ROBOMINERS DELIVERABLE D3.2
ROBOT CONCEPTUAL DESIGN REPORT

Summary:

This document provides information on the robominer conceptual design including structural design and systems design. The design concept is based on Deliverable 1.2 New Bio-Inspired Locomotion Strategies Concepts for Mining Environments and Deliverable 3.1 Robominer Requirement Specification.

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Version 1	The base document
Version 2	**General modifications:** Different chapter were modified to respond changed design solutions and add more information about the robominer design solutions. **Additions:** Chapters 2 Robominers eco-system Chapter 3.1 Ground support requirements Appendix 3 Robominers screw design calculations Appendix 4 Screws hydraulic cylinder and anchoring force Appendix 5 Screws hydraulic artificial muscles calculation Appendix 6 Robominer moving speed **Specific modifications:** The chapter 4 was modified to be more accurate to the design and the design solutions The chapter 4 was modified to show the current design solutions
Version 3	**General modifications:** General modification to figures and text to answer to questions Formatted and updated calculation appendixes

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EXECUTIVE SUMMARY

Task 3.2 Miner Concept development (M12-M18) is part of WP3 Miner design and development (M6-M36). The objective of this task is to provide finalized conceptual design for the robominer. Task also develops function structure and solution principles which enable required main functions of the robominer. Based on both requirement specifications and further requirements set by function structure and solution principles the heterogeneous modular structure of the miner is developed. Modular structure of the robominer will support robot self-assembly, re- and self-configurability as well as its scalability.

Deliverable 3.2 Robot Conceptual Design Report shows finalized conceptual design solution for requirements outlined in the Deliverable 3.1. The conceptual design solution includes robominers mechanical, electrical and hydraulic systems which fulfil D3.1 requirements.

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1. INTRODUCTION

ROBOMINERS -project aims to develop a modular, bio-inspired, reconfigurable, and self-assembly-capable robotic miner for small mineral deposits, which are not economic for exploitation by traditional mining methods. The project will design, assemble, and test a fully functional modular robot-miner prototype, which can navigate, operate, and perform selective mining in harsh, flooded underground environment.

A mining ecosystem of expected future upstream or downstream raw materials processes will also be designed via simulations, modelling and virtual prototyping. The key functions of the robominer will be validated to a level of TRL-4. The prototypes will be used to study and advance future research concerning scalability, resilience, re-configurability, self-repair, collective behaviour, 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.

Project task 3.2 defines conceptual design solutions of the robominer extraction machine considering requirements set in Deliverable 3.2. Design solutions defined in the task are mainly targeted in the robominer prototype which will be built in the ROBOMINERS -project. Because of practical reasons the prototype will have certain differences to future robominer vision, such as external power supply and tethered communications

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

- Synthesis of design solutions on the basis D3.1 Robominer Requirement Specification
- Workshops of the system, mechanical, electrical design, and solutions
- Designing the robominer concept on basis of synthesis of design solutions and topic which arouse during workshops

2. ROBOMINERS ECO-SYSTEM

The robotic miner to be conceptualised by the ROBOMINERS project will be operated as part of a larger mining eco-system. The main operations in this eco-system are: Data acquisition, ore production and transport. As the foreseen robot miner environment is most likely submerged, the devised eco-system envisages hydraulic transport methods. As such, the operational steps in the eco system can be defined as: Production, comminution, slurrification, horizontal transport (haulage) and vertical transport (hoisting). These steps as well as the related material streams in the eco-system are presented as a Block Flow Diagram (BFD) in **Error! Reference source not found.**.

