competing against teams with several years of experience in this kind of competition, and inspiring confidence in the team's ability to perform even better in future editions. The majority of the points were obtained thanks to the preliminary documentation sent to the jury, proving the team's ability to produce highly professional technical documentation and confirming the correctness of the approach to the design and the validity of the solutions adopted by the team. The team was also highly praised by the jury and other experts in the field for the quality of the overall project which increased the personal satisfaction and confidence of the team members. In table 4.6 the final results are shown.

Table 4.6: ERC 2018 final results

Place	*Team name*	*Points*
1	Impuls	432.05
2	Raptors	333.7
3	Robotics for Space Exploration	293.8
4	Argo	285.5
5	RoverOva	269
6	University of Warsaw Rover Team	268

7	Legendary Rover Team	258
8	BLUEsat	253.3
9	SKA Robotics	249.2
10	AGH Space Systems	246.7
11	Continuum	242.2
12	ITU Rover Team	230.8
13	Kameleon Team	228.5
14	IUT Avijatrik	220.8
15	**Team D.I.A.N.A.**	**212.8**
16	UCL Rover	186
17	Project Scorpio	171
18	SEDS VIT	164.3
19	Silesian Phoenix	155.75
20	IUT Mars Rover	148.5
21	Fupla Team	144.35
22	Team BEAR	139.5
23	Robocol	136.5
24	Mind Cloud	124
25	Ogrodoot	116
26	OzU Rover Team	108.5
27	AUST Little Step	106.2
28	WARR Exploration	88.5
29	ASHVA	82.25
30	KNR Team	77.5
31	Meteoria	73
32	MISC (Mars Institute Student Chapter)	70.5
33	LU_Durbar	63.5
34	Reactor (Space Robotics Peru)	63
35	McGill Robotics	59
36	PIONNER	55.5
37	WE MARS	52.5
38	Ancha Space Technologies Team	51
39	With the Hammer to Mars	48.5
40	Pioneers	47.7
41	AIUB Robotic Crew	45
42	Breakin Point	44
43	Eagle X Robotics	42.5
44	RoSToK	40.5
45	IUB Attendant	39.5
46	Cocodile Rover Team	39
47	HADES	36
48	Alma-X	34.5

49	URzRover	23.75
50	PCZ Rover Team	21.5
51	OU Rover Team	20.5
52	Ten In Black	19
53	UAA Robotics	19
54	Hyperloop UPV	18.5
55	Gurkha	18.1
56	Mongol Barota	18
57	Team A.R.E.S.	17.5
58	BRACU Mongol-Tori	15
59	AMPERE Robotics Team	13
60	BekkerTeam	12.5
61	Rakshaq	9.5
62	CUET Mongol Ovizatrik '71	8
63	NSU_Phobos	3.5
64	KCT DHRUVA	2.5
65	Atlas Team	2

Figure 4.38: Picture taken on the competition field of the ERC2018

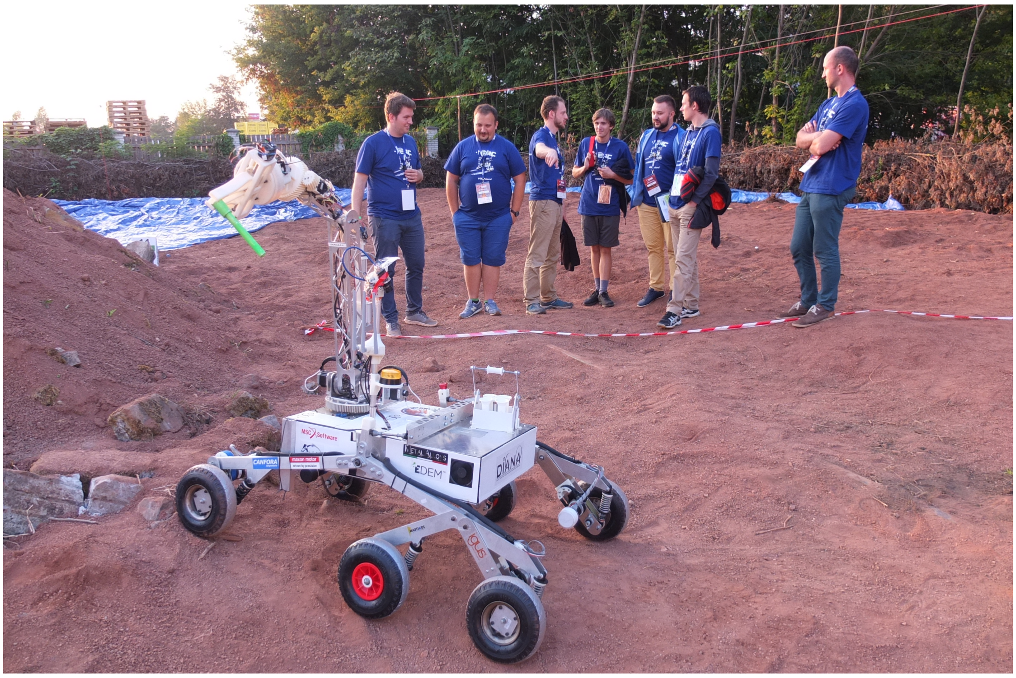


Figure 4.39: Picture taken during the cache collection task

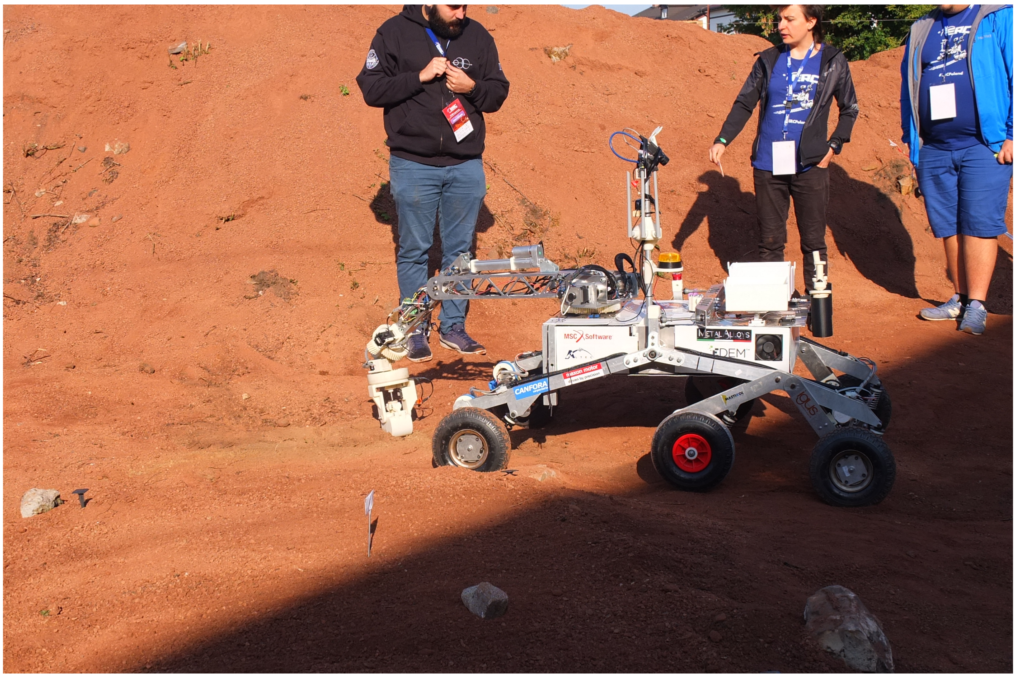


Figure 4.40: Picture taken during the scientific task

Figure 4.41: Picture taken during the maintenance task

Chapter 5

Conclusions and future developments

The work carried out with this project has led to the development of a fully functioning analog rover for astronaut assistance which was able to successfully compete in the European Rover Challenge 2018 accomplishing an important milestone in the history of Team DIANA.

The T0R0 project has presented many challenges. It has given the team the opportunity to acquire significant, real-world experience in many fields: design, production, organization and, above all, team work.

To design and produce the rover, it has been necessary to draw on and put into practice theoretical notions studied over the years in the field of mechanical and electronic engineering, communications, information science and systems – the building blocks of mechatronic engineering. Other practical and manual skills were also acquired, due, for example, to the need to produce and adapt components, make parts using 3D printers, and resolve problems as they arose, often immediately.

Exercising the role of team leader and project manager has meant learning to define objectives, to prioritize the tasks to be performed and to entrust those tasks to the most appropriate groups and members of the team by recognizing the skills and capabilities of the individuals. Planning the budget and administering the team's funds and accounting is also in the hands of the team leader, and, consequently, important experience was also gained in sourcing components and suppliers.

The heavy workload and tight deadlines of the competition can put the members under a lot of strain, especially considering they are all volunteers fitting the work on the Team into their already busy schedules of lectures, coursework and exams The author's experience has taught that one of the most important jobs of the team leader is to create and maintain a positive, cheerful atmosphere – working on the team has to be an enjoyable and rewarding experience if people are to continue to dedicate their time and energy to it. A climate of mutual respect and support is essential and leads to results that the whole team can feel proud of.

Regarding the future developments still lot's need to be done in order to implement the software necessary for transforming the rover from tele-operated in to semi-autonomous and in a longer term fully autonomous, but the rover is fully equipped with the necessary systems in order to achieve these goals.

