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ROBOMINERS

ROBOMINERS DELIVERABLE D3.1
SYSTEM REQUIREMENTS

ROBOMINER REQUIREMENT SPECIFICATION

Summary:

This document provides an overview to system requirements of the robot miner mining robot being developed in ROBOMINERS -project.

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EXECUTIVE SUMMARY

Task 3.1 System requirements (M6-M12) is part of **WP3 Miner design and development** (M6-M36). The objective of this task is to define the key performance metrics of the robot miner system. Task 3.1 dedicates outcomes from WP1, WP2 and WP5 and other held workshops during the task and assemble the different requirements as a document (D3.1)

Deliverable 3.1 Robominer Requirement Specification addresses mechanical, electrical and electronic requirements (power, hardware interfaces, communication, design, etc.) in selected typical operation scenarios. These requirements create a framework which enables other work packages and tasks to adapt solutions they develop to the robot miner and set the common goals for development processes.

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1. INTRODUCTION

There are ever-changing needs of industries for raw mineral material, fossil energy, water etc, but the natural resource management industries react slowly to innovations. In order to reach this goal, the project aims to develop a bio-inspired, modular and reconfigurable robot miner for mineral deposits, which are not economic for exploitation by traditional mining. The project is designing and assembling a fully functional modular robot-miner prototype, which is able to operate, navigate and perform selective mining in harsh, flooded underground environment. A mining ecosystem of expected future upstream/downstream raw materials processes will also be designed via simulations, modelling and virtual prototyping. The key functions of the robot-miner will be validated to a level of TRL-4. The prototypes will be used to study and advance future research challenges concerning scalability, resilience, re-configurability, self-repair, collective behavior, operation in harsh technologies on an overall mining ecosystem level. The ROBOMINERS technology will not be a robotic extraction machine alone, instead, the whole production cycle should undergo serious modifications, creating not only an upgraded variety of old established technologies, but a revolutionary new approach. It may be a powerful tool of the resource management industries of tomorrow or even in the more distant future in a narrow segment of mineral raw materials.

Task 3.1 define the Key Performance Metrics (KPI) of the robot miner developed in ROBOMINERS-project considering end-user requirements via consultations with the Advisory Panel, dedicated workshops and the outcomes of WP1, WP2 and WP5. KPI's are defined on basis of the typical operational case scenarios defined in WP5 and reported in D5.1. KPIs are used to develop requirements for the mechanical design e.g. dimensions of the robot, maneuverability (e.g. turning radius, degrees of freedom), energy consumption and durability, autonomy, computational power, definition of hardware interfaces (e.g. powering and communication protocols).

The workflow of the task has been done as a threefold process:

- Synthesis on requirements foundation from research plan presented in the proposal using SysML-modelling (CHAPTER 2,)
- Synthesis of robot miner technical requirement specification table based on requirements foundation and technological limits (APPENDIX)
- Synthesis of KPIs

The requirement specification was reviewed and validated by the project Advisory Panel and their suggestions and remarks were taken into consideration when the final specification was synthesized. Advisory Panel was included as the final step of the process to give an adequate emphasis on the industry perspective and opinion.

2. SYNTHESIS OF REQUIREMENT FOUNDATION USING SYSML-MODELLING

The first set of requirements comes from the project proposal / research plan. These requirements were collected using a SysML model that links the requirements to the specific sections where they are mentioned and groups them for easier analysis and tracking. The research plan / proposal was divided into sections and placed into the SysML model as blocks that enclose html formatted text that can also include pictures. These blocks act as the source elements that the first set of requirements is elicited from. The diagram defining the source elements is very simple and the main purpose is that the source elements can be linked to requirements. In Figure 1 the ROBOMINERS project proposal / research plan has been divided into sections. These sections are small enough that when a requirement is elicited from the source, it is easy to see where the requirement has come from. Small text snippets were combined into sections/chapters using containers which helps readability of the diagram.

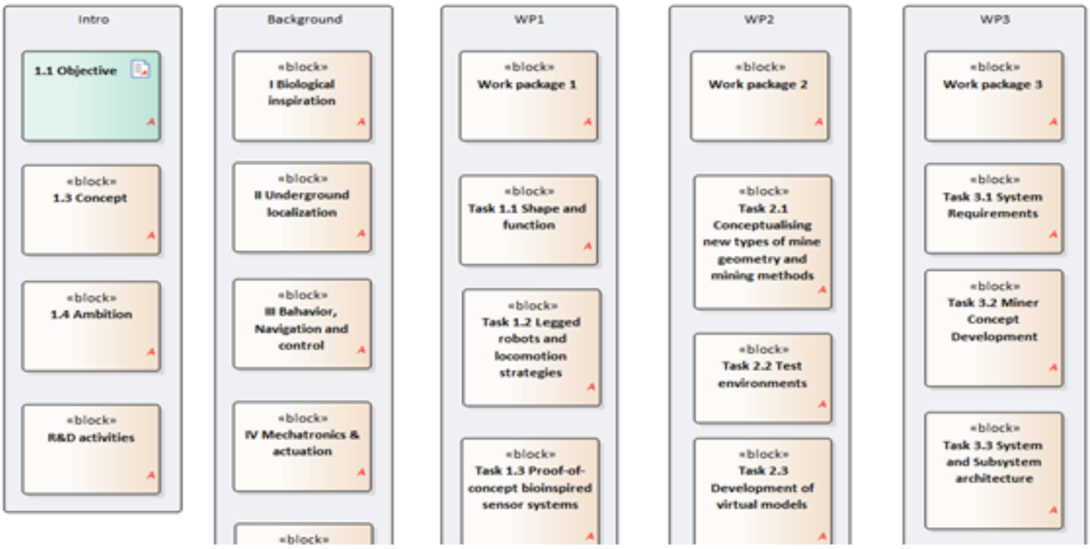

Figure 1. *Source elements*

The individual source elements were modeled as blocks that enclose the source documentation. Before eliciting the requirements from the source material, it was decided to categorize the requirements based on their type (Figure 2). This was done in order to keep individual diagrams from growing too large. The categorization was done based on the design domain a requirement would be associated with. This resulted the categories being: Electric, mechanical software and general.