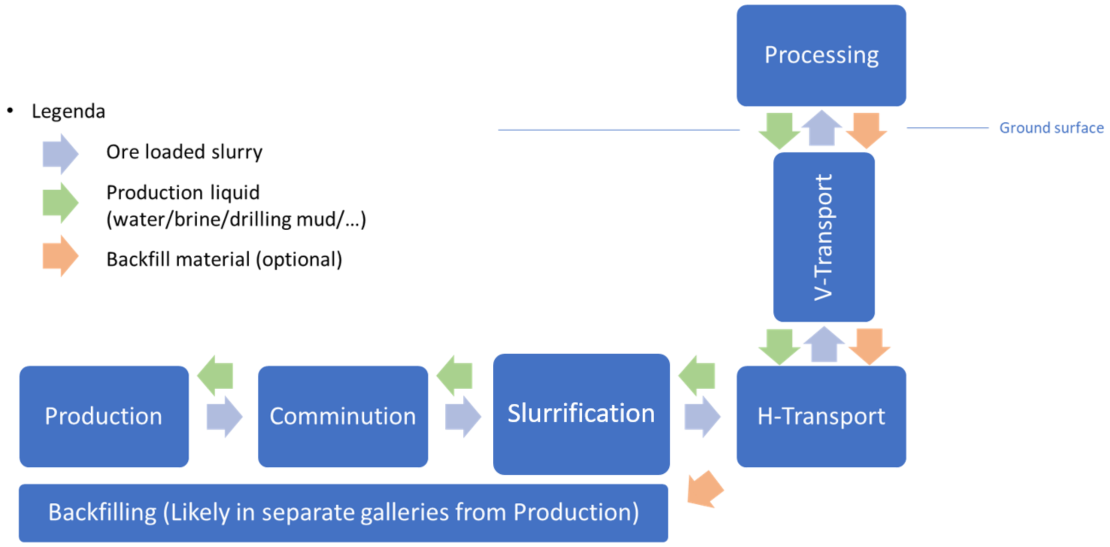


Figure 1 Block Flow Diagram of the ROBOMINES eco-system

Not all the steps shown in **Error! Reference source not found.** are needed in all cases. For instance, the production tool could produce ore rock with a grain size distribution which allows direct slurrification and comminution of the ore before slurrification is not necessary in such a case. All the required steps will however need to be fulfilled by the robot miner and/or auxiliary equipment and therefore the concept for the ROBOMINERS eco-system centres around the actual robot miner to maximise the autonomy of the robot miner in the eco-system. When translating steps in the BFD shown in **Error! Reference source not found.** to the environment in which the robot miner operates the following functions of the robot miner can be distinguished: production, comminution, slurrification, horizontal transport and sensing & data acquisition. As the ROBOMINERS project envisages the development of a modular robotic miner concept, the mentioned functions can be separated over multiple robotic miner modules: This is shown in **Error! Reference source not found.**. In the ROBOMINERS concept, the modules of the robotic miner are technically identical when considering the construction, locomotive functions, and overall control system. However, each module can carry a payload, which dictates the function of a module in the eco-system.

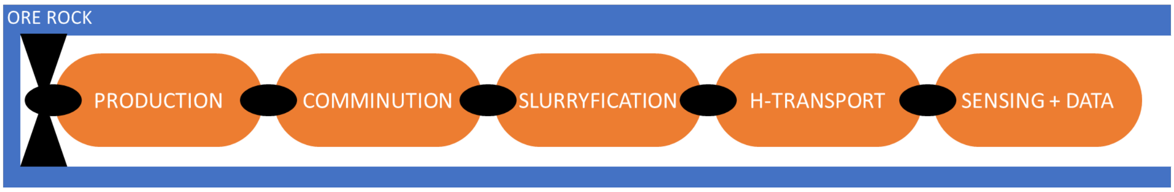


Figure 2 Modular robotic miner concept with differentiated functions for each module

A short description of the different functions shown in **Error! Reference source not found.** is provided below:

Production:

- Production tool platform
- (Forward) sensing tools platform
- Broken ore collection

Comminution:

- Comminution of broken ore (in case the production tool alone is not able to provide sufficient comminution capability)
- Sensing tools platform for external sensors (mineralogy, rock quality, etc.) and internal sensors (ore quality, ore properties, etc.)

Slurrification:

- Slurrification of the comminuted ore by mixing it with a carrier liquid
- Sensing tools platform for external sensors (mineralogy, rock quality, etc.) and internal sensors (slurry density, solids content of slurry, flow rate, etc.)
- Potential diverting valve for ore slurry which does not fulfil the cut-off grade (for example diverting the slurry to a backfill room rather than the processing plant)

Horizontal transport:

- Pump for horizontal transport
- Sensing tools platform for external sensors (mineralogy, rock quality, etc.) and internal sensors (pump effort, rheological behaviour of the slurry, etc.)

Sensing and Data:

- Centralised control modules (when not included per module)
- Data processing equipment
- Data transfer equipment and infrastructure

Again, as with the BFD presented in **Error! Reference source not found.**, not all the mentioned functions will be required in all cases. The modular layout of the ROBOMINERS concept for the robot miner allows for a flexible operation which, when the right modules are available, can quickly switch between operational modes depending on local conditions in the mine. For instance, when the rock strength decreases and the production tool is able to produce ore rock grains which are small enough to be hydraulically transported, the comminution, module can be (temporarily) removed and thereby simplify the overall layout of the robot miner. In reverse, when the horizontal transport distances become larger over time (which is common in mining as the production areas are usually moving away from the hoisting shaft) the pumping module might not be capable to transport the material at the desired rate. An additional robot module with a (booster) pump can be added to the robot miner to mitigate the risk of pipeline clogging.