Appendices

Appendix A

Drawings

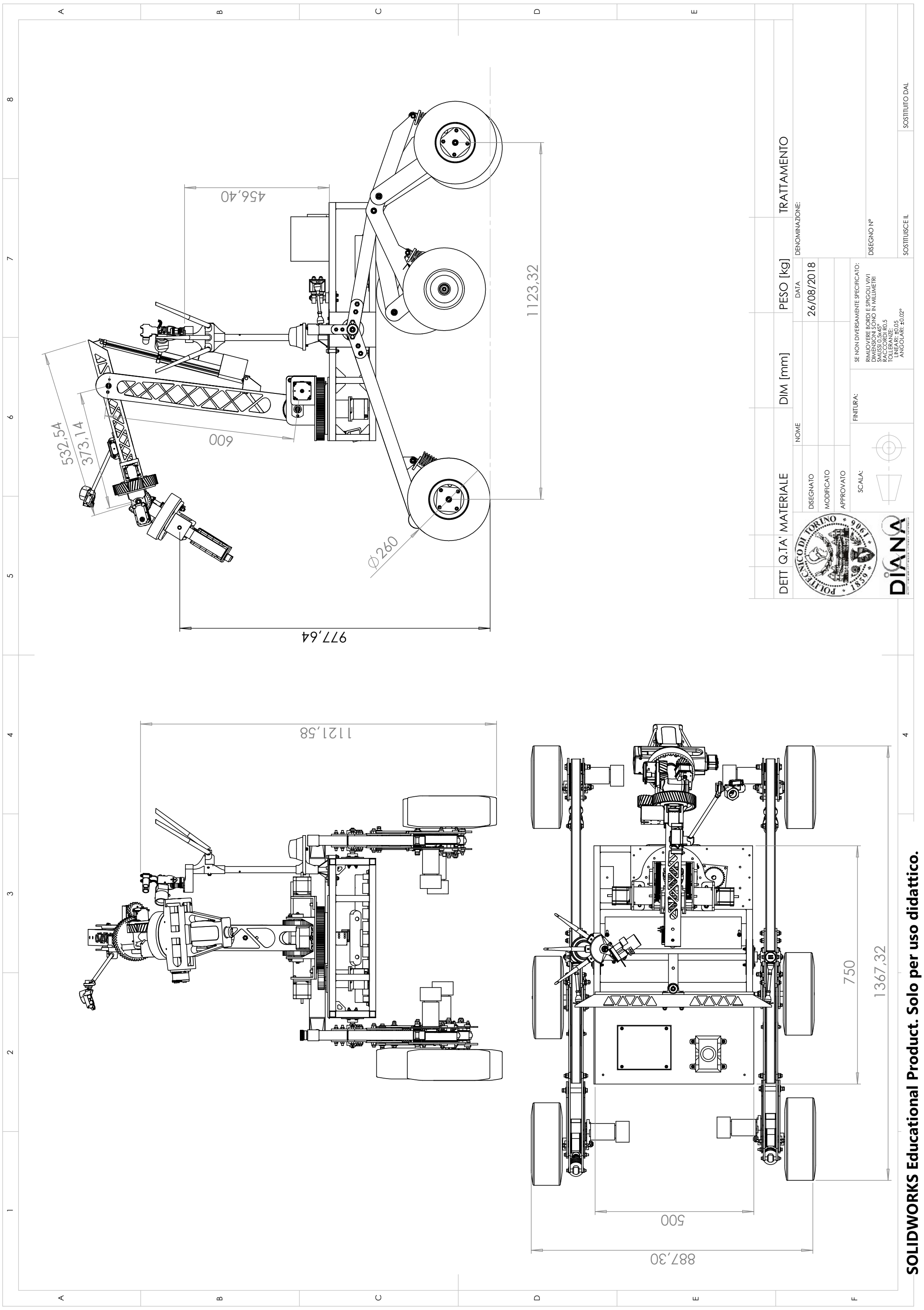


Figure A.1: General dimension of rover T0-R0

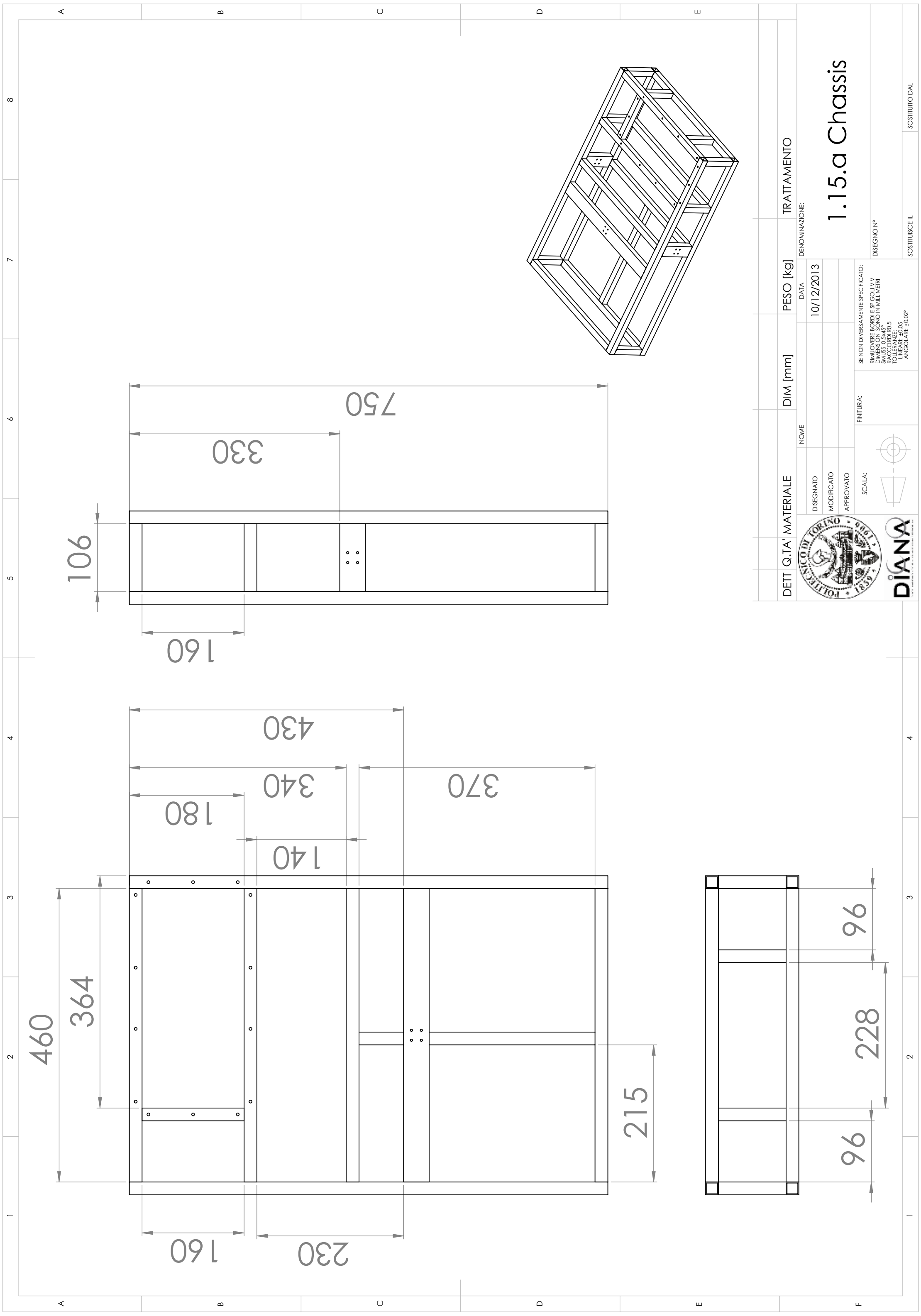


Figure A.2: Assembly of the chassis

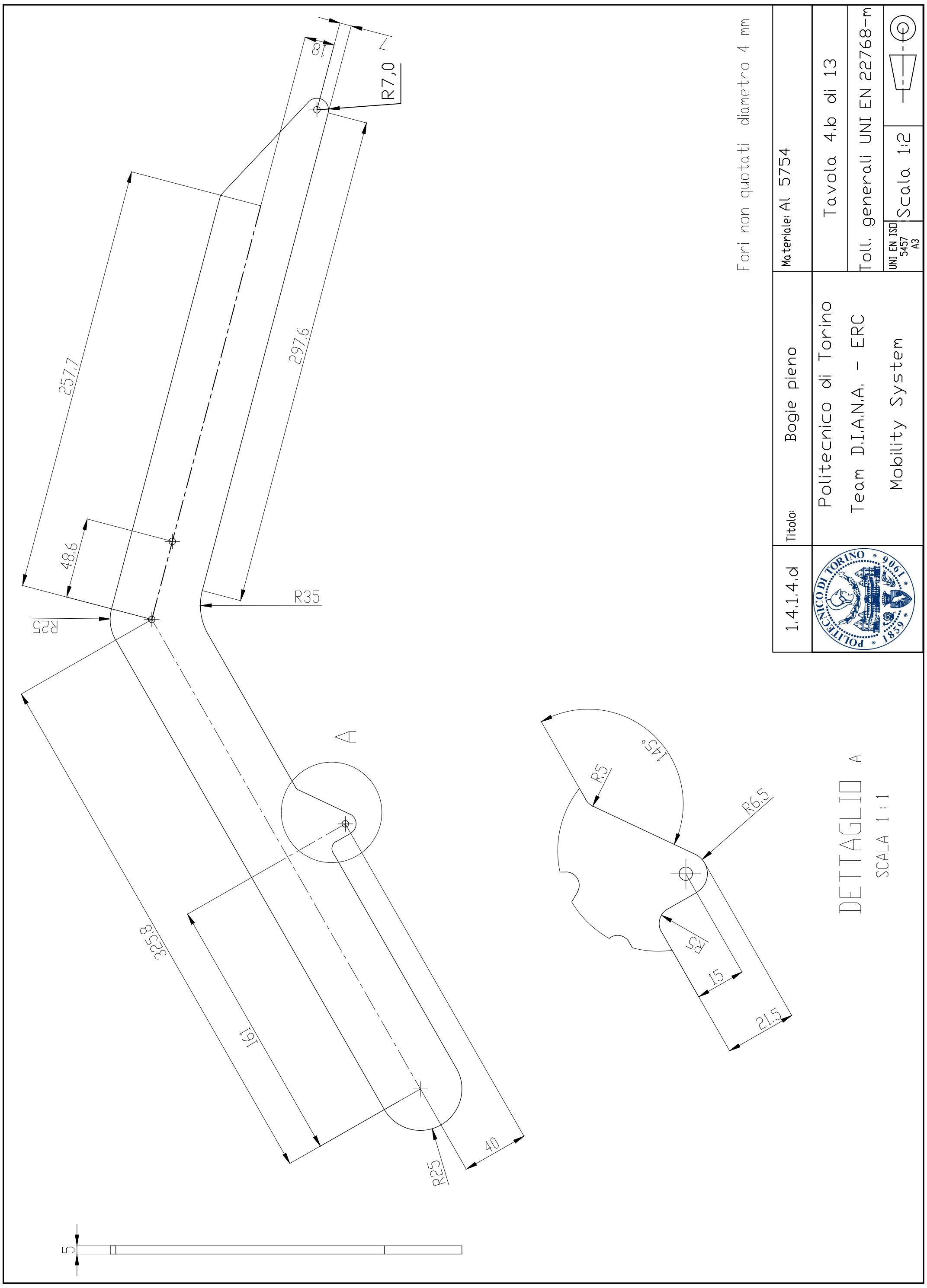


Figure A.3: Bogie plate

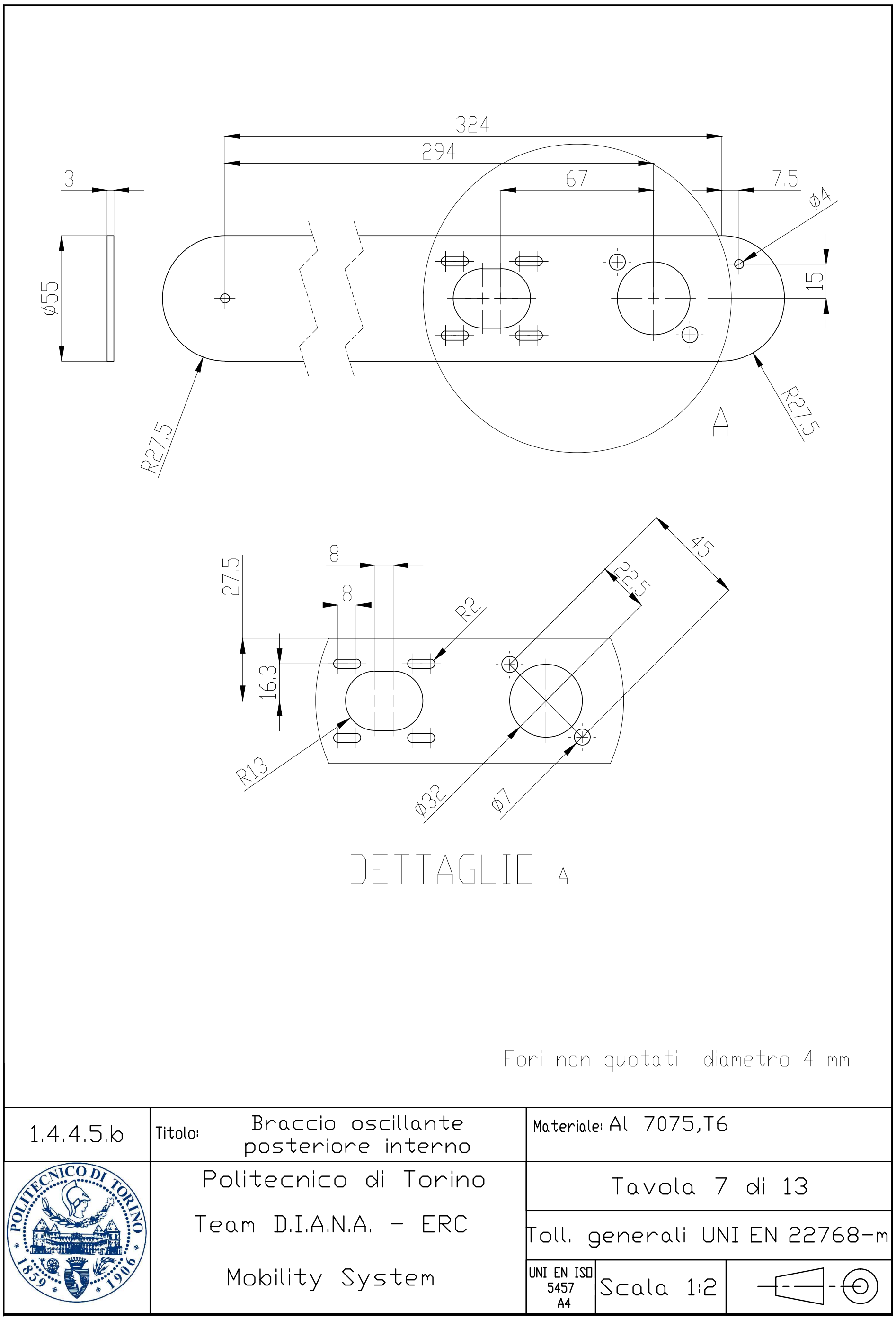


Figure A.4: Example of swinging arm, in particular of rear wheel motor connection side.