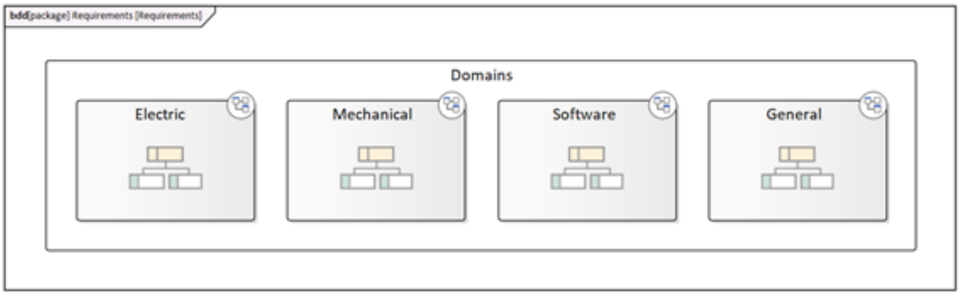

Figure 2. *Requirement domains*

Requirement diagram was created under each domain, to house the requirements elicited from the source material. Diagrams form a hierarchical tree structure, that starts from a source and fans out as sub requirements and derived requirements. There can be multiple trees in one diagram. In the example below (Figure 3) the tree starts by deriving requirements from earlier ones. Requirements are modeled as SysML requirement blocks; however, default requirement profile doesn't have all the properties that are needed to specify requirements properly. In the Figure 3 the blocks used are system requirement blocks that are defined with a custom profile that adds more properties to the default requirement block.

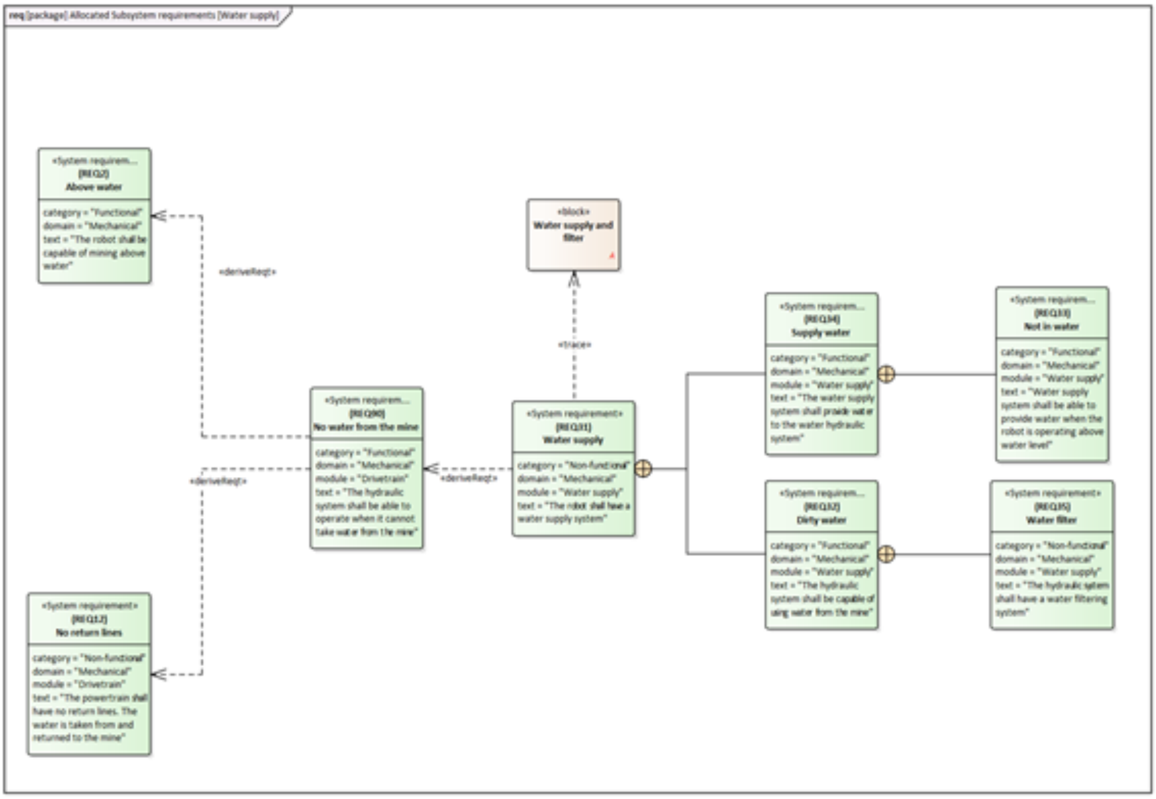

Figure 3. *Requirement diagram*

Each requirement in the requirement tree is linked to a source block even though these are not visualized they remain in the background. This makes the requirement diagram easier to read as it becomes less cluttered. Source elements were drawn only for the primary requirements and if a secondary requirement had different source, only that was drawn. Secondary requirements with the same source as the primary requirement would have their sources hidden. On the other hand, requirements diagrams are more of a modeling tool than a design reference, so these diagrams are not looked at directly, but rather act as an underlying model for traceability.

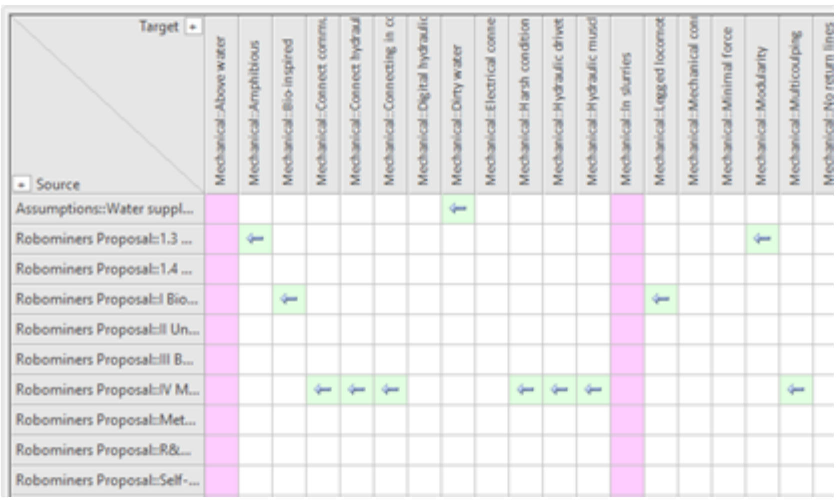

Figure 4. *Relationship matrix*

Relationship matrix (Figure 4) was used to study model integrity in order to check if all requirements are linked to a source and vice versa. The matrix picks one relationship type and maps two packages with that relationship. The figure above shows mapping between requirements and requirement sources with trace relationship. Elements missing a relationship are automatically flagged. In this table requirements missing a source are flagged purple, directions can also be reversed by flagging sources that don't have requirements extracted from them.