3. DESIGN REQUIREMENTS

Conceptual design of the Robominer includes developing function structures and solution principles for functions and functionalities of the robot. These requirements can be found in appendix 1. The overall system design is the uppermost level of design and defines the topmost modular structure which consists of robot, ground support module system and underground support module. Robominer itself can also be seen as a system of modules which contain numerous subsystems. Robominer design can be separated in:

- Mechanical design - Mechanical solutions which fulfill mechanical design requirements considering mobility, survivability, coupling of modules and hull structure etc.
- Mechatronic design - Actuation systems and actuation power systems.
- Electronics and low-level control system design – Electronic, electrical, and low-level control systems.

Figure 3 presents overall system modular structure with submodules.

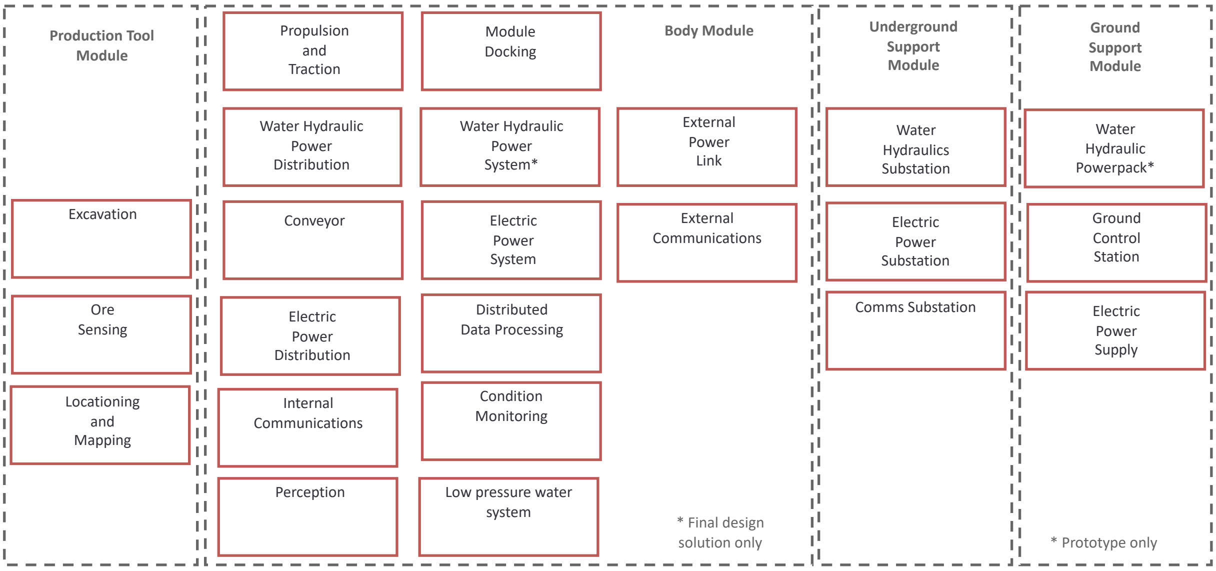


Figure 3 Robominer system functions and functionalities

Ground and underground support modules are independent modules which are used to provide prototype robominer high pressure water, communications, and electricity via tether. The purpose of underground substation is to provide a stationary point for the tether, so that robominer does not have to move the whole length of tether with it.

3.1.Ground Support Requirements

3.1.1. General Requirements

Ground support measures will not always be required but must always be a consideration. Details of the geomechanical constraints are discussed in D5.2, some of the implications for mine design are covered in D2.2, and conventional approaches that have been used are treated in more detail in D5.4.

In new mines, whether near-surface or ultra-depth, and whether flooded or dry, the support requirements will depend on the rock properties and on the mining strategy and layout. Certain options will require additional specialised robots whose functions can be identified but which are not developed even as prototypes within the current project.

In re-opening abandoned mines, there may be a range of ground support problems depending on the size and stability of openings and the condition of any existing supports (props, rock bolts, pillars, etc.), but for new development the issues are the same as for new mines. Ground support remediation in old mines is beyond the scope of this project. General-purpose robots could be developed for this task, remotely controlled from surface.