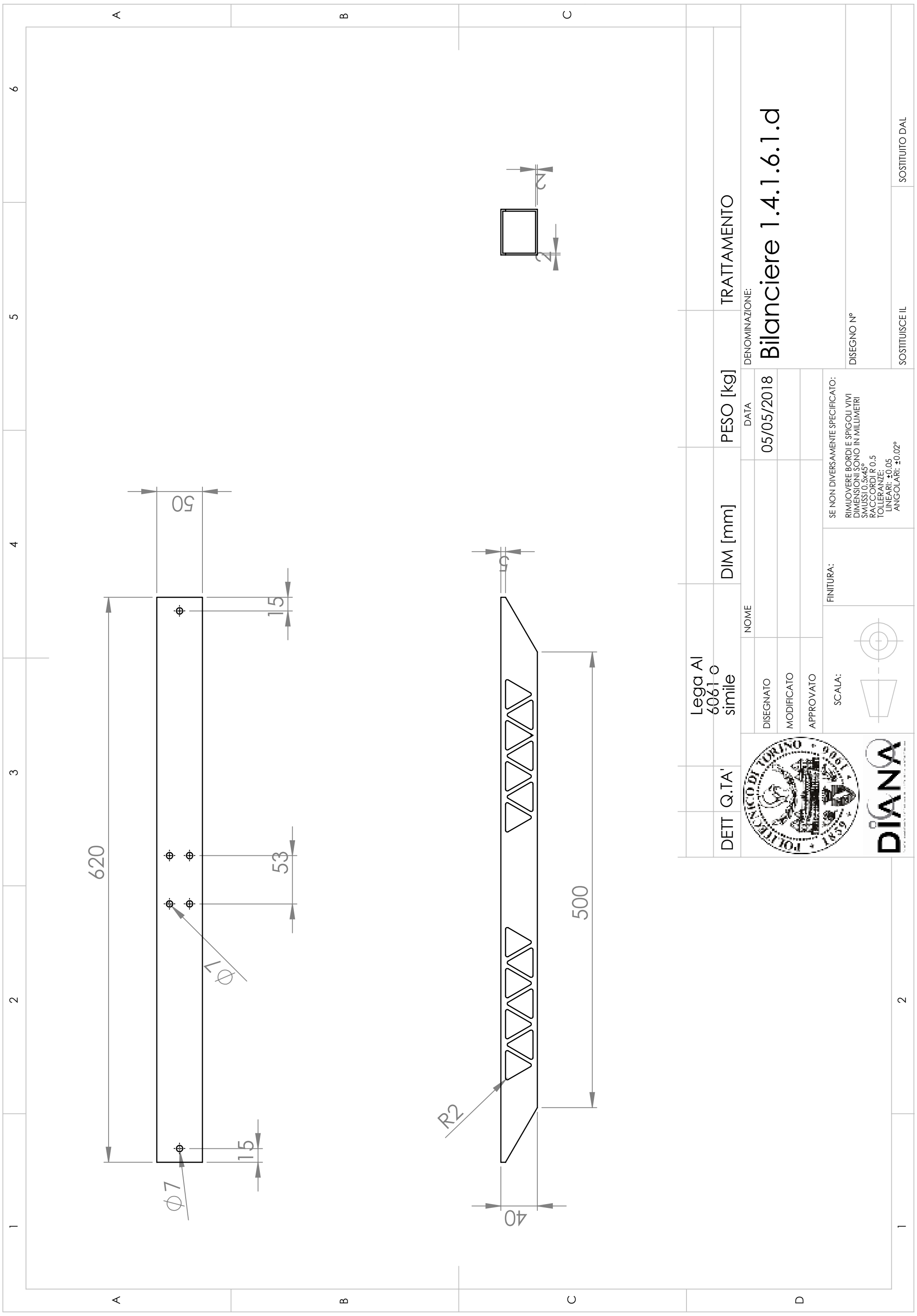


Figure A.5: Differential bar

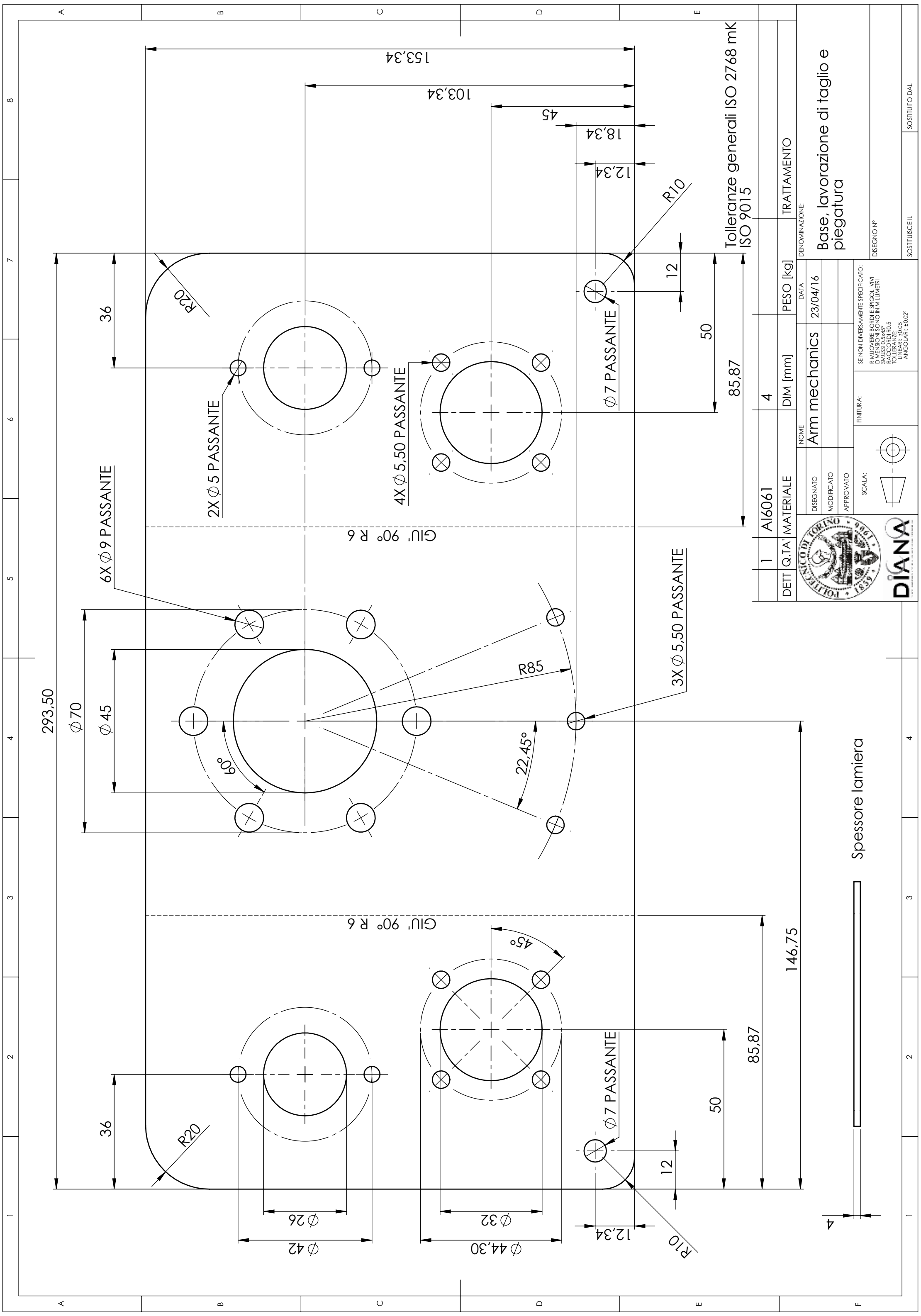


Figure A.6: Robotic arm - shoulder joint U support

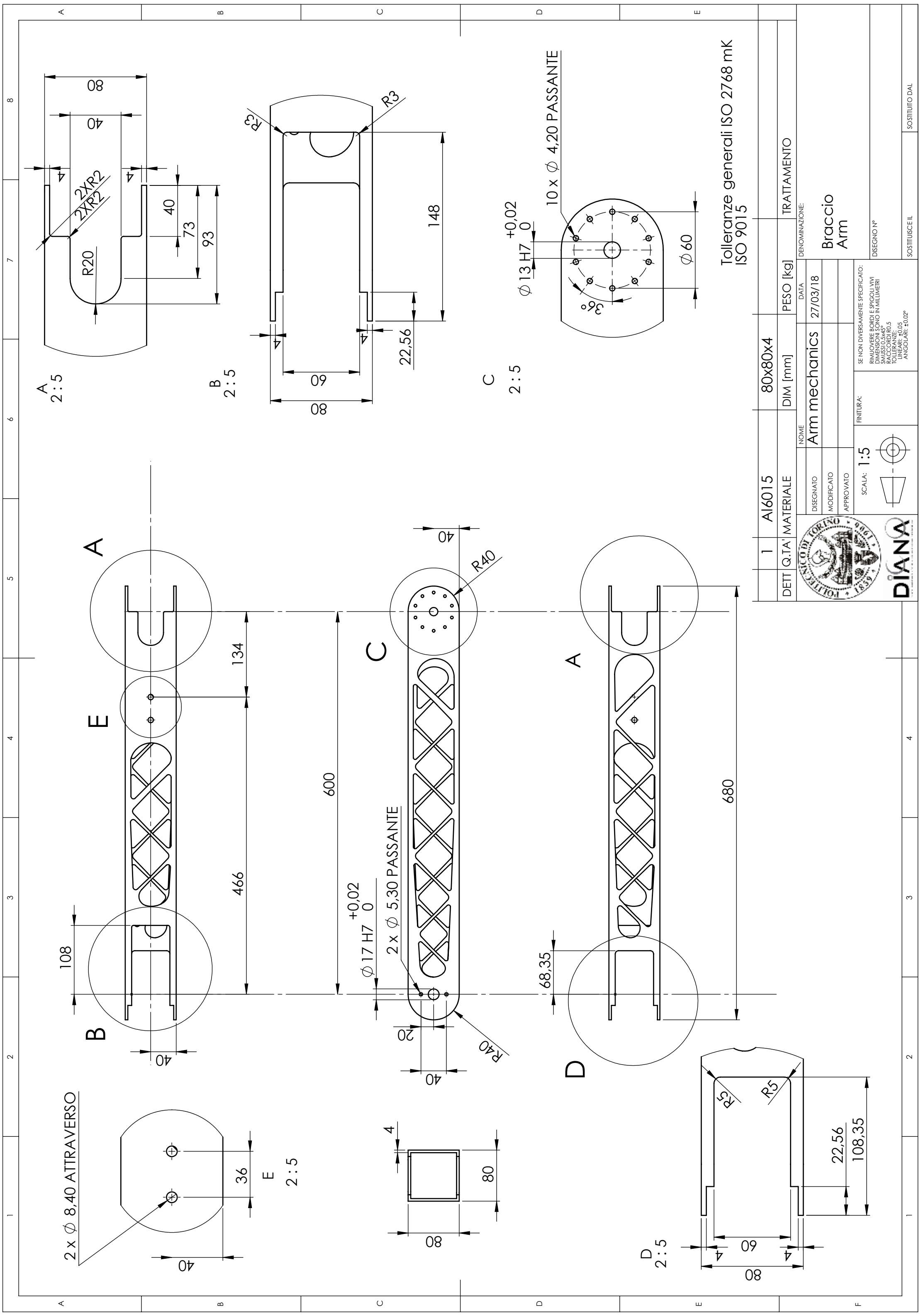


Figure A.7: Robotic arm - arm link

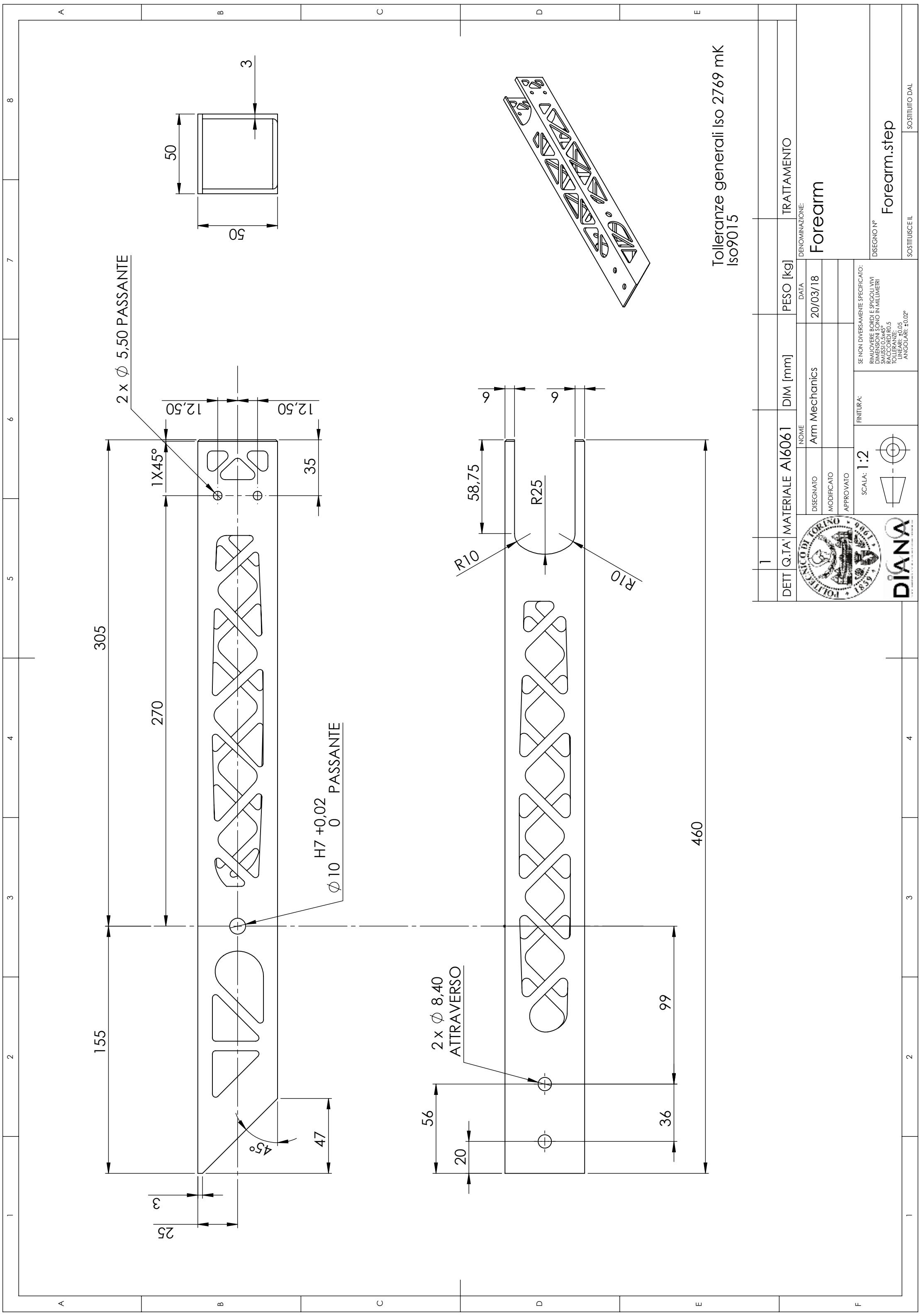


Figure A.8: Robotic arm - forearm link

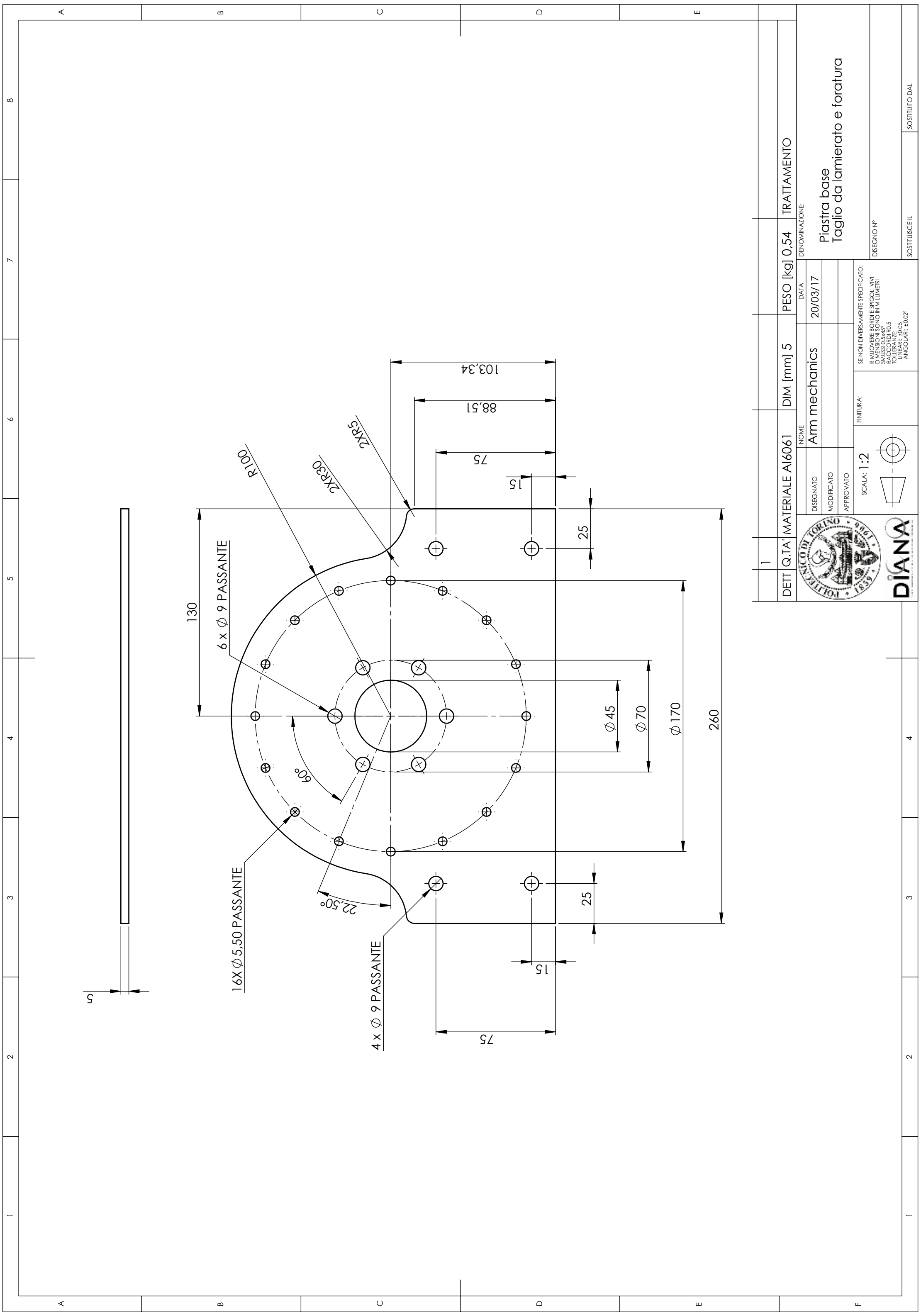


Figure A.9: Robotic arm - base plate

Appendix B

Electronic schemas

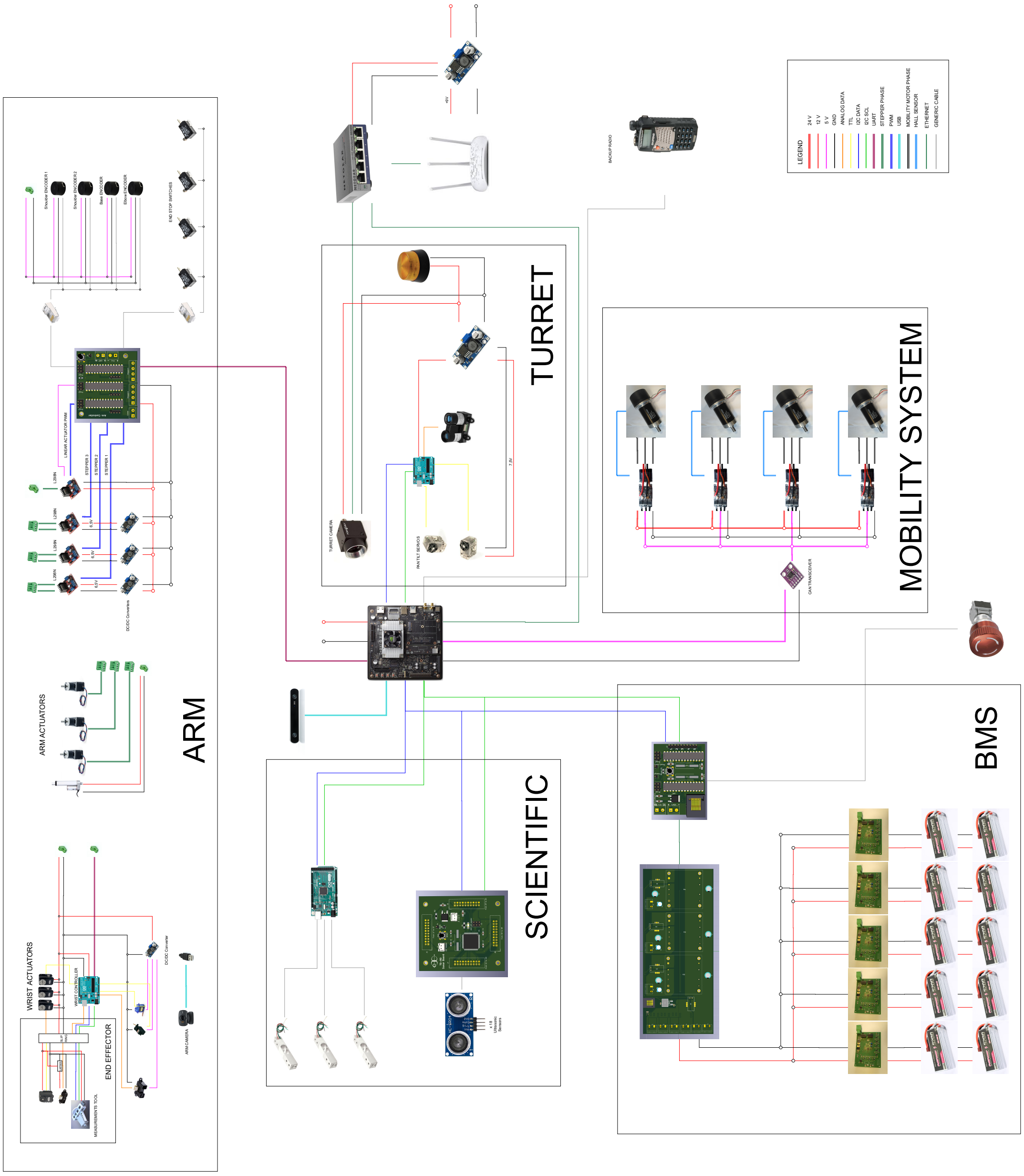


Figure B.1: Complete electrical and electronic schema of rover T0-R0

Appendix C

System requirements

Table C.1: Identified system requirements

REQ. ID	REQUIREMENT	REF
TR 1.0.0	**GENERAL REQUIREMENTS**	
TR 1.1.0	Rover shall be a stand-alone platform	ERC rule 3.1
TR 1.1.1	Rover shall have an independent power supply	TR 1.1.0
TR 1.1.2	Rover shall provide a wireless communication system	TR 1.1.0; ERC rule 3.6
TR 1.2.0	Rover max total weight shall not exceed 60 kg in every configuration	ERC rule 3.2
TR 1.3.0	Rover speed shall not exceed 0.5 m/s (1.8 km/h)	ERC rule 3.3
TR 1.4.0	Rover size shall be max 0,75 m radius	ERC rule 3.2
TR 1.5.0	Rover shall present differentiated commands driving automated phases such as ”start”,”work”,”wait”,”resume”,”stop”	ERC rule 3.4
TR 2.0.0	**SCIENCE TASK REQUIREMENTS**	
TR 2.1.0	Rover shall collect and cache 3 surface samples	ERC rule 5.5.1.2.b S
TR 2.1.1	Surface samples weight shall be greater than 25 g preferably (50-150 g)	ERC rule 5.5.1.2.b
TR 2.2.0	Rover shall collect and cache 1 deep sample	ERC rule 5.5.1.2.b

TR 2.2.1	Deep soil sample shall be collected between 15-35 cm below surface	TR 2.2.0; ERC 5.5.1.2.b
TR 2.2.2	Deep soil sample weight shall be greater than 25 g	ERC rules 5.5.1.2.b; 5..5.1.4.a
TR 2.3.0	Rover shall provide photographic documentation of samples and sampling areas	ERC rules 5.5.1.2.c; 5.5.1.4.c
TR 2.4.0	Rover shall perform scientific measurements	ERC rule 5.5.1.2.d
TR 2.4.1	Measure: temperature, with ±1 °C	ERC rule 5.5.1.2.d
TR 2.4.2	Measure for all samples: weight, with ±2 g maximum	ERC rule 5.5.1.2.d
TR 2.4.3	Measure: humidity, with + TBD %	ERC rule 5.5.1.2.d
TR 2.4.4	The boxes shall provide sealed closure	ERC rule 5.5.1.2.f
TR 2.5.0	Rover shall excavate a trench	ERC rule 5.5.1.2.e
TR 2.5.1	Trench size shall be of 30 cm long and 5 cm hight	ERC rule 5.5.1.3.l
TR 3.0.0	**MAINTEINANCE TASK REQUIREMENTS**	
TR 3.1.0	Rover shall be able to interact and manipulate knobs, electronic switches, ext	ERC rule 5.5.2.3
TR 3.1.1	Rover shall have the ability to interact with control panel designed for humans	ERC rule 5.5.2.3.a
TR 3.1.2	Rover shall have the ability to remove and manipulate soft cover from elements	ERC rule 5.5.2.3.k
TR 3.1.3	Rover shall manipulate multiple elements, desired action and homing fully automated	ERC rule 5.5.2.5.e
TR 3.1.4	Rover shall be able to plug type IEC 60309 socket	ERC rule 5.5.2.3.h
TR 3.1.5	Rover shall be able to measure a voltage between 1 and 24 VDC from German type F socket	ERC rule 5.5.2.3.f
TR 3.2.0	Rover shall avoid arm collisions	ERC rule 5.5.2.3.f
TR 4.0.0	**COLLECTION TASK REQUIREMENTS**	

TR 4.1.0	Rover shall storage cached samples and reporting their location	ERC rule 5.5.3
TR 4.1.1	Rover shall take photo of the caches before picking them up	ERC 5.5.3.2.c
TR 4.1.2	Rover shall automatically approach, pick-up and store caches	ERC 5.5.3.1.a
TR 4.2.0	Rover shall be able to place cache container at marked point	ERC rule 5.5.3.2.c
TR 5.0.0	**TRAVERSAL TASK REQUIREMENTS**	
TR 5.1.0	Rover shall navigate point-to-point with tele-operated control	ERC 5.5.4.3.e
TR 5.2.0	Rover shall navigate point-to-point with automated control	ERC 5.5.4.4.d
TR 6.0.0	**COMPUTER SYSTEM REQUIREMENTS**	
TR 6.1.0	All the computational processes shall be executed on board	ERC rule 5.5.4
TR 6.1.1	Rover should mount powerful graphical computation capability	TR 2.1.0
TR 6.1.2	Computer system shall control all the rover subsystems	Project Requirement
TR 7.0.0	**MOBILITY SYSTEM REQUIREMENTS (MS)**	
TR 7.1.0	MS shall be capable of moving on different and bumpy terrains	Project Requirement
TR 7.1.1	The MS shall work on hard compact terrain	URC rules
TR 7.1.2	The MS shall work on rocky terrain	URC rules
TR 7.1.3	The MS shall work on loose and sandy terrain	URC rules
TR 7.2.0	The MS shall support the weight of the entire rover, in every configuration (max 60 kg)	Project Requirement
TR 7.3.0	The MS shall be able to overcome different obstacles	Project Requirement
TR 7.3.1	The MS shall be able to climb up solve with max 60° of inclination	URC rules
TR 7.3.2	The MS shall be able to descend steps up to 50 cm high	URC rules
TR 7.3.3	The MS shall be able to traverse boulder terrain, with max 30 cm high obstacles	URC rules
TR 7.4.0	The MS shall be capable of steering in place	Project Requirement

TR 7.5.0	The MS shall have a max weight of 30 kg	Project Requirement; ERC rule 3.2
TR 8.0.0	**CHASSIS SYSTEM REQUIREMENTS (CH)**	
TR 8.1.0	CH design shall be as simple as possible	Project Requirement
TR 8.1.1	CH shall permit easy maintenance of electronic parts, MS, boxes plates and robotic arm	Project Requirement
TR 8.2.0	CH shall have appropriated size to interface with other system and to host internal electrical components and task's elements	Project Requirement
TR 8.2.1	CH shall support robotic arm system	Project Requirement
TR 8.2.2	CH shall host sensors, cameras and equipment	Project Requirement
TR 8.2.3	CH shall host science task boxes (min 3)	TR.2.1.0
TR 8.2.4	CH shall host detachable cache containers (min 4 cache)	ERC rules 5.5.3.3.b; 5.5.3.3.f
TR 8.2.5	CH shall host driller containers (min 1 cache)	TR.2.1.0