To use the requirements on a design process, the requirements should be exported to a more formal document. The modeling tool used (Sparx Enterprise Architect) supports csv-format. CSV-format was used to export the requirements to a spreadsheet. Requirements from the SysML diagrams were documented in a tabular format (Figure 5) in order to enhance usability.

Exporting the requirements from the model to a spreadsheet gives a more usable representation of the requirements. On a spreadsheet, the requirements are more accessible and can be easily arranged based on different tags.

	A	B	C	D	E	
1	Category	Domain	Type	ID	Name	Text
2	Functional	Mechanical	System requirement	REQ32	Dirty water	The hydraulic system shall be capable of using wate
3	Non-functional	Mechanical	System requirement	REQ35	Water filter	The hydraulic system shall have a water filtering sy
4	Non-functional	Mechanical	System requirement	REQ6	Bio-inspired	The robot shall be bio inspired
5	Functional	Mechanical	System requirement	REQ1	Amphibious	The robot shall be capable of mining underground,
6	Functional	Mechanical	System requirement	REQ4	Underground	The robot shall be capable of mining underground
7	Functional	Mechanical	System requirement	REQ5	Underwater	The robot shall be capable of mining underwater
8	Functional	Mechanical	System requirement	REQ3	In slurries	The robot shall be capable of mining in slurries
9	Functional	Mechanical	System requirement	REQ2	Above water	The robot shall be capable of mining above water
10	Non-functional	Mechanical	System requirement	REQ7	Legged locomotion	The robot shall use legs for locomotion
11	Non-functional	Mechanical	System requirement	REQ13	Open loop	The powertrain of the robot shall be based on an o
12	Non-functional	Mechanical	System requirement	REQ15	Water hydraulics	The robot shall use water as a pressure medium to
13	Non-functional	Mechanical	System requirement	REQ12	No return lines	The powertrain shall have no return lines. The wate
14	Non-functional	Mechanical	System requirement	REQ31	Water supply	The robot shall have a water supply system
15		Mechanical	System requirement	REQ16	Mechanical connection	The multicoupling shall connect modules machanic
16	Functional	Mechanical	System requirement	REQ90	No water from the mine	The hydraulic system shall be able to operate wher
17		Mechanical	System requirement	REQ8	Electrical connection	The multicoupling shall have an electrical connecto

Figure 5. *Excerpt from the requirement foundation table ()*

The benefit of using SysML to model requirements rather than going straight to a table is that in a table the requirements are detached from the system and cannot be easily traced up- and downstream. With SysML, the requirements are part of the model and linked to the rest of the system. This allows traceability that can be used to resolve conflicts between requirements and track where and how a certain requirement has been satisfied. While there is no direct link between the model and spreadsheet, the requirements can be searched by their ID.

As the research plan doesn't fully cover all stakeholders or scenarios and only offers raw unrefined requirements, further analysis was done based on these preliminary requirements in order to avoid conflicts later in the development. These raw requirements might also include things that are not feasible to be realized in the timeframe of this project but are part of the 2050 vision.

3. REQUIREMENTS SPECIFICATION

This chapter identifies different specification limits and ranges and where they come. These are gathered from different deliverables and workshop memos and follow a requirement specification workshop where these requirements were discussed with the project consortium to obtain a consensus about different specification and their limitations, range and feasibility. Figure 6. shows different functions and functionalities where these specifications rely on.

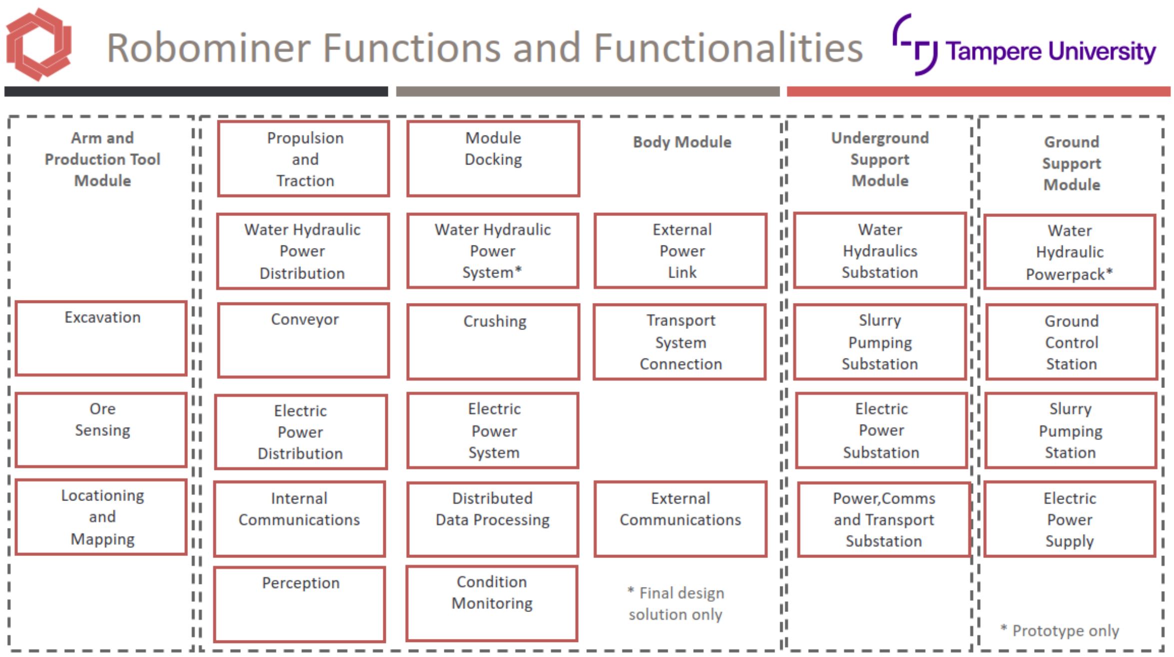

Figure 6: *The robot miner functions and functionalities*.