3.1.2. Instrumentation

Ground stability can be tested using instrumentation such as the Schmidt hammer which may be mounted on the robot miner, as well as visual inspection using optical or sonar imaging or laser scanning. These capabilities are described in detail in D5.2, D5.4, and D6.3.

3.1.3. Pillars

Leaving unmined sections of rock within or between mined openings is a conventional method of supporting the roof (hanging wall) of a stope and is an integral feature of room-and-pillar mining of horizontal seams or other tabular deposits. Pillars are left between stopes in steeply dipping deposits as well. Pillars act as a continuous medium through which carry the vertical stress. Pressure redistributes around underground openings. This causes a compressive pressure to build up around the underground opening extremities. There is a tensile pressure build up in the back over the stope. Rock being weaker in tension could therefore fail. Circular underground openings beside each other should be more than 3 radiuses apart so their stresses do not combine in the rock mass. It is also an essential feature of the recently developed "honeycomb" mining strategy which can be considered as a generalisation of room-and-pillar operations for deposits of any geometry. This is described in more detail in deliverable D2.2.

3.1.4. Backfill

Backfill by waste (the material that is left after the required mineral has been extracted from the slurry or the broken rock) may be emplaced either in the form of a slurry, using the same slurry-transport methods as for transfer of mineral slurries to the surface processing plant, or in a more solid form using conventional trucks or wagons. In either case, if sufficient water is expelled from the mix to leave a solid backfill, there may well be sufficient strength to support the mine openings. It should be noted that the backfill does not replace the untouched rock. It doesn’t carry vertical stress in the same manner. When the stress field encounters another medium, such as backfill, it creates a discontinuity, and the field goes around the discontinuity. Where additional strength may be required, addition of Portland cement or other cementing medium to the slurry can improve the compressive strength of the backfill. More detail is given in deliverable D2.2.

3.1.5. Additional Reinforcement Methods

External means of reinforcement include props, traditionally timber, or more recently steel. The steel could be simple vertical columns or may be arches that support the roof. Steel mesh is often used. This mesh may have concrete sprayed on it which is termed shotcrete.

This mesh is usually pinned to the back with rock bolts which is one means of internal reinforcement. These rock bolts are flush to the back with a metal plate and have an anchor on the end of the bolt. As the bolt rotates in the anchor, the anchor expands. This serves to anchor the bolt in the rock mass. The bolt also tightens as it is rotated through the anchor. This causes the plate to be pushed into the rock mass. The compressive force between the anchor and the steel plate binds the rock more tightly together. This increases the direct strengthening of the rock around the mine opening. Other methods of internal reinforcement include split sets and cable bolts. These are not anchored into the

ground. Split sets and cable bolts can be set into the ground with grout. The bolts supply reinforcement to the ground similar to reinforced concrete. They therefore provide support.
The methods of support described are not easy to automate. They may require a suitable general-purpose robot under direct control from a human operator at surface. Appendix 2 shows more specific different ground support systems.

3.1.6. Monitoring

Once supports of any sort are installed, routine monitoring of rock stability is advisable. This could be done by a number of methods, but the most commonly used are micro-seismic detectors and strain gauges, or both in combination. Movement can also be detected by the use of laser surveying methods. Emplacement of such instrumentation is not easy to automate, but once emplaced, the data from such instruments can itself be monitored automatically at surface and alarms raised if any significant movement is detected. This type of instrumentation is not required in the robot miner itself and is not within the scope of this project.
Pull tests, torque tests, load cell for bolts and visual checks are means of reinforcement discussed in section 1.1.2.

3.2. Modular Structure

The modular structure concept of the robominer is presented in Figure 4. This structure should allow the robominer to be delivered in modules via a large diameter borehole. It will then self-assemble and begin its mining operation.

The robominer will consist of at least two separate modules linked together via an active coupling unit:

- Body module (see Chapter 4.1): will include the hydraulic and electrical power distribution systems, electronics, batteries, etc.
- Production tool (see Chapter 4.3): will include the production tool and its actuation, sensing modules and an anchoring system.
- Active coupling unit (see Chapter 4.6): self-locking, self-aligning coupler with three active DOF.

Another coupling unit on the back of the body module will allow another module to be attached. The robominer will be able to self-assemble and re-configure in-situ. However, this feature is not realized in the prototype.

Locomotion of each module is based on screw propulsion principle (see Chapter 3.3).