TR 8.2.6	CH shall permit to keep electronic elements at stable temperature	Project Requirement
TR 8.3.0	CH shall be structurally stable and as much as possible horizontal	Project Requirement
TR 8.4.0	CH shall have interchangeable host plates to permit stable centre of mass in every configuration	Project Requirement
TR 8.5.0	CH structure shall weight max 3 kg	Project Requirement
TR 9.0.0	**ROBOTIC ARM SYSTEM REQUIREMENTS (RA)**	
TR 9.1.0	RA shall have an optimal size to complete all the competition tasks	ERC rule 5.5.2.3
TR 9.1.1	RA shall be able to reach up to 1.5 m from ground, and operate keeping the end effector horizontally	ERC rule 5.5.2.3.a
TR 9.1.2	RA shall be able to reach up to 0.2 m from ground, and operate keeping the end effector horizontally	ERC rule 5.5.2.3.a
TR 9.1.3	RA shall reach 20 cm from far end of CH	ERC rule 5.5.2.3.a

TR 9.1.4	RA shall reach at least the area of the CH where the boxes and tools are located	ERC rule 5.5.2.3.a
TR 9.2.0	RA shall sustain forces and torques generated from lifting weights up to 5 kg	Project Requirement; ERC rules 5.5.1.4, 5.5.3.2, 5.5.3.3, 5.5.2.3
TR 9.2.1	RA shall be strong enough to execute-deep soil sampling by extracting at least 50 N into the soil	Project Requirement; ERC rules 5.5.1.4, 5.5.3.2, 5.5.3.3, 5.5.2.4
TR 9.3.0	The gripper shall have at least 12 cm of max opening	Project Requirement; ERC rules 5.5.1.4, 5.5.3.2, 5.5.3.3, 5.5.2.5
TR 9.3.1	The scoop shall be designed to grab soil auger position in the back of the rover to use to take samples and to grill firmly the soil	Project Requirement; ERC rules 5.5.1.4, 5.5.3.2, 5.5.3.3, 5.5.2.6
TR 9.3.2	The scoop shall collect 50-150 g rocks, and 50-150 g loose superficial soil	Project Requirement; ERC rules 5.5.1.4, 5.5.3.2, 5.5.3.3, 5.5.2.7
TR 9.4.0	RA should be easily removed for the tasks where is not needed	Project Requirement; TR.1.2.0

TR 9.5.0	RA should have at least 6 DoF, to permit precision and accuracy positioning	Project Requirement
TR 9.5.1	RA should have 3 DoF on the wrist for correct orientation to centre electrical plug	Project Requirement
TR 9.6.0	RA shall move automatically to complete the tasks requirement (refer to tasks requirements)	TR.2; TR:3; TR:4
TR 9.6.1	Each joint position shall be controlled by imposing a certain position	Project Requirement
TR 10.0.0	**POWER SYSTEM REQUIREMENTS**	
TR 10.1.0	BMS shall constantly monitor batteries voltage, current and temperature	Project Requirement
TR 10.1.1	BMS shall provide filtered power supply at different voltage levels (5 V, 9 V, 12 V, 24 V)	Project Requirement
TR 10.1.2	Battery pack shall provide at least 750 Wh	Project Requirement
TR 10.1.3	BMS shall be able to perform batteries cells balancing	Project Requirement
TR 11.0.0	**SAFETY SYSTEM REQUIREMENTS**	
TR 11.1.0	An emergency button shall disconnect the batteries from the system	ERC Rules 3.5.1
TR 11.1.1	The power system shall stay disconnected even after the button is released	Project Requirement
TR 11.1.2	The emergency button shall be easily accessible	ERC Rules 3.5.1
TR 11.2.0	An activity indicator lamp shall be present and clearly visible	ERC Rules 3.5.2
TR 11.2.1	The indicator lamp shall be active for 5 seconds before any operation	ERC Rules 3.5.2
TR 11.2.2	Autonomous operations should start with delay of at least 5 seconds	ERC Rules 3.5.3
TR 12.0.0	**COMMUNICATION SYSTEM REQUIREMENTS**	
TR 12.1.0	Communication between rover and control base shall be available for up to 150 m	ERC Rules 3.6.1
TR 12.1.1	Communication between rover and control base shall be available for any terrain morphology	ERC Rules 3.6.1
TR 12.1.2	Communication shall use radio amateur bands and/or WiFi bands	ERC Rules 3.6.2

TR 13.0.0	**VISION AND NAVIGATION SYSTEM REQUIREMENTS**	
TR 13.1.0	Rover shall provide only its position in the map	ERC rule 5.5.4.5.b
TR 13.1.1	Rover shall map the environment with on-board computation	ERC rule 5.5.4.5.b
TR 13.1.2	Rover shall compute its position and orientation	ERC rule 5.5.4.5.b
TR 13.1.3	Rover shall have an IMU sensor	Project Requirement; TR.13.1.3
TR 13.1.4	Rover shall have a SLAM system	Project Requirement; TR.13.1.4
TR 13.1.5	Rover shall have a stereo-camera	Project Requirement; TR.13.1.5
TR 13.2.0	Rover shall send data to base station during challenging situations	Project Requirement
TR 13.3.0	High quality remotely positionable camera should be mounted on the rover	ERC rule 5.5.1.3.j
TR 14.0.0	**LOGIC UNIT SYSTEM REQUIREMENTS**	
TR 14.1.0	The main logic unit shall have the necessary computational power to run all the algorithms that control the rover	Project Requirement
TR 14.2.0	The main logic unit shall be connected to every subsystem of the rover	Project Requirement
TR 14.3.0	The main logic unit shall record and store relevant data for post elaboration	Project Requirement
TR 15.0.0	**OPERATION CONTROL STATION REQUIREMENT (OPS)**	
TR 15.1.0	OPS shall be the only place where the rover is manually operated	ERC rule 5.4.c
TR 15.2.0	OPS shall provide its interface for rover control	Project Requirement
TR 15.3.0	OPS shall provide a way to receive feedback from the rover	Project Requirement
TR 15.4.0	OPS shall always provide a way to communicate with the rover	Project Requirement

Appendix D

ERC 2018 rules

1. General information

1.1. What is ERC

The European Rover Challenge (ERC) is an integrated programme towards technological development specifically in a area of space exploration and utilization. The ultimate goal of ERC is to become standardised test trials and benchmark for planetary robotic activities with strong professional career development platform.