3.1. Locomotion Principle

The robot miner's locomotion principles were explored in deliverable D1.2 *New bio-inspired locomotion strategies concepts for mining environments,* by Maarja Kruusmaa and Simon Godon. In this deliverable were explored locomotion systems suitable for mine exploration, concentrating on locomotion strategies in difficult environments.

From this deliverable the selected locomotion system was screw-leg locomotion. In this system there are connected screw and leg to achieve robust, bio-inspired, durable concept to withstand harsh mining conditions.

3.2. Production Capability

For purpose of this project the robot miner should be able to mine general rock types which can be found in Europe. The robot miner should be able to mine up to 0,2 m^3/h 100 MPa (uniaxial compressive strength) hard rock and transport the same amount to the processing plant. This was concluded in Workshop at Saariselkä, where this capacity was calculated from the available power.

Also, in ROBOMINERS proposal/research plan were calculated investments return time in chapter *2.1.2 Economy impact* for eight units with 1 m^3/h production capability which means 0,125 m^3/h per unit.

Table 1: Production capabilities

Mining capability	0,2 m^3/h solid rock
Extracted rock transport capability	0,2 m^3/h
Excavation capability	max. 100 MPa uniaxial compressive strength

3.3. Robot miners Operational Case Scenarios

The Robot miner's operational case scenarios are defined in *ROBOMINERS Deliverable 5.1: Review document giving scope and examples of deposit types of interest.* Basically, the robot miner is designed to mine in abandoned old mines, ultra-deep and to mine small deposits which are not economical to mine with today's equipment. These operational conditions give other requirements for different specifications.

3.4. Ambient Conditions

These ambient conditions are the conditions where the robot miner must be able to perform mining. Ambient conditions achievable with full scale protype during this project differ in some areas from the 2050 vision.

The robot miner must be able to ascend and descend vertically when following the ore base.

The full-scale prototype's maximum operating depth is specified to 50 m (5 bar) and demonstrations with this prototype are shown in up to 40 meters, but the design solutions will be at 5000 meters (500 bar) for the purpose of ultra-depth mining possibilities. Operational temperatures for the prototype are from non-freezing up to 45 degrees of Celsius. In design solutions the temperature range is from 0 °C up to 85 °C without any extra cooling of components, but with water cooling 125 °C.

Table 2: Ambient conditions

Descent	90 ° to vertical downwards following the ore base
Ascent	90 ° to vertical upwards following the ore base
Maximum operating depth	Full scale proto 50 m (5 bar) (Demonstration up to 40 m)
	Design solution up 5000 m (500 bar)

Temperature	Full scale proto from 0°C up to 45°C
	Design solutions from 0°C up to 85°C, with cooling water circulation 125C°

3.5. Production Method

The robot miner's production capabilities are introduced in chapter 3.2 but the production tool itself and its different structures and mining operation methods are introduced in presentation of *H2020- ROBOMINERS: Status MUL (May 12, 2020) by Michael Berner*. The status report analysed different mining methods and what kind of tools these methods use for purpose to study which method would be suitable for the ROBOMINERS project. From the different tools information was gathered to analyze and compare between each other. Also, these production methods were analyzed with respect to how they fit within robot miner's concept as main production tool.

The robot system (not necessarily just one robot) both extracts rock and transports the extracted rock for further processing. Thus, the extracted rock most likely needs to be crushed (depending on the production tool) to smaller size to enable transporting. The crusher must be able to crush solid rock 0,2 m^3/h and with maximum power of 7,5 kW (reserved).

3.6. Manipulator Arm for Production Tool

Manipulator arm is for the robot to manipulate the production tool. The arm's dimensions depend heavily on the size of the production tool. The reach of the manipulator arm is specified to 0,5 m + robot radius, which comes from that the robot can make turning at the tunnel when following the ore vein. Functions of the manipulator arm: the arm has 2 to 3 degrees of freedom which are fulfilled with 1 to 2 joints which are moved with 2 to 3 actuators to be able to move the production tool to the wanted position. Also, the arm is equipped with a sensor which has the capability to sense the ore vein, which is followed.

3.7. Maneuverability

The robot must be able to operate in very harsh conditions and in tight spaces. The turning radius in open area must be on the spot (in the space taken by the robots), but in the tunnel 0,5 m + the robot diameter must be achieved. The robot miner is specified to climb vertically and step over obstacle which is 45% of the robot's own height. The movement speed of the robot in transport mode is 0,25 m/s and during mining it depends on the production tool used.

The robot must be capable to adapt to different environments: from tunnels, where it mostly operates, to an open pit where it might move in transport mode (changing place) or start new tunnels. Because of the screw propulsion system, the robot is capable to move on open land and even fully or partially submerged in mud, water or slurry.

Table 3: *Maneuvrability*

Turning radius	In open área	In its place
	In a tunnel	0,5 m + diameter of the robot
Climbing capability	Max ascent and descent	90 ° to vertical upwards and downwards
	Stepping capability	Can step over obstacle which is 45% of the robot's height
Degrees of freedom	One module	4 DOF
Movement speed	Transport	0,25 m/s = 0,9 km/h
	Mining	TBD (Depends on production tool)
Environmental adaption	Tunnel	Mostly working the hole made by itself
	Open pit	Transport
		Starting new tunnel
	Fully/partially submerged	Mud/slurry
		Water
	Open Land	Transport
		Starting new tunnel

3.8. Energy

Robot miner utilizes two different power sources. 30 kW open loop water hydraulic system provides power to the drilling, crushing and moving. The hydraulic fluid used is potable water. In a prototype, the hydraulic power pack is located at the surface station or in the underground support station, but in both cases off the robot itself. Hydraulic fluid is not returned to the reservoir of the hydraulic power pack but released into the mine after use. Fluid can be used simultaneously for cooling. The pressure is 160 bars with the flow of 85 l/min. It should be noted that pressure is 160 bars over the ambient pressure at the robot.
Electric power of 150 W is supplied over the 2x4-6 mm^2 cable and can be used to charge batteries onboard. These batteries offer a possibility to compensate peak electric power which might be needed.