The modular structure, consisting of several modules, gives the robominer a bio-inspired, flexible body to navigate underground.

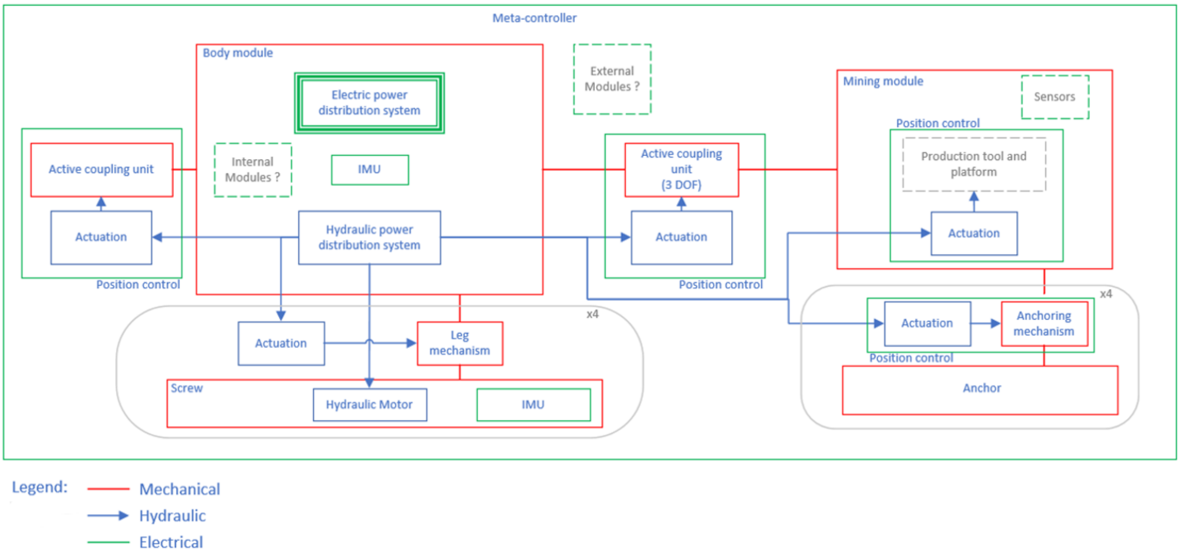


Figure 4 Robominer modules task breakdown

3.3.Locomotion Principle

The robominers locomotion system was chosen to be propulsion screw and a leg system. Screw-leg system is needed for robominer to operate in old abandoned mines. These old mines could be under water or fully or partly filled with water, slurry, or mud. The tunnels floor can be then covered by slurry or mud or sand which is mixed with water. These mediums are very demanding to the locomotion system. Various bio-inspired locomotion systems were studied in the deliverable D1.2 New Bio-Inspired Locomotion Strategies Concepts for Mining Environments. The study found different kinds of locomotion systems which can be adapted by the robominer. Deliverable D1.2 presents the principle and bio-inspired foundation of the screw propulsion. The propulsion screw and the leg system mimic turtle’s and mudskipper fish flipper locomotion where the motion of the flipper is simplified by actuating a single powered rotational joint.

As the screw is rotated around its longitudinal axis the screw blade generates the force moving the robot. /4-6/

The force can be expressed in two components, lateral (F_{Lat}) and longitudinal (F_{Lon}) (Figure 5). When there are two parallel screws with opposite thread directions driving at the same angular velocity, the lateral components counter act each other and the robot moves forward. When the angular velocity and direction are changed the robot’s direction and velocity is changed. /4-6/