ERC is split between two program tracks. ERC-Student delivers career development platform with major focus on space engineering. It includes workshops, and all year activities and mentoring around designing and building student planetary rover. All the effort is finalised by yearly event where student teams compete on specially landscaped area.

Second track, called ERC-Pro is designed to provide opportunity to demonstrate abilities in solving field tasks inspired by space robotics roadmaps. It is suited for startups, any companies, research groups and others working in space robotics domain. On the other hand, those not yet connected with space industry and having solutions solving given tasks can benefit from participation by presenting their strengths and getting introduced to the domain challenges and community of 'doers' in this specific field.

In a long term ERC-Pro want to provide platform for monitoring and benchmarking on realisation of robotics exploration roadmaps to strategic institutions and other interested actors. As a implication of aforementioned activities, ERC-Pro is aspiring to disrupt pattern of single-mission systems and following best practices form terrestrial robotics, bring iterative development and improvement in field of space robotics projects by annual trials and demonstrations.

Both tracks are the part of one community network managed under ERC flag. Such solution provides unique opportunity to collect people on different level of career focused on (robotic) space exploration. Community works as a motor of continuous improvement effort one way, providing transfer of expertise and feedback from professional teams to students and other, creating transfer of talents to engaged companies. It also connects universities, companies and other institutions promoting their strengths and identifying opportunities for collaboration.

The European Rover Challenge is owned and coordinated by European Space Foundation, organised in cooperation with group of independent experts creating steering and jury board. Mars Society Polska is a partner of the programme.

1.2. Elements of ERC-Student

ERC-Student track includes:

a) During a year lasting project:

- creation of the team
- submission of proposal
- organisation of the project and acquisition of the funds
- design and build / iterative improvement of robotic mobile platform with accompanying equipment according to requirements
- delivery of preliminary documentation
- delivery of final documentation
- organisation of test campaign
- delivery of promotional video
- feedback and mentoring from domain professionals

b) At the Challenge event:

- participation in 4 terrain tasks
- presentation of different project aspects
- participation in the workshops and meetings with guests
- networking

c) Life lasting:

- participation in broad community of people focused around topic of space exploration and robotics
- excellent opportunity to build experience, hard and soft skills, create long lasting teams and businesses and have a lot of great fun!

1.3. Schedule and Venue

ERC is an venue independent, all-year programme. For information about ERC 2018 event venue please follow updates on challenge website (see *Information channels and contacts*). Official schedule can be found as appendix to this document.

1.4. Information channels and contacts

The Challenge website address: www.roverchallenge.eu

Teams' Contact Point email address: teams@roverchallenge.eu

Official communication channel for challenges announcements is list consists of emails given by teams during registration.

2. Teams

2.1. General

The 2018 edition of the challenge is planned for limited number of teams. ERC Board will select which of the registered teams will be invited to compete in the challenge. The choice will be made based on documentation which teams are required to send to the organizer by deadlines given in program schedule. The organizer will announce qualified teams by deadline given in program schedule.

2.2. Registration

For registration dates please refer to challenge schedule. Registration details shall be sent to the organizer in English, via teams contact point email address (see *Information channels and contacts*). If this document is not submitted before specified deadline, team will be not allowed to participate in the challenge.

The team registration email shall include:

a) Name of the higher education institution with which the team is affiliated (if the team is affiliated with more than one institution, please list all the names, in descending order of involvement);

b) Team name;

c) Rover name (may be the same as team name);

d) Project proposal (see section Documentation);

e) Approximate number of team members who plan participate in the Challenge event (i.e. appearing on site of the event);

f) Team contact point: person name and surname, telephone number and e-mail address;

g) University team coordinator/supervisor: name and surname, telephone number and e-mail address;

h) Project website address or/and social media fanpage (preferably Facebook as a main social media platform used by ERC team);

i) The following declaration in English:

"By sending this application and registering the team to the European Rover Challenge each team member fully accepts all terms and provisions of the European Rover Challenge rules and all final decisions of the European Rover Challenge organizer."

2.3. Team members

Team must consist of at least 75% higher education students and recent graduates: undergraduate and graduate masters-degree level students (with no limitations) and PhD students (but no more than half of the team). It is highly recommended that teams cooperate with specialists from different institutions, but students must prepare and sign all the required documentation themselves.

A team may consist of students of more than one higher education institution. An institution may also affiliate more than one team. Team membership is exclusive – each person can be a member of only one team.

3. Rover system requirements

Each rover must be compliant with requirements listed below to take part in the challenge. Special cases of non-compliance should be discussed with organiser as soon as possible in development process. Organiser has right to exclude team from field trials especially when non-compliances are reported too late (e.g. during challenge event). It is highly recommended that teams present status of compliance with specified requirements within Technical Reports in highly transparent way.

3.1. General requirements

The rover has to be a standalone, mobile platform. No cables or tethers are allowed for connection to external data links or power sources during its operation.

Teams should design and build their own rover, but COTS (Commercial-Off-The-Shelf) components are allowed and recommended. COTS rover platform would be considered, but all such cases will be discussed separately to ensure that competition is fair play.

3.2. Dimensions and weight

The suggested rover weight is 50-60kg and envelope about 0.75m radius. The limitation applies to every task (i.e. task-relevant rover configuration) separately. Equipment used for rover maintenance and preparation, unused spare parts, and elements not mounted during a particular Task are not included in this limit.

There is no weight or dimensions limit on equipment used to steer and control the rover from the rover control area, communications equipment in that area or maintenance equipment.

Rover lighter than limit will be rewarded and heavier penalized by number of points defined in Scoring rules in appendix to this document.

3.3. Control and operations

The rover maximum speed cannot be greater than 0.5 m/s.

Team should be able to control rover via radio link in real time. Each task will require rover to travel a certain distance, but never further than 100m from the starting point. The starting point will be no farther than 50 meters from the antenna mast. All communication equipment, including antennas, should be deployed in vicinity of control station. Teams should be prepared to place antenna mast maximum 20m from control station location.

The rover should be built to handle challenging terrain, appropriate dust and general weather conditions resistance described in *FIeld Trials* section.

3.4. Autonomy

Rover autonomy or capabilities of automation of particular tasks are highly recommended to be presented during competition trials. They can provide major advantage in scoring for all the tasks.

In automated control, states and commands defined below should be differentiated:

a) “start” command - command to be send at the beginning of the attempt;
b) “working” state - nominal work during attempt;
c) “wait” command - enter “wait” state. Team can use it at any time for sensor readings stabilization;

d) ”waiting” state - rover should wait still for “resume” command. This state should be automatically entered if rover reaches task check-point. System should be prepared that during this state sensors can be obstructed by judge or team members presence in rover vicinity (e.g. checking distance to the check-point). Operator cannot influence a system during this state. Reaching this state do not stop task time;
e) “resume” command - transition from “waiting” to “working” state;
f) “stop” - rover immediate stop - control can be switched to manual.

Above list is not exhaustive and teams can define additional states and commands.

In order to achieve points for autonomy or single task automation, teams cannot touch the controls once the attempt begins. The only exception is to send commands listed above. If team members touch the controls, then the autonomy points for that attempt will not be awarded. However, at any point teams may switch to manual control to complete the task tele-operating rover. Rover telemetry should be monitored during autonomous/automatic operations and its recording and open access sharing after the event is highly recommended but not mandatory.

In autonomy mode extra safety precautions should be taken. Minimum requirements are specified in *Rover Safety* section of this document.

3.5. Safety System

Elements listed in this section are mandatory for all teams and compliance with them should be clearly presented in technical documentation and during checks before field trials. This compliance will be strictly checked, could be tested by judge during any EMC test and failure to present it can result in disqualification of the team from entire trials.

3.5.1. Emergency stop

The rover shall be equipped with an easily accessible red emergency stop button. It must be part of highly reliable circuit which action is to isolate the batteries from the system by single button hit until reset procedure is executed. Only laptops with own batteries can stay powered on on-board. Therefore, an unmodified, industrial, commercial-off-the-shelf, emergency stop button and other parts of safety circuit are required. If an unsafe event occurs, judges must be able to access button and deactivate rover without any additional actions necessary. Operation must be possible by open hand hit. Button mounting should withstand hard hit and should be attached to stiff element of rovers body.

Even if RF certified EM button is in use at least one physical emergency button must be placed on the rover construction.

As additional safety recommendation, teams should avoid implementation of safety switched in software e.g. on the ground control application as it can cause operator to relay (even not fully consciously) on this feature instead informing his teammates to use hardware switch. That doesn't mean that team shouldn't implement stop button in control application at all, but operator should be trained to use other more reliable solution if exists.

3.5.2. Activity indicator

Rover should be equipped with indicator lamp informing about readiness to receive commands. Indicator should be clearly visible from at least 10m attracting attention of people in vicinity by blinking or flashing. It should be active in any case when rover is ready to move (drive or e.g. operate manipulator). Recommended colours are: yellow, orange or red. It is highly recommended to use industrial grade device.

Activity indicator lamp should be active for 5 seconds before any rover operation is executed. During this time rover should be completely still and safe.

3.5.3. Automatic/Autonomous functionality

Any autonomous or automatic operation should start with delay of at least 5 seconds after activation.

By all means teams should prevent overflowing any communication/interface buffers or keeping commanding rover or its subsystems when should be still or deactivated to avoid situations when immediate or rapid movement is executed after system activation or commanding.

Judge should be informed about all planned autonomous/automatic attempts before they are executed.

It is also recommended that platform is equipped with additional indicator showing that robot is performing task (or its part) autonomously.

3.6. Communication requirements

3.6.1. General

Radio communication with the rover has to use legally available frequencies and power levels. It is expected that maximum distance between rover and antenna mast would be less than 100 m. Direct line-of-sight between control base and rover antennas can be occluded by different forms of terrain morphology.

3.6.2. Accepted frequences

3.6.2.1. Radio amateur bands

Accepted bands up to 1 W signal transmitted and up 10 W EIRP.

144 - 146 MHz

430 - 440 MHz

1240 - 1300 MHz

5650 - 5850 MHz

It is highly recommended that each team should have at least one member with radio amateur license (CEPT class T/R 61-01).

3.6.2.2. WiFi

At 2.4 and 5 GHz WiFi bands only WiFi communication standard is accepted. Other systems like analog video cameras or RC controllers using frequencies 2412-2472 Mhz and 5260-5700 MHz are forbidden.

For 2.4GHz:

- accepted channels: 1-13 (2412 MHz – 2472 MHz);
- up to 100 mW EIRP;
- accepted standards: 802.11b/g (802.11n forbidden);
- Rover can use only one 20 MHz channel.

For 5GHz

- accepted channels: 52, 56, 60, 64, 100, 104, 108, 112, 116, 120, 124, 128, 132, 136, 140 (5260 MHz – 5700 MHz)
- up to 100 mW EIRP.
- accepted standards: 802.11a/h/n (802.11ac forbidden);
- Rover can use only one 40 MHz channel.

WiFi SSID should be set to “<erc_teamname>”.

Channels will be assigned by judge during RF check before each task attempt.

3.6.2.3. ISM bands

It is possible to use ISM bands within their limitations but team must designate which rule is compilant with in accordance to Polish regulations (http://prawo.sejm.gov.pl/isap.nsf/download.xsp/WDU20140001843/O/D20141843.pdf).

ERC does not accept ISM bands which are not accepted in Poland (e.g. 915 MHz).

Voice communication using 500 mW PMR licensed transceiver is allowed on following channel frequencies (MHz):

1. 446,00625
2. 446,01875
3. 446,03125
4. 446,04375
5. 446,05625
6. 446,06875
7. 446,08125 - *reserved for organising team*
8. 446,09375 - *reserved for organising team*

3.6.2.4. Other frequencies

Other frequencies are allowed only when relevant licence valid on venue territory is presented by the team. Those communication channels must be described in documentation and agreed with organisers.

3.6.3. Other communication rules

Before the competition, rovers and ground stations must be checked and accepted by radio communication judge during EMC (electromagnetic compatibility) test.

During competition, rovers and ground stations will be randomly EMC tested. Unauthorized changes to the RF configuration may result in immediate disqualification. Usage of any communication channels for testing (any time outside competition attempt duration) must be consulted with organiser/judge. Testing that could be done without RF communication is preferred. The organiser will provide rules of RF links usage for main parts of challenge venue and any requests limiting usage of RF links can be expected and should be respected during entire duration of the event.