3.9. Mechanical Design

The robot miner's mechanical design, size, cross-sectional area and weight are thought as small as possible to avoid unnecessary excavation around the ore vein. In this perspective the design for one module is specified: length of the module is < 1 m, diameter 0,8 m (cross-section area of the tunnel 0,5 m^2) and the target weight of the robot is 1500 kg. The robot miner's movement system is screw propulsion with legs. Legs are equipped with actuators (hydraulic artificial muscles) and they give capability to step over obstacles.

Because the robot miner's is modular and consists of two or more modules, there is coupling (Figure 7.) between the modules. The coupling has maximum 6 degree of freedom and it is able to articulate steering between modules. The coupling has docking function to dock modules together. For that the coupling has relative location to know it location toward another module, power coupling modules to share power from another module to another and close-range wireless comms to communicate between modules during docking phase.

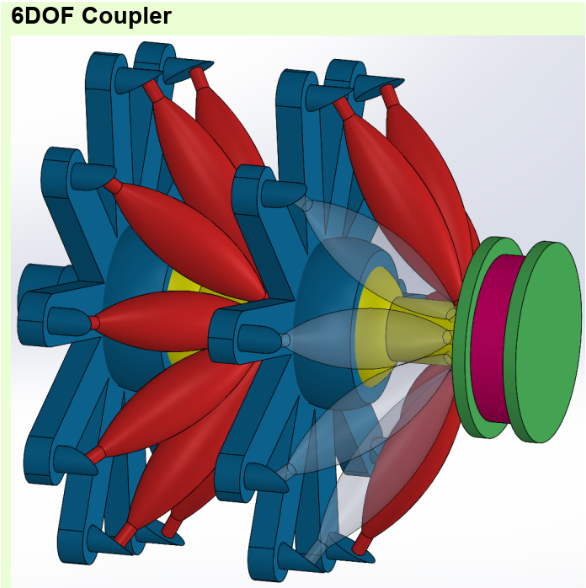

Figure 7: *An example solution principle for 6 DOF coupling.*

The robot miner needs anchoring system, because the robot's weight itself is not enough to offer necessary traction to counteract forces cause by production tool. The anchoring system shall give 10 000 – 15 000 N total traction force.

To support the robot miner we need an underground support module which gives electrical power (48 VDC via 4-8 mm^2 cable), hydraulic power (87 l/min @ 160 bar – via 16(DN25) hose) and rock extraction transport (0,2 m^3/h + water over 0,2 m^3/h).

Table 4: Mechanical design specifications

Body (One module)	Length	< 1 meter
	Diameter	Ø 0,8 m (cross-section area of the tunnel 0,5 m^2)
	Target weight	1500 kg
Movement system	Screw propulsion	

	Legs	Actuators- Hydraulic artificial muscles
		Capability to step over an obstacle
		Capability to increase traction
Module coupling	Max 6 DOF active cou-pling	
	Capable to articulated steering between mod-ules	
	Module docking function	Relative location of modules
		Power coupling of modules
		Close range wireless comms
Anchoring	Anchoring capability to in-crease traction	10 000 – 15 000 N total traction force
Underground support module	Electrical power	48 VDC via 4 – 6 mm cable
	Hydraulic power	87 l/min @ 160 bar via 16 mm (DN 25) hose
	Extracted rock transport	Crushed rock 0,2 m^3/h + water over 0,2 m^3/h

3.10. Reliability and Availability

Dependability under environmental hazards present in mine environment is an essential. The robot 2050 vision is designed, and its components are selected, so that it will survive one year in mine conditions, it can self-replace and carry wear parts and it is capable of autonomous operation for one year.

The robot can self-recover (from rock collapse, when falling 2,4 m high, temperature change, flow velocity change), at minimum it can send its location and status to operation center. The robot miner also has damage tolerance that no single failure of main component should render robot in operational and there is fail-safe of main components. Also, the robot has condition monitoring for awareness of failures.

3.11. Onboard Electronics

As the cable system from the ground level can be multiple kilometers and 100 meters from the possible last support station, electric power can turn to be physical limit. Limit comes from the weight and dimensions of the cable itself. To overcome that problem, electric power of the robot miner is limited to about 150 W continuous. Voltage is chosen to be 48 V direct current and current to 3 A. 48 V components are widely available. This voltage is available at the supply end of the cable. Transmission losses of the cable will decrease available voltage at the robot. Connected modules can work with these voltage fluctuations.

Some subsystems might need more power temporarily. This can be achieved with

rechargeable battery pack. To make that work, all the modules should offer possibility to choose different power schemes over ROS interface. At minimum two stages are
System is usable at ambient temperature from non-freezing conditions up required: sleep and full operation.

Final vision 2050 design concept will work in 5 km deep flooded mine. Water column will create pressure of 500 bar. The robot miner will remain operational in that pressure. To decrease overall system weight and volume nearly all electronics of the robot miner are pressure tolerant and do not need any pressure tight casing. If needed, miniature casing can be used for the specific subsystem.

Every module offers ROS interface, and it is the only way, in operation, to communicate with the module. Physically this is done with gigabit ethernet hub. Every module will use one connector in the hub.
to 85°C degrees and 125° when water cooling is used.

3.12. Hardware Interfaces

The robot miner hardware interface to surface is established via optical ethernet cable of military grade for high bandwidth fast data transfer from the robot and to ensure that the cable can stand those harsh environments. The robot's internal data transfer will be handled with cabled ethernet.
The robot electrical power consists of two different electricity power sources: wired high 48 V 3A and wireless low power 5 V 1 A.

4. KEY PERFORMANCE INDICATORS

Key Performance Indicators are overall targets for robot miner's development. They relate to robot miner's capability to perform the mining process and processes directly related to that. KPIs stem from both requirements and foreseeable limits of the technology development. The most imperative limits to KPIs come from robot miner's power and size requirements. Robot size mostly stems from typical operational scenarios and, on the other hand, power stems from limits of technology. Together these set limits to robot miner's capability to extract rock, process rock and transport rock ahead.

Key Performance Indicators of robot miner are:

1.	Extraction capability	0,2 m^3/h solid rock
2.	Transport capability	0,2 m^3/h
3.	Extracted rock strength	Max. 100 MPa uniaxial compressive strength
4.	Minimum diameter of tunnel	0,8 m
5.	Max operation depth	Full scale proto 50 m, 2050 design solution up 5000 m
6.	Max inclination during operation	90°
7.	Max operation temperature	Prototype from 0°C up to 45°C, 2050 design solution from 0°C to 125C°
8.	Tunnel turning radius	0,5 m + diameter of the robot
9.	Maximum weight	1500 kg
10.	Power	30 kW

5. CONCLUSIONS

The ROBOMINERS project is a complex project where is build complex robot mining concept and it connects experts from many fields to achieve wanted result. Outcome of task 3.1 is this document *D3.1 System Requirements: Robominer Specifications Requirements* for consensus inside of the project consortium on what kind of specifications are required from the robot and what are their limitations or range. The document gathers different specifications (design, power, maneuverability, etc.), limits and where these limitations or specification come from and what are connection points between other specifications under one documentation.

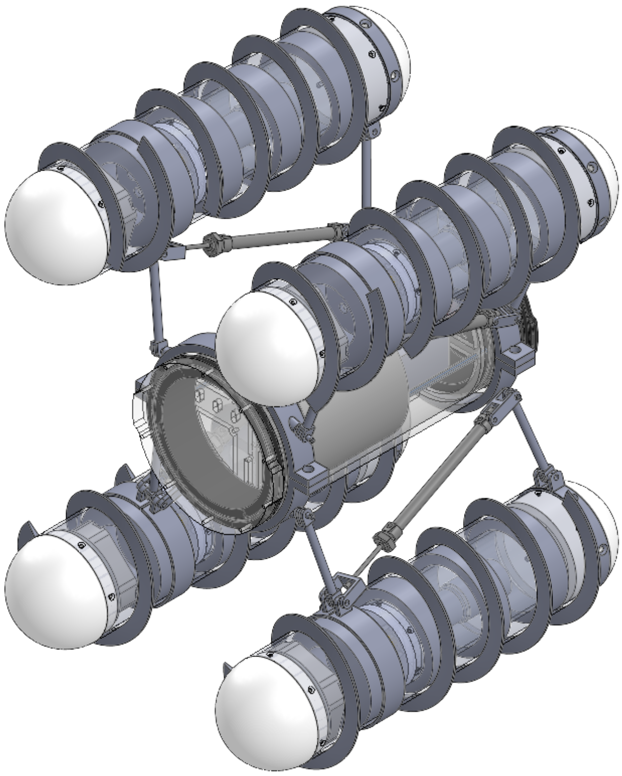

Figure 8: *Laboratory scale / locomotion test model design solution.*

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APPENDIX 1 REQUIREMENT FOUNDATION TABLE

Domain	Type	Name	Text
Mechanical	System requirement	Pressure transformer	The hydraulic system shall have a miniaturized ultra-high pressure (over 400 MPa) power supply system for hydrodemolition
Mechanical	System requirement	Amphibious	The robot shall be capable of mining underground, underwater, in slurries or above water
Mechanical	System requirement	Underground	The robot shall be capable of mining underground
Mechanical	System requirement	Underwater	The robot shall be capable of mining underwater
Mechanical	System requirement	In slurries	The robot shall be capable of mining in slurries
Mechanical	System requirement	Above water	The robot shall be capable of mining above water
Mechanical	System requirement	Bio-inspired	The robot shall be bio inspired
Mechanical	System requirement	Legged locomotion	The robot shall use legs for locomotion
Mechanical	System requirement	Modularity	The robot shall have a modular structure
Mechanical	System requirement	Reconfigurability	Robot's mechanical structure shall allow physical reconfiguration of the robot modules
Mechanical	System requirement	Parallel valves	The hydraulic muscle configuration shall have multiple control valves in parallel
Mechanical	System requirement	Parallel redundancy	Parallel redundancy shall be incorporated into the hydraulic muscle configuration
Mechatronics	System requirement	Selective mining	The robot shall be capable of selective real-time mining by sensing and following main mineralization directions, while refining the ore-body model in real-time
Mechatronics	System requirement	Mineral sensors	The robot shall have sensors for selective mining
Mechatronics	System requirement	Difficult deposits	The system shall be capable of mining small and difficult to access deposits in a completely novel way
Mechatronics	System requirement	Self assembly	The Modular robot shall be capable of assembling itself
Mechatronics	System requirement	Automatic shutdown	Each hydraulic muscle line shall have the capability to automatically shut down separately in case of damage/failure, and allow other muscle lines to compensate
Mechatronics	System requirement	Minimise downtime	Robot shall be able to operate continuously with minimal downtime