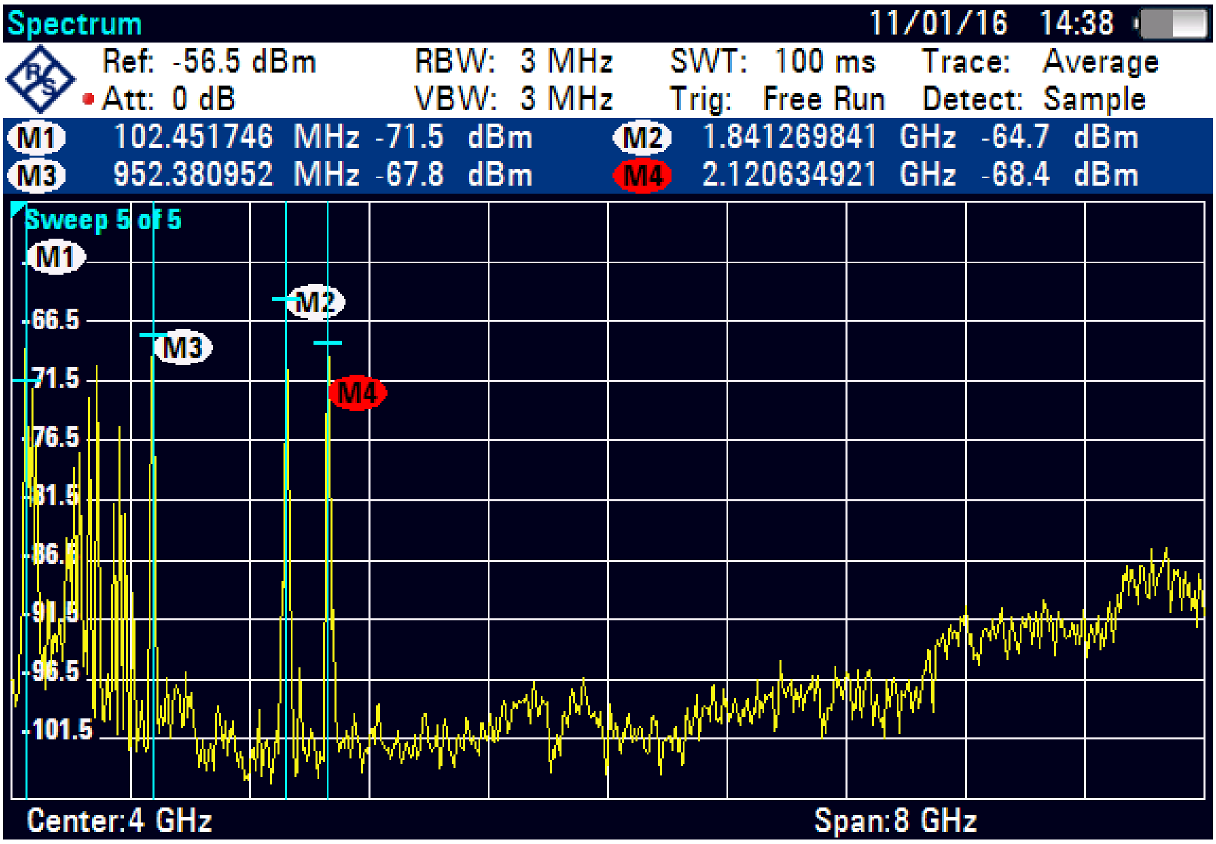
For the whole duration of the challenge, the team is responsible for the legal use of frequencies on venue territory. The organiser can only help in frequency coordination, but does not take responsibility for any license violation like exceeding RF power, frequency band or area of use.

3.6.4. Radio Frequency Form

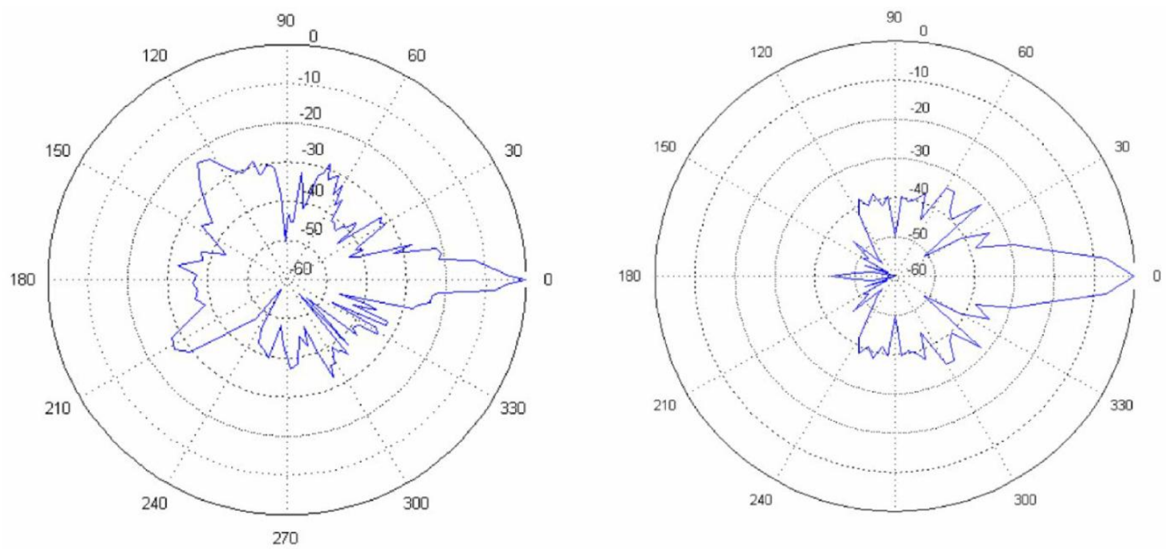
Each Team must fill Radio Frequency Form for every RF module used. It shall be included in relevant Technical Reports as an appendix (see documentation specification). If these documents are not submitted in the requested form, team will not be allowed to participate in the Challenge.

RF Form shall contain:

a) Team name;
b) Country;
c) How many different communication systems are planned to be used;
d) Name of the person responsible for communication system;
e) Contact to the person responsible for communication system (e-mail address);
f) Photo of the rover;
g) Photo of the ground station;
h) System information (this part should be filled for every RF system):
    - RF system name;
    - Frequency;
    - Bandwidth;
    - RF power (output power + EIRP);
    - Antennas on rover and ground station - models, radiation patterns (see Pic 2 as example);
    - Modulation;
    - Short description
i) Two RF spectrum measurements - when all systems are on and off. Spectrum must be measured from 100 kHz up to double maximum frequency + 1 GHz used by Team (for example if highest band used is 2.4 GHz, Team has to measure pattern up to 2.4*2+1= 5.8 GHz); See example in the Pic 1. It is advised to measure RF spectrum using wideband reference antenna in RF anechoic chamber but it is not obligatory.



Pic. 1.: Example of the RF spectrum analyses



Pic. 2.: Example of the Horizontal and Vertical RF antenna radiation pattern for ground station

3.7. Miscellaneous

It is recommended that teams will collect data (e.g. power parameters, accerations, received commands and other system states) about state of their rover for future evaluations.

During trial team could be asked for (non-invasive) access to their main power line cables (connecting with battery) and designated spot for attachment of external logging system. Details will be agreed individually during design phases.

4. Documentation

4.1. General

Each Team shall provide a technical documentation which will cover following topics:

- management,
- technical design,
- safety,
- financial.

The project documentation is divided into three parts. The first set of information, called Proposal, shall be submitted with the registration form. The second and third, called Preliminary Report and Final Report accordingly should be submitted until dates designated in challenge schedule (see *Schedule* appendix) to the organizer.

The documentation is intended to be a substantial set of information describing a project and giving a clear image on how the project is being managed and developed.

Furthermore, the intention of documentation is to motivate the teams to develop their project according to the standards widely used in space industry. The organizer wants to emphasize quality management, strategy of development and risk management and testing topics. The intention is to improve quality of the rovers and minimize a risk of occurring simple and obvious errors and mistakes which might negatively impact on the project performance. The workflow of the three phases shall present how you manage the project, how you work on systems and subsystems and how you solve discovered problems and issues. Please note that the documentation is not intended to be a big paper with lot of excessive information. The documentation should be “from engineers to engineers”.

All documents are scored and counted to challenge final points (for details see *Scoring* appendix). Scoring is designed to consider documentation as an aspect that can influence order of teams on the podium so it is important to deliver all documents in the best quality according requirements listed below and on time according schedule (see *Schedule* appendix).

4.1.1. Proposal

Proposal should introduce team and contain information why project presented by the Team should be chosen for ERC competitions based on technical expertise, team experience and first draft of proposed solutions. It should confirm that Team read, analysed and understood system requirements (rules of the competition).

In the Proposal the Teams shall include following information:

1) Team introduction contains information about team experience and expertise (short profiles of key people, experience of team esp. in similar engineering projects and research work key for delivering this project in time and good quality, general focus, other projects etc.);
2) Initial project assumptions and initial technical requirements, derived assumptions, analysis of challenge tasks;
3) First draft of project risk analysis and planned mitigations;
4) First conclusions how your project could be commercialised/which elements and how could be continued as further potential research considering current technological trends..

Document requirements:

1) First page: Team name, project name, heading “European Rover Challenge 2018”, affiliation, title “Proposal”;
2) Format: A4, searchable PDF;
3) Length: max 6 pages (including a title page);
4) Language: English;
5) Appendixes: no.

4.1.2. Preliminary report

This document should be written after analysis and design phase, what means that team should present in it idea how to solve presented problems under limits and boundaries listed in requirements and additional identified by a team. It should be a next iteration of team proposal without repeating basic, already closed points. Document should also contain (management and system) breakdown of the project and chosen technologies and technical solution to achieve goal.

The Preliminary Report shall include following information:

1) Project assumptions (compare them with those presented in the proposal, if changed, please describe why and how changes have an impact on the project);
2) Technical requirements definition (compare them with those presented in the proposal, if changed, please describe why and how changes have an impact on the project; make a full list of your technical requirements and present the way you want to fulfill them);
3) Technologies you want to use, designs you have and you are working on (at any stage);
4) Pre-final System Breakdown Structure (pSBS);

5) Safety Systems description;
6) Present preliminary financial planning (sources and expenditures);
7) Lesson learnt - present problems and issues you are facing (management, engineering, logistics, etc.) and how you solved them and/or plan to solve;
8) Risk assessment - identified risks for continuation of the project development and attendance in competitions (main focus (but not limited to) technical aspects) with assesment of impact and mitigation plan;
9) Pre-final Radio Frequency Form (pRFF) as an appendix (see *Communication Requirements* for details).

Document requirements:

1) First page: Team name, project name, heading "European Rover Challenge 2018", affiliation, title "Preliminary report";
2) Format: A4, searchable PDF;
3) Length: max 20 pages (including a title page);
4) Language: English;
5) Appendixes: yes (optional; only additional information which could not be included in main document, for example: drawings and charts).

4.1.3. Final report

The Final Report is a continuation and extension of the Preliminary Report. It shall contain detailed information on the elements presented in the Preliminary Report and summarise project after manufacturing and testing phase:

1) Final project assumptions (fixed);
2) Final technical requirements (fixed);
3) Testing methodology and test plan;
4) Final design:
    a) System Breakdown Structure (SBS) + description;
    b) System architecture - hardware and software diagrams and description;
    c) Operational scenarios;
    d) CAD drawings (2D, 3D, dimensions, assembly, details);
5) Safety Systems description;
6) Final financial report (sources and expenditures);
7) Lessons learnt - difficulties and solutions applied;
8) Risk assessment;

9) Final Radio Frequency Form (RFF) as an appendix (final version of the form presented in preliminary documentation).

Document requirements:

1) First page: Team name, project name, heading “European Rover Challenge 2018”, affiliation, title “Final report”;
2) Format: A4, searchable PDF;
3) Length: max 30 pages (including a title page);
4) Language: English;
5) Appendixes: yes (optional; only additional information which could not be included in main document, for example: drawings and charts).

4.2. Promotional video

Each team shall prepare a promotional video, which must be completed and submitted by the date presented in challenge schedule (see *Schedule* appendix). The file should be submitted in MP4, MOV or AVI format with information about any necessary codecs to view it. The organizer will provide an FTP server to which the video file must be uploaded. If the promotional movie is not submitted in the correct form (or it is not playable by organizer) and within the time laid down, team will not be allowed to participate in the challenge.

Promotional video shall be 3-5 minutes long and shall present rover’s capability to take part in the challenge and it shall contain following elements:

1) Introducing team name, rover name, and the higher education institution name;
2) Introducing the team members and their responsibilities, presenting team work;
3) Introducing the reasons for proposing the team to the challenge;
4) A presentation of a safety systems (including emergency stop button) performance;
5) A presentation of remote control ability;
6) A presentation of rover’s ability to ride and operation of manipulation subsystem;
7) Quality and proper visual aesthetics value of the movie and presentations skills.

In special cases video could be the basis to question and request more details about team readiness to participate in the competitions. Failure to present enough level of readiness can influence to what extend team will be allowed to participate in the trials.

4.3. Official statement

By providing the Organizer with the design draft, technical specification, other data, promotional materials and visuals (e.g. photos and videos), the Teams indicate they agree to any and all of this data being stored and processed in the Organizer’s computer systems.

Teams grant permission to the organizer to use promotional materials and visuals (e.g. photos and videos), as well as any additional photos, videos, portraits, documents, interviews and other materials resulting from participation in the Challenge (using the name of the Participant or not) on all media, in any language, anywhere in the world, in any manner, for advertising and promotional purposes.

On the other hand, the organizer will keep all technical documentation confidential and will not publish or disclose it to third parties without earlier approval of a team representatives. The sole exception to this is the Challenge jury board.

5. Field trials

Field trials are organised as benchmarking activity allowing to compare performance of teams in resolution of several tasks. Each task present independent set of problems to be solved connected to particular technologies required by future space robotics missions.

5.1. General

a) The challenge tasks take place in front of an audience as a public event;

b) Challenge attempts are independent. Teams will be permitted to change rover configuration between tasks. A certain amount of time will be scheduled in between tasks to allow Teams to modify, repair and optimize their rovers;

c) The challenge jury consists of a number of specialists selected by the organizer. While judging the challenge, jury acts independently of the organizer, but adheres to the schedule provided by the organizer. In case of any unforeseen issue not specified in competition rules jury board will propose a solution.

d) Technology Priorities assigned to each task describe areas of focus of each task in priority order. This order will be reflected by scoring summarised in appendix.

e) Scoring of each task is independent and summarised in appendix to this document.

f) Excellence showed in particular task will be awarded.

g) Technology priorities and excellence promotions could be adjusted for different editions to focus teams on elements with low quality or robustness presented in previous editions. Changes will also reflect shift of focus in international roadmaps.

5.2. Schedule

a) On the first day, teams shall register themselves at the challenge location;

b) Additionally, for all teams, warm-up day is planned the day before challenges. This day should be used for calibration and other preparation activities. Organiser gives each team limited time slot. Teams are allowed to do any kind of measurements agreed with organiser based on final report specification. Some of tasks elements,considered as too detailed, can be removed for this day by organiser. All dynamic elements could be presented not in final locations. Organiser cannot assure that challenge area and its elements will be 100% ready for this day;

c) At the last day of the challenge, total scores are calculated, winners announced and the prizes awarded.

d) Detailed schedule, also containing the exact time window for each task, will be announced by the organizer one week before the event in preliminary version and final one on the first day of competitions;

e) Schedule is rigid – no team is allowed to exceed the permissible time limit or postpone time window designated for task attempt. A certain amount of time will be scheduled in between tasks to allow teams to modify, repair and optimize their rovers.

5.3. Challenge site details

a) Each challenge task can be organized indoor or outdoor independently. The part of outdoor challenge elements can be placed under the tents. Teams can expect typical interior furnishing, buildings, industrial installations (metal pipes etc.) and natural objects (e.g. trees, bushes) in vicinity of challenge arenas.

b) For outdoor tasks, teams and their systems should be prepared for different weather conditions. Temperatures between 15 and 30 degrees Celcius, wind gusts, light drizzle, strong or weak sunlight level are acceptable. During conditions unfavorable for particular design, team can ask for task reschedule but final decision will be made by trial judge considering schedule, other requests and impact on team performance. In case of major weather problems organiser will put effort to reschedule/reorganise trials within available days and facilities but it cannot be assured that all trials will take place or will be organised strictly following presented specifications.

c) The organizer will provide a map of the challenge area no later than at the first day of competition with all reference points;

d) The organizer provides each team with workspace equipped with tables, chairs and a 230V, 50Hz power socket (type E, compatible with 'German' type F);

e) Challenge location is separated from teams area to avoid RF interferences but organiser cannot guarantee that extra precautions will not be requested to avoid disruption of the challenge attempts;

f) The challenge field (place where terrain dependent tasks are held) will be artificially landscaped specifically for the event. Sandy, non-cohesive soil as well as hard, dry terrain should be expected. In case of tasks which do not score locomotion aspects, flat industrial surface (e.g. concrete) can be expected.

5.4. Operations

a) The challenges aim is to demonstrate and evaluate performance and robustness of the proposed solutions. All tasks are designed to eliminate 'luck' from challenges and promote repeatability. Therefore, teams should present high level of readiness for each tasks and platforms should be equipped with all devices allowing solving all task elements. Rovers that are not equipped with all necessary elements could be not allowed to attempt task;

b) For reasons stated above, teams can expect dynamic elements in task description i.e. elements that will be defined separately for each team at the beginning of the attempt (e.g. changing start position, different positions of task elements etc.). In those cases jury will propose fair modifications and team cannot influence those decisions.

c) Teams will control their rovers from rover control areas. The areas will be set up so that team members will not see their rover during the tasks;

d) Each team have about 25 minutes (if task description does not state different) to complete a task. This value will be fixed in time of final schedule release. In case of successful autonomous operation judge can award team with additional time but only to compensate longer autonomy operation comparing to manual control. Length of this bonus time is a decision of the judge and cannot be challenged. Judge can stop the task at any time outside task original time window.

e) Each team must designate two observers, who are allowed to follow the rover at a safe distance to ensure the machine basic safety. Observers are allowed to communicate with team from control area only through judge and only one way - from control base to observer - to react for non-task situations like task reset, abort or unsafe event. No communication during task normal execution is allowed. The observers must be able to carry rover but they should stay in safe distance from the working machine and cannot interfere with any rover's sensors (e.g. be visible on the image from the camera) during realisation of the task attempt;

f) During tasks only judges and team observers can access field of the task. No manual intervention is allowed except events for which task rules stand different;

g) Any maintenance made by the team during tasks (any operations made by the team with rover hardware on the field) causes restart of the task from the start line and cancellation of the all earned points;

h) The team can use video systems to tele-operate the rover if task requirements do not state different;

i) The team shall not use any voice/visual communication with the crew on the field. Only judge can communicate between task arena and control base.

j) The operator has the right to interrupt the task at any time by notifying the judge about it. The team will receive the points gathered to the moment of notification according to the rules of the task;

k) During entire event rover or any other part of the system must not do harm or interfere with systems of the other teams. Any report about such breach will be investigated independently by judges or organizer and violation of this rule can lead to disqualification from the challenge;

l) Any erratic behaviour of the rover or one causing damage to task infrastructure can result with immediate interruption of the task attempt and cancellation of collected points.

5.5. Tasks descriptions

5.5.1. Science task

For any scientific or prospecting mission rover need to be able to deliver measurements of samples of soil properties from different geological layers. In general, samples taken from deeper layers are more valuable due to weathering conditions on the bodies surface (space weathering effects appears also on bodies without atmosphere due to e.g. solar radiation). It is also worth to mention that many scientifically and resources-wise samples require drilling in water reach soil under really low temperatures which can be harder than concrete. Equipping rover with complicated laboratory devices is limited because of system mass, volume, power requirements, risks of failure related to complex systems etc. Rovers should be able to assess sample quality and cache it for delivery to more sophisticated laboratory (in particular to Earth as Sample Return type mission). Because sampling environment conditions and ecosystem itself could be dramatically different than laboratory one, it is crucial to prevent any cross-contamination and isolate samples to keep them in conditions similar to original ones.

The aim of the task is to obtain samples of surface and subsurface layers of the soil each taken from different locations specified by judge. Samples should be cached into prepared containers. Additionally in-situ measurements and automatic documentation (photographic etc.) of collection place as well as samples will be scored.

5.5.1.1. Technology priorities

1) drilling - different level of soil cohesion and hardness (soil or rock)
    1) separation of reaction forces from rover body
    2) robustness and repeatability
    3) task automation

        4) performance (energy, scalability, operation time)
    2) caching
        1) delivery - quality of operation of transporting sample from sampling place to container
        2) accuracy of placing - controlled way to put samples accurately to the container
        3) quality of container sealing design
        4) accuracy of container design regarding to real missions requirements.
    3) in-situ sample analysis/processing
        1) effectiveness and quality of self made solutions for sample analysis/processing
        2) accuracy of proposed solutions regarding to real missions requirements.
    4) scooping - unknow soil density
        1) separation of reaction forces from rover body
        2) robustness and repeatability
        3) task automation
        4) performance (energy, scalability, operation time)

5.5.1.2. Task Scenario

a) Reach sampling areas pointed by judge and target sampling location accurately;
b) Collect and cache 4 geological samples from terrain:
    - 3 surface samples from different locations,
    - deep sample (15-35cm below surface);
c) Prepare photographic documentation;
d) Collect several measurements of samples or sampling area that could be valuable for planetary science like each sample weight, volume and other parameters;
e) Excavate trench and document result;
f) Deliver samples in sealed containers.

5.5.1.3. General requirements

a) For this task multiple layers of different soil are prepared;
b) Surface sampling device should be prepared to handle different type of loose soil;
c) Deep sampling device should be prepared to handle materials from loose soil to hard gypsum;
d) Deep sample should at least contain material from the deepest reached point. In ideal scenario team should present unmixed, undisturbed cross-section of all layers from the surface to the deepest reached point.
e) The rover should be equipped with at least one sampling device.

f) Rover must be equipped with at least one sample container;
g) Samples should be delivered in dedicated containers, one container for each sample;
h) Containers can be manipulated and removed from the robot only in the company of judge;
i) Container design and sample insertion method/device should be inspired by real missions requirements;
j) Minimum resolution of the images is 800x600 pixels. Object of the image (sample location or sample itself) should occupy major part of the image. Image quality should be reasonable for scientific needs;
k) Any additional physical parameters must be documented in the control station and stored till judge inspection after task attempt end. Judge will evaluate quality of received data;
l) The trench should have minimum 30cm length, minimum 5cm depth and at least one wall steep enough to present clearly visible soil layers. This findings should be documented on a photo.
m) The method for sampling reaction forces/torques separation from rover body should be presented and will be scored by judge based on operation observation.

5.5.1.4. Expected results

a) Samples with correct weights in separate, sealed containers:
    1. each sample should weigh at least 25g and preferably 50-150g according to scoring (see appendix)
    2. deep sample containing at least the deepest material, ideally cross-section from surface to the deepest point
b) Results of in-situ measurements and observations of the samples and sampling area. Scored higher for automatic measurements acquisition;
c) Photographic documentation showing different aspects of samples, sampling areas and operations;
d) All data stored at least until reviewed by the judge;
e) Presentation of innovative methods of samples extraction (e.g. device design, operation, way to mitigate transfer/elimination of reaction forces/torques to rover body etc.), measurements (custom made sensors design, sample preparation and interaction methods) and caching (including cache design specifics).

5.5.1.5. Additional information

a) Every additional manipulation of the containers/samples (adding material, shaking/hitting rover etc.), not done by the rover equipment during task attempt, will be the basis to cancel all points for this task;
b) Teams are not required to follow the sample extraction method suggested in the rules;
c) After the rover returns to the start line, each sample will be judged and weighed;
d) Judges will verify sampling depth based on the sample material characteristics according to the reference key;
e) Additional points could be scored if extra functionalities of the system will be demonstrated during task. No part of additional equipment can operate standalone;
f) The deep sample should be clearly visible in undisturbed state at least before the sample is placed into the container. It is possible to leave detached part of sampling device inside container.
g) Extra points could be awarded if deep sample caching is done without sample exposure to above-surface conditions.

5.5.2. Maintenance task

Most of manned missions tries to limit human operation outside orbiting or surface habitats. For this reasons astronauts need dexterous robotic systems to support extravehicular operations on infrastructure suited to be operated by humans. Expecting human-robot cross-operation on such infrastructure it is also important to properly design future infrastructure elements to simplify operational aspects. Due to operations complexity, this tasks can be tele-operated but humans needs support for many operations to increase their awareness about situation and robustly automate tasks that need higher level of focus for longer time what is tiring (e.g. safely approaching switch that shouldn't be damaged). This is why roadmaps are specifying need for fully immersive teleoperator interfaces with extended spatial awareness, force feedback, intuitive interfaces design and systems with automation of typical tasks like manipulator approaches, low level control etc.

The maintenance task is intended to demonstrate rovers and teams ability and performance in operating electrical panels on which several switches and other electrical components are mounted. The Team has to use rover's manipulating device to set switches to correct positions, measure electrical parameters, set other panel controls and observe device feedback. These units are placed in two different locations, thus mobility capabilities in fine positioning of a rover are also necessary to achieve a goal.

5.5.2.1. Technology Priorities

1) tele-operator interface

   a) dynamic operator feedback (e.g. presentation of feedback measures, force-feedback/control interfaces, etc.)
   b) operator situational awareness (e.g. vision, parameters presentation and displays ergonomy, etc.)
   c) ergonomy of operator control interface
2) tasks automation
   a) automatic elements detection (e.g. spatial parameters, possible actions etc.)
   b) automatic approach
   c) automatic manipulation
3) end-effector performance
   a) tool relevance for specific scenario
   b) multiple tool systems (interfaces, exchange) or universal tool design
   c) operation robustness (flexibility etc.)
   d) operation accuracy and quality for specific scenario
4) manipulator performance
   a) operation robustness
   b) operation accuracy and quality for specific scenario

5.5.2.2. Task Scenario

1) Approach panel 'A';
   a) Set switches into states specified by judge;
   b) Measure voltage on panel terminals;
2) Approach panel 'B';
   a) Turn designated switch on;
   b) Set knob to value specified by judge;
3) Grasp the high-power plug from the ground and insert it into the socket.

5.5.2.3. General requirements

a) The rover should be equipped with manipulation device allowing to interact with control panel designed for human operator

b) Switches and other controls will be industrial grade elements;

c) Switches could need different forms of translation or rotation of handle element to change their state;

d) Controls can be located on vertical panels between 0.2m and 1.5m above the ground;

e) Voltage measurement is conducted on standard German type F/French type E similar (https://en.wikipedia.org/wiki/AC_power_plugs_and_sockets#CEE_7.2F3_and_CEE_7.2F

4 .28German .22Schuko.22.3B Type F.29) power socket or terminals with similar dimensions and connection requirements;

f) Voltage level is between 1.0VDC and 24.0VDC and should be reported with 0.5V accuracy;

g) Knob value display/scale can placed not further than 15cm from rotation axis;

h) High-power plug type is IEC 60309 with maximum 10cm handle diameter;

i) Any excessive force transferred to the Challenge infrastructure can result with assignment of zero points for particular element and if behaviour will be repeated judge can finish task attempt immediately;

j) Some panel elements are sensitive to forces and torques exceeding operational limits; Those elements should not be 'damaged' during operations and are scored differently than stiff ones;

k) Some of the panel elements can be covered by MLI-like (Multi-Layer Insulation) material attached e.g. with velcro and additional manipulation capabilities could be necessary to remove it/uncover those elements without causing any damage to material.

5.5.2.4. Expected results

a) Panel 1: switches set to correct positions and voltage measurement reported to the judge;

b) Panel 2: switch set to "ON" position and knob adjusted to desired position;

c) High-power plug inserted into the socket;

d) No panel damage events occured (control elements, connectors, covers, foils etc.);

e) Presentation of design proposition for control elements suited for human-robot cross-operation.

5.5.2.5. Additional information

1) Most of panel elements will be specified before challenges by photo and general dimensions. Location of panel elements will be unknown and could be changed between task attempts.
2) Multiple AR/QR tags will be placed on the panel surface. Tags type will be specified before challenges. Relative distance between tags will be published.
3) Examples additionally scored elements:
a) presenting results from automatic panel controls detection and characterisation. All or some of the parameters like element position, element type, element dimensions,

possible actions, direction of possible action etc. should be presented on operators screen at least based on single picture;

b) tracking of controls positions and etiquettes during robot and arm movement;

c) depth position of reported elements;

d) automatic end-effector approach and optional homing to the 'idle' position. Functionality presented on few elements. 'Idle' position is defined as any point where end-effector is in the distance of minimum 20 cm from the panel surface.

e) full automatic manipulation presented on multiple elements - approach, desired action and homing.