Mechatronics	System requi-rement	Resilience	The robot shall have the capability of recovering original func-tions after partial breakdown
Mechatronics	System requi-rement	Redundancy	The key systems shall be designed with a positive adaptive re-dundancy to tolerate minor faults that would otherwise inca-pacitate conventional mining equipment
Mechatronics	System requi-rement	Physical reconfigu-rability	Robot has to be able to change its physical structure in order to adapt to situations
Mechatronics	System requi-rement	Adaptive beha-viour	The robot shall be able to adapt its behavior based on the avail-able resources and environment
Mechatronics	System requi-rement	System reconfigu-ration	The robot shall be able to redistribute power internally to uti-lize the resources available
Mechatronics	System requi-rement	Sensor perfor-mance	The sensors shall be able to operate in turbid environment with zero visibility, with constant noise and vibration
Mechatronics	System requi-rement	Autonomy	The system shall be able to perform complex tasks in changing environment without human intervention
Mechatronics	System requi-rement	Redistribute po-wer	In case of a muscle failure the robot shall have the ability to learn to redistribute power to other muscles internally
Mechatronics	System requi-rement	Self-awareness	the system shall be aware of the state of all its components (both hardware and software) and of the degree they are com-plying with their functions
Mechatronics	System requi-rement	The â€œadvanced mineralogical body segmentâ€	The robot shall have an optional central segment (module) con-taining additional sensors acting as an artificial â€œdigestive systemâ€ to perform in-stream analysis of the drilling slurry
Mechatronics	System requi-rement	The simplest, fully integrated onboard sensors	The robot shall have basic mechanical and electro-geochemical sensors
Mechatronics	System requi-rement	Situational aware-ness	The sensors shall enable the robot to have full 3D situational awareness in terms of its position in relation to the ore body
Mechatronics	System requi-rement	Drilling optimiza-tion	The robot shall be capable of In-operation optimization of pro-duction tools, chemical physical properties of the mined mate-rial will be inserted in the miner feedback-loop to refine drilling parameters.
Mechatronics	System requi-rement	Self contained	The advanced minerological body segmant shall be entirely self-contained, protected by the robotâ€™s armor and the sensing itself will need to take part deep inside the body of the robot.
Electronic	System requi-rement	Electric power supply	The robot shall have an electric power supply system
Electronic	System requi-rement	High instanta-neous power	The power supply system shall be able to provide high instanta-neous power
Electronic	System requi-rement	Operating time	The power supply system shall provide approximately 2 hours of independent operation time (tetherless)
Electronic	System requi-rement	Power bus	The robot shall have a power bus

Electronic	System requi-rement	Distribute power	The power buss shall distribute power provided by the power supply system
Electronic	System requi-rement	Power within mo-dule	The power bus shall distribute power within a single module
Electronic	System requi-rement	Connect modules	The power bus shall connect modules to each-other utilizing the multicoupling
Electronic	System requi-rement	Pack-up power	The power bus shall have a pack-up power supply
Electronic	System requi-rement	Power during as-sembly	The pack-up power supply shall provide power to for rudimen-tary functions of modules without own power supply system during assembly and reconfiguration
Software	System requi-rement	hierarchical con-trol	The control system of the robot shall be organized hierarchi-cally
Software	System requi-rement	Body level	Behavioral body level shall be in charge of generating control directives (e.g., gait modes) to the limbs
Software	System requi-rement	Meta-controller	Meta-controller shall be integrated in the control architecture
Software	System requi-rement	Meta-control	The meta-controller shall be capable of perceiving the dysfunc-tional components of the system and reconfiguring it, just as feedback loops are used in classical control engineering process .
Software	System requi-rement	Meta-model	Meta-model specifies the system properties that are controlled by the meta-controller
Software	System requi-rement	Data management	Centralized data management system shall be implemented
Software	System requi-rement	Data visualization	Data visualization tools shall be implemented
Software	System requi-rement	Integrate data	The centralized data management system shall integrate all data (including the possibility of multiple robots) to monitor progress and to predict direction of resources
Software	System requi-rement	Combine data	The data management system shall be able to combine pre-ex-isting geological data/models with new instrumental data.
Software	System requi-rement	Query the system	The meta-controller will query the systemâ€™s knowledge to take run-time decisions on its optimal configuration.
Software	System requi-rement	Gait level	Gait level shall control the walking patterns of the robot
Software	System requi-rement	Limb level	Limb control shall be in charge of generating trajectories for each of the components/segments of the limb

Software	System requirement	Actuator level	low level controllers shall be in charge of generating suitable reference points (position, speed, force) for the individual actuators
Software	System requirement	Fault tolerant	The software architecture shall be cross-layer fault tolerant
Software	System requirement	Health map	The architecture shall have a health map
Software	System requirement	Diagnostic features	The architecture shall have diagnostic features
Software	System requirement	Export data	The software shall allow data to be exported from the robotic environment
Software	System requirement	Videos	The tool shall support production of videos showing the progress of mining activity
Software	System requirement	Use with geological simulation	The software to be developed shall also be suitable for use in conjunction with the geological simulations
Software	System requirement	Navigation software	The navigation software shall calculate the desired position of the robot center, according to the current behaviour, task and perceived localisation.
Software	System requirement	Low level sensor acquisition	Low level sensor acquisition software shall be responsible for data acquisition and signal pre-processing (e.g. filtering and resampling).
Software	System requirement	Sensor fusion	The navigation and sensor fusion architecture shall be developed so that it is always possible to extend it and include new sensor modalities
Software	System requirement	Based on ROS	The robot middleware shall be based on ROS
Mechanical	System requirement	Digital hydraulics	The water hydraulic control valves used to control hydraulic muscles shall be digital hydraulic valve
Mechanical	System requirement	No water from the mine	The hydraulic system shall be able to operate when it cannot take water from the mine
Mechanical	System requirement	Open loop	The powertrain of the robot shall be based on an open loop water hydraulic system
Mechanical	System requirement	Water hydraulics	The robot shall use water as a pressure medium to transmit power to various actuators
Mechanical	System requirement	No return lines	The powertrain shall have no return lines. The water is taken from and returned to the mine
Mechanical	System requirement	Hydraulic muscle	Hydraulic muscles shall be used for actuating limbs and manipulators
Mechanical	System requirement	Harsh conditions	The drivetrain and actuators shall withstand harsh wet and muddy conditions

Mechanical	System requirement	Power density	The drivetrain and actuators shall have high power density
Mechanical	System requirement	Hydraulic drivetrain	The robot shall have a hydraulic drivetrain
Mechanical	System requirement	Mechanical connection	The multicoupling shall connect modules mechanically
Mechanical	System requirement	Electrical connection	The multicoupling shall have an electrical connector to transmit electric power
Mechanical	System requirement	Self-connection	The multicopling shall have self-connection capabilities
Mechanical	System requirement	Self-locking	The multicoupling shall be self-locking
Mechanical	System requirement	Minimal force	The multicoupling shall require minimal force to connect
Mechanical	System requirement	Self aligning	The multicoupling shall be self aligning to enable mating it with limited perception
Mechanical	System requirement	Connecting in contaminated environment	The multicoupling shall be able to connect in a heavily contaminated environment
Mechanical	System requirement	Connect hydraulic power line	The multicoupling shall connect hydraulic power lines of two robot modules
Mechanical	System requirement	Connect communication bus	The multicoupling shall connect communication busses of two robot modules
Mechanical	System requirement	Multicoulping	Individual robot modules shall be connected with via a multicoupling
Mechanical	System requirement	Dirty water	The hydraulic system shall be capable of using water from the mine
Mechanical	System requirement	Supply water	The water supply system shall provide water to the water hydraulic system
Mechanical	System requirement	Not in water	Water supply system shall be able to provide water when the robot is operating above water level
Mechanical	System requirement	Water filter	The hydraulic system shall have a water filtering system
Mechanical	System requirement	Water supply	The robot shall have a water supply system

APPENDIX 2 ROBOMINER TECHNICAL REQUIREMENT SPECIFICATION TABLE

Locomotion

Articulated screw propul-sion with four screw units	High traction	All screws are pushed against tunnel walls
	Reliability and survivability	Simple compared to fully ar-ticulated legs, track or wheels
	Modular	

Production capability

Extraction capability	0,2 m/h solid rock
Rock transport capability	0,2 m/h
Excavation capability	Max. 100 MPa uniaxial compressive strength

Operational Case Scenarios

Three case scenarios	Operating abandoned mines with known remaining unfea-sible resources	Example for scenario: Neves-Corve
	Ultra-depth	Example for the scenario: Kupferschiefer, Fore-Sudetic Monocline
	Small deposits uneconomic for traditional mining	Example for the scenario: United Dows project, Corn-wall

Ambient Conditions

Descent	45 ° to vertical downwards following the ore base
Ascent	45 ° to vertical upwards following the ore base
Maximum operating depth	Full scale proto 50 m (5 bar) (Demonstration up to 40 m)
	Design solution up 5000 m (500 bar)
Temperature	Full scale proto from 0°C up to 45°C
	Design solutions from 0°C up to 85°C, with cooling water circu-lation 125C°

Production method

Production tool	Drilling and blasting/ hydrocracking	See MUL position paper about production tools
	Grinding	
	Interchangeable	
Size	Dimensions	
	Shape	
	Weight	
Crusher	Max particle size	
	Capacity	0,2 m^3/h
	Power	7,5 kW

Manipulator Arm for Production tool

Size	Dimensions	TDB (Depends on production tool)
	Weight	TDB (Depends on production tool)
	Reach	Robot radius + 0,5 m
	Effector weight	TDB (Depends on production tool)
Function	DOF	2 - 3
	Joints	1 - 2
	Actuators	2- 3
	Sensor	Sensor for the mineral vein

Maneuverability

Turning radius	In open area	In its place
	In a tunnel	0,5 m + diameter of the robot
Climbing capability	Max ascent and descent	90-degree vertically
	Stepping capability	Can step over obstacle which is 45% of the robot's height
Degrees of freedom	One module	4 DOF
Movement speed	Transport	0,25 m/s = 0,9 km/h
	Mining	TBD (Depends on production tool)
Environmental adaption	Tunnel	Mostly working the hole made by itself
	Open pit	Transport
		Starting new tunnel
	Fully/partially submerged	Mud/slurry
		Water
	Open Land	Transport
		Starting new tunnel

Energy

Electric power	Constant electric power through tether	48 VDC/ 3A, peak power from the batteries
Water hydraulic power	Through tether*	30 kW (85 l/min @ 160 bar)
	*Prototype only	

Mechanical Design

Body (one module)	Length	<1 meter
	Diameter	Ø0,8 m (cross-section area of the tunnel 0,5 m^2)
	Target weight	1500 kg
Movement system	Screw propulsion	
	Legs	Actuators - Hydraulic artificial muscles
		Capability to step over an ob-stacle
		Capability to increase traction
Module coupling	Max 6 DOF active coupling	
	Capable to articulated steering between modules	
	Module docking function	Relative locationing of modules
		Power coupling of modules
		Close range wireless comms
Anchoring	Anchoring capability to increase traction	10 000 - 15 000 N total traction force
Underground support mo-dule	Electric power	48 VDC via 4 - 6 mm^2 cable
	Hydraulic power	87 l/min @ 160 bar via - 16 (DN25) hose
	Extracted rock transport	Crushed rock 0,2 m^3/h + water over 0,2 m^3/h

Reliability and Availa-bility

Durability	System robustness	One year in mine conditions*
	System endurance	Robot has to be able to self-re-place wear parts*
		Robot has to carry wear parts *
		One-year autonomous opera-tion time *
Survivability	Robot has to be able to self-recover	Rock collapse etc.
	Minimum is that robot should be able to transit its location and status	
	Falling	Falling height 3 times its own diameter
	Temperature changes	Puncturing geothermal well or stream wall
	Flow velocity changes	Puncturing subterranean stream wall
Damage tolerance	No single failure of main components should render robot in operational	
Fail safe	Self -recovery from failure in main components	Communication fiber (military grade and double fi-ber)
Condition monitoring	Self aware of failures	
	*Final design solution, not prototype	

On board Electronics

Software	Orchestration
	Tool usage
	Power control
	Communication
	Coupling
	Locomotion
	Sensor interfacing
	SLAM
System electronics	Computers
	Communication
Sensor electronics	Sensors
	Adapters (communication)
Power & Control electronics	Power for systems
	Battery Management
	Control electronics (actuators)
Communication electronics	Internal communication
	Module communication
	External communication

Hardware Interface

Wired optical ethernet (external)	
Wired ethernet (internal) RJ45	
Wired high power electricity, 48V 3A	
Wireless low power electricity, 5V 1A Qi	
Hydraulics	Pure water without additives @160 bar