5.5.3. Collection task

Scientific rovers are precious piece of laboratory and they should be used to examine areas suggested by scientists. When one of mission objective is a delivery of samples to the more sophisticated laboratory (or return them to Earth in particular case), their work should not be spent on delivery activities which can take substantial amount of time. Additionally such scenario creates single point of failure - if scientific rover fails to deliver samples, all the samples are lost. For that reason concept of Sample Fetching Rover (SFR) was introduced. In this scenario scientific rover leaves cached samples on the ground reporting their location and continues its work. Then, another rover (characterised with better mobility and generally faster) responsibility is to collect them and deliver to specified location. In time when SFR arrive to cache location different weather activities can cause that cache will not be fully visible etc. so system must be prepared to search and identify cache. Additionally, ground control in the loop of SFR operations can slow mission down so it is highly desired to automate mission elements as much as possible. Moreover, some specific missions like sample return to earth specifies extra requirements on design of the container that should be used for samples collection.

This task is intended to demonstrate ability to perform cache fetching scenario. The Team has to reach locations marked on map, search and pick up the cache and place it into container on-board in a required orientation, then deliver container with caches to final destination.

5.5.3.1. Technology priorities

1) tasks automation
    a) automatic elements detection and localisation
    b) automatic approach
    c) automatic pickup
2) end-effector performance
    a) tool relevance for specific scenario

b) operation robustness
c) operation accuracy and quality for specific scenario

3) container and cache design
   a) container/mechanism design allowing placing caches by limited accuracy manipulator into container with requirements for high cache protection
   b) accuracy of container design regarding to real missions requirements
4) manipulator performance
   a) operation robustness
   b) operation accuracy and quality for specific scenario

5.5.3.2. Task Scenario

a) Collect 3 caches from different locations
   a. Reach area where cache was dropped;
   b. Search for a cache
   c. Approach cache, take a photo and pick it up
   d. Place cache into the container on-board
b) Deliver container with catches to designated place
c) Place entire container with caches inside in marked point

5.5.3.3. General requirements

a) The rover shall be equipped with manipulation device which is able to pick up cache and place it into container on-board;
b) The rover shall be equipped with detachable container allowing for stable transport of caches traversing over challenging terrain;
c) The rover system should be able to deliver container with caches from rover to designated place;
d) The container should keep caches in vertical position and prevent from movements during traverse;
e) There should be at least 4 slots for cache in the container
f) Cache is be represented by green cylinder (20mm diameter, 200mm height). One end of cylinder is cone-shaped and 50mm part from second is thicker (30mm diameter). Maximum weight of cache is 300g and COG position is unknown. The caches should be stored cone-shaped-end (thinner-end) down. Detailed design of cache will be given for preliminary design phase.

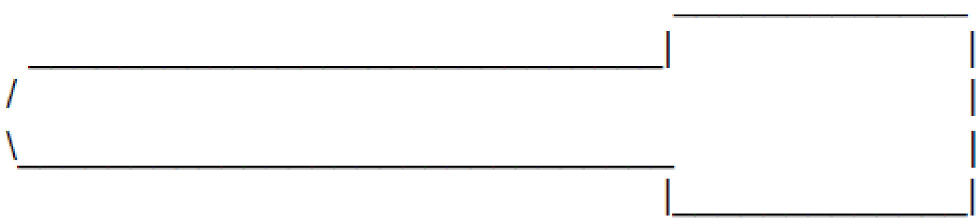


Fig. Schematic view of preliminary cache design.

5.5.3.4. Expected results

a) Demonstration of rover manipulation equipment (a robotic arm or equivalent) and operator performance in remote control;
b) Demonstration of system automation capabilities;
c) Placement of the caches in a proper position into the container;
d) Delivery of container to final destination;
e) Presentation of operational approach, used algorithms and other system solutions;
f) Presentation of proposed container design and accompanying elements.

5.5.3.5. Additional information

a) The cache will lay on the soil but could be also partially buried and end-effector should be able to stable grasp cache in both such conditions
b) The Cache could be partially covered with soil and detection system should be prepared for such situation.

5.5.4. Traverse task

A traverse task is core element of rover operation. It must be fully robust and optimised activity. It is probably one of most critical operations and at the same time having major impact on overall system performance. Traverse through unknown planetary surface characterised by properties that are not intuitive for humans due to harsh environment, neglected effects in Earth scenarios and different gravity by non-maintainable, non-recoverable vehicle is a great challenge. On the other hand, safe traverse operation is costly in terms of time and resources limiting science outcomes from relatively short rover lifetime. Obviously, major operation optimisation can be found in removing ground control from control loop, thus making traverse autonomous. Traverse is not single element but rather chain of many operations that need to be coordinated like: perception sessions, planning, traverse execution and monitoring. Moreover, what if during traverse some scientifically valuable, easy accessible - just “on the way” spots can be missed? This is why concept of autonomous scientist was introduced into roadmaps guiding towards future missions.

This task is intended to demonstrate system ability of semi to fully autonomous traverse. The Team has to develop a project which gradually evolves into fully autonomous system, traversing and gathering important data on its way. At early stage system can be decoupled with operator in the loop but all planning and parameters estimation operations must be done by system itself. This limits operator to navigate rover blindly i.e. without access to visual or other reach spatial information. However, any kind of data can be processed on-board providing operator support information about localisation and operation. The smart navigation strategy, sensor fusion and image data processing are essential in this task.

5.5.4.1. Technology priorities

a) autonomous navigation
b) robust traverse
c) data processing and fusion
d) localisation
e) obstacle avoidance
f) mapping
g) planning
h) trajectory control
i) Data processing and visualisation

5.5.4.2. Task scenario

a) Send rover position and way-points positions to the system
b) Reach consecutively 4 way-points;
c) Reach additional point 'X' located in more challenging terrain;
d) After and/or during traverse present used techniques, visualise system data, compare results with plan calculated at the beginning etc.

5.5.4.3. General requirements

a) The rover mobility system should be able to drive over challenging terrain in conditions described in *General Rules* in *Test Trials* section.
b) On-board data processing application should be used for rover localisation based on natural terrain features, however navigation landmarks can be placed for absolute reference on team request.
c) The rover system can utilise coarse heightmap of the arena provided by organisers, however solutions working without usage of a-priori map will be scored extra
d) Use of GNSS receivers and any other localisation reference system is not allowed. Any other type of sensor (i.e. camera, lidar, IMU, odometer, sonar, etc.) can be used for on-board processing.
a) Teams should take care to minimise usage for navigation purposes of features that are not part of competition area (e.g. infrastructure around, people etc.) by e.g. limiting field of view of the sensors to necessary minimum.

e) At any time during task attempt only data can be presented to the operator are position ([x, y, z]) and orientation (Euler angles or quaternion)
f) The rover start position and way-points coordinates to reach will be given in local coordinate frame, before task attempt
a) System should be able to plan optimal path based on given map and way-points coordinates and refine it when more data available.

5.5.4.4. Expected results

a) Reach all way-points;
b) Present system that support operator in rover control;
c) Reach way-point X;
d) Present autonomous traverse capabilities and gathered data anaysis (e.g. map, paths, plans, reached way-points position errors etc.).

5.5.4.5. Additional information

a) Initial rover position and orientation will be drawn at the beginning of each trial from a set of designated locations and in limited heading;
b) The rover can be tele-operated but only with position and orientation estimate available. Those data can be visualised in any form (e.g. projecting rover position on provided arena map or top view picture etc.);
c) Team can make multiple attempts toward next way-point and final way-point score will be the average from all started attempts;
d) If for some reason rover has to be moved, the way-point attempt is scored with 0 points and rover can be placed back to the:
    - last successfully reached way-point preserving original orientation
    - start point.
a) Technical Reports shall include a list of all sensors together with detailed information about working modes, ways they are used in navigation task and how rover will be operated. Teams are entitled to consult all solutions with judges before documentation submission. Documentation will be verified by judges and in case of any doubts team could be asked to reconfigure devices and/or communication strategy. Any difference between approved configuration and the one used during challenges can cause a disqualification (0 points for this task);
b) Task arena:
    - Final map with grid coordinates and POIs (Point Of Interests) will be provided not later than 3 days before the competition and will be subject of updates till the first day of trials;
    - Most landmarks will be visible from starting point but part of them could be obscured by terrain or other objects during traverse;
    - Two types of landmarks are foreseen: natural landmarks which are elements of landscape placed on the map, e.g. craters, small embankments, hills and artificial

landmarks, e.g. artificial points for localisation purposes. Artificial landmarks can contain characteristic hi-visibility labels, unique geometric figure, alphanumeric sign or AR/QR tag matching POI label on the map;

- Artificial landmarks will be visible for camera from different direction on a field and will have physical base which can be detected by proximity/range sensors (e.g. placed on element of infrastructure or natural landmark);
- Check-points will be flat characteristic elements with similar labels like on artificial landmarks;
- First definition of the way-points and landmarks will be provided for preliminary design period and final one not later than 30 days before the competition;
- Team cannot place any additional passive landmarks or active beacons on challenge field outside starting area but such elements can be deployed using rover during trial. All those landmarks must be documented in Technical Reports and presented for judges acceptance at least 10 working days before submission of the final documentation. These equipment can be subject of negotiations so teams should leave enough time to redesign/modify it in case of comments/rejection by judges. Such equipment must comply with other rules of the competitions and if active radio beacons are used, they must be compliant with radio communication rules (see *Radio Communication* section) and described in RF form;

c) Rover can be stopped and moved/rotated by Team members when it is stuck or in case of any other technical problems. Judge has to be informed before any action is undertaken;

d) During Task attempt several photos of the current state of the Field will be delivered to the Team by Judge. Photos will be delivered periodically but the frequency does not allow Team to accurate navigate their rover. Photos will be taken from static position (in perspective, top-view or both) and can be used to correct control methodology by operator or control software;

e) Details of the task such as landmarks appearance, location, map format, allowed custom landmarks and beacon types etc. will be discussed with the teams and presented preliminary design phase. Teams are encouraged to initiate and actively participate in this discussions.

5.5.5. Presentation Task - project review

The presentation task lets teams to introduce themselves and present their projects. The Judges expect to learn how the team worked on the project, what kind of technical solutions are implemented in the rover and how the team solved problems and issues occurred during development. The Team should be also prepared for Q&A session.

5.5.5.1. Goals

a) Introduce team (expertise and experience) and project;

b) Present organization structure, management methods and work-flow;

c) Present an engineering approach;

d) Present technical design;

e) Present difficulties occurred and applied methods to solve them;

f) Present elements designed to fulfill rest of the trial tasks expected results;

g) Present project outreach and impact.

5.5.5.2. General requirements

a) Time for presentation is limited to 15 minutes and after that time presentation will be interrupted immediately;

b) Q&A session takes 5-10 minutes;

c) The team can use a projector provided by the organizer (VGA connector as a standard, other connectors might be available);

d) The organizer does not provide any computer;

e) Presentation must be conducted in English;

f) Presentation can be done in any format and creativity is welcome.

5.5.5.3. Expected results

a) Demonstration of team presentation skills;

b) Detailed information on:

   a. technical key-drivers which influenced the team to build exactly this design, engineering approach, system breakdown structure, management, difficulties and solutions;

   b. Scientific/engineering inventions, design propositions;

   c. Spin-off, spin-out/in ideas and opportunities;

   d. Outreach - promotion of programme and event as well as research/technical activities (where ERC was clearly promoted); social project impact; research - thesis / side projects; activities and results derived from ERC like new projects opportunities, startups, campaigns, generated IPR; All documented (only summary should be presented but detailed information should be put after end slide) with relevant factors values (e.g. number of people, number and details of theses (e.g. title, short description of topic, affiliation), value of the projects, number of events) and photo documentation possibly presenting direct promotion of ERC.

6. Miscellaneous

6.1. Awards

The award for 1st place, Grand Prix ERC, is a cash award. Smaller cash awards will be given for the 2nd and 3rd place. The award amounts will be announced on the challenge website. The organizer will also give a separate Special Excellence Award to the team with the outstanding performance during challenges. The form of the award will be specified on the challenge website. The organizer may also announce other awards and allow awards funded by third parties. Third party award funders must have the organizer's approval.

6.2. Organiser disclaimer

Teams are taking full responsibility for any damages, accidents, unsettling events caused by their hardware software as well as members of the team. Teams are obligated to follow all safety and good conduct rules specified by organisers. Britch of any safety rules and requirements will result disqualification of team from entire competition.

6.3. Changes to Competition Rules

The organizer has the right to extend the deadline for submission of documents and provide essential but inevitable changes to the competition rules. However, introduced changes cannot concern the key issues for the rover's design. All introduced changes will be reasonably announced in advance and provided on the challenge website.

6.3.1. Deadline extension

The organizer has the right to extend the deadline for submission of documents and announce it reasonably in advance and provide on the challenge website.

6.3.2. Q&A

Answers to any challenge related questions that arise will be provided on the challenge website. If you have questions, contact the challenge contact point (see *Information channels and contacts*).

The organizer will provide 'European Rover Challenge 2018 Questions & Answers' as a part of the competition rules. All arrangements contained therein are ultimately binding – even if they change the competition rules. FAQ will be announced in advance and provided on the challenge website.

6.3.3. Challenge scoring issues

Any and all issues with scoring during the challenge shall be resolved solely by the independent jury (i.e. challenge judges). Teams may not appeal to any other party.

6.3.4. Organizational issues

Organizational issues, including: team eligibility, challenge organization and the execution of jury decisions, shall be resolved by the organizer.

6.3.5. General Challenge issues

Should there arise any conflict related to the challenge, the organizer's decision shall be considered final and binding.

6.4. Disqualification

The organizer may disqualify a team in the event of a serious breach of rules or fair play.

6.5. Personal data storage

Team members agree to their personal data being stored and processed in the organizer's computer systems and also for the purpose of ERC's integrated programme towards technological development specifically in a area of space exploration and utilization. They also give the organizer, parties designated by the organizer and the audience, the right to disclose and publish any photos, videos or other visuals; their names and surnames, identifiable pictures of themselves and any other persons, as well as pictures of machines, devices and equipment in any and all of the available formats, by any and every known method, in any and every known medium. Personal data and information about team members other than their names and surnames will not be published without prior consent of the each team member.

6.6. Team members responsibility

Teams and team members accept sole responsibility for securing and ensuring the safety of their equipment and luggage in the challenge location. They indemnify and release the organizer of any responsibility in the event of damage, destruction or theft of any property.

6.7. Organizer responsibility

The organizer's civil liability is limited solely to the responsibility for organizing a mass event in accordance with Polish law and local regulations.

6.8. Copyrights

The organizer keeps all the copyrights to the competition rules especially description of the tasks. You may not make alterations or additions to the competition rules, or sell it. Rules can be used and/or copied only for ERC-connected activity (eg. registration process).

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