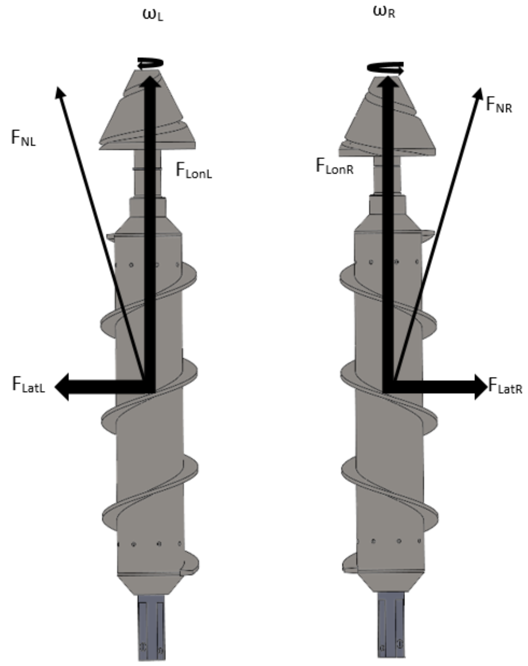
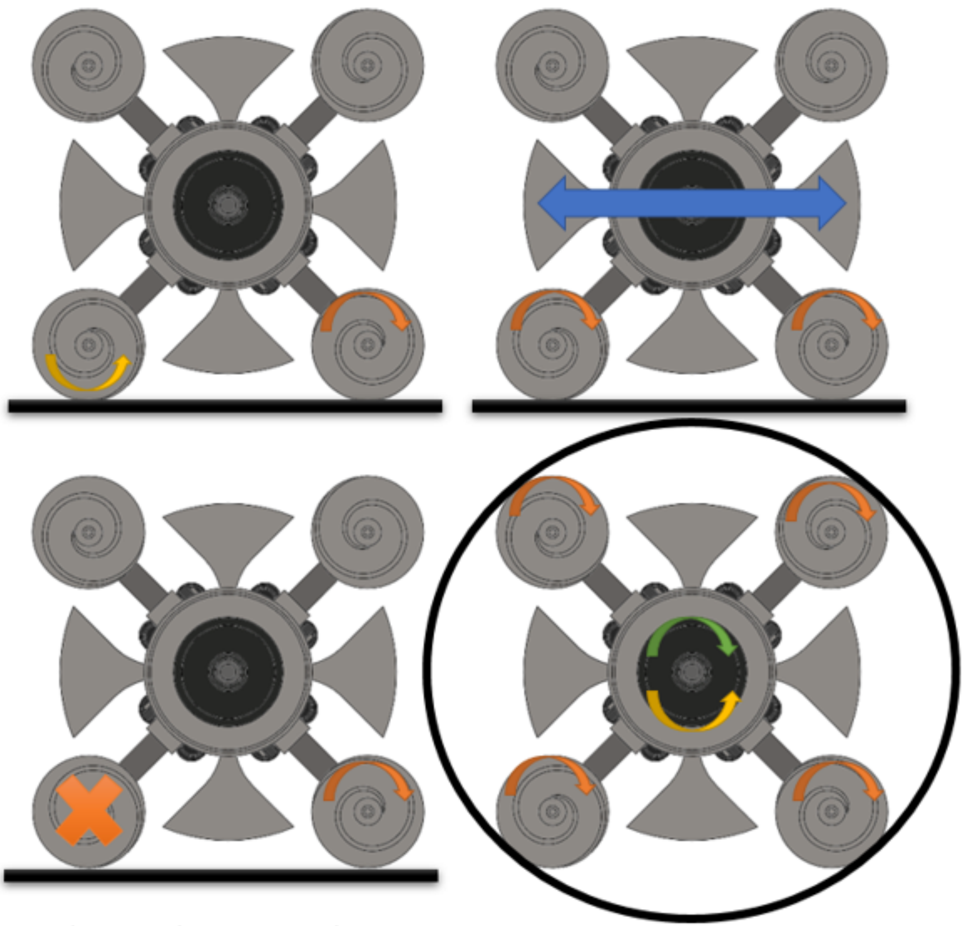


Figure 5 Normal forces components of the screw, F_{LatL}, F_{LatR} are lateral components of left and right screw and F_{LonL}, F_{LonR} are longitudinal forces of left and right screw /4/

The screw-leg locomotion system (S-LLS) gives multiple locomotion possibilities besides of simple forward and backward movement and turning to the robominer, which is a benefit when working tight confined spaces. The S-LLS is gives the robot possibility to drive sideways by operating screw to same direction. The robot can turn almost in place by driving screws to different directions. The four-unit S-LLS robot can turn around its longitudinal axis inside the tunnel when it is driving all unit at the same time to same direction. These movement directions are showed in the Figure 6.

Foward and backward by changing the rotation direction

Side by side changing the rotation direction



By diriving only one screw, the robot turns almost it place

When driving all units to same direction in a tunnel, the robot pins over its middle axel

Figure 6 Robominer’s movement capabilities

Also, this screw can act as an anchor (like the mudskipper which uses a flipper under its belly as an anchor) when it is pressed against the tunnel wall by the leg. By that it can provide anchoring force in two different directions (Figures 6. and 7.). Calculated approximation of the anchoring force is presented in the Appendix 4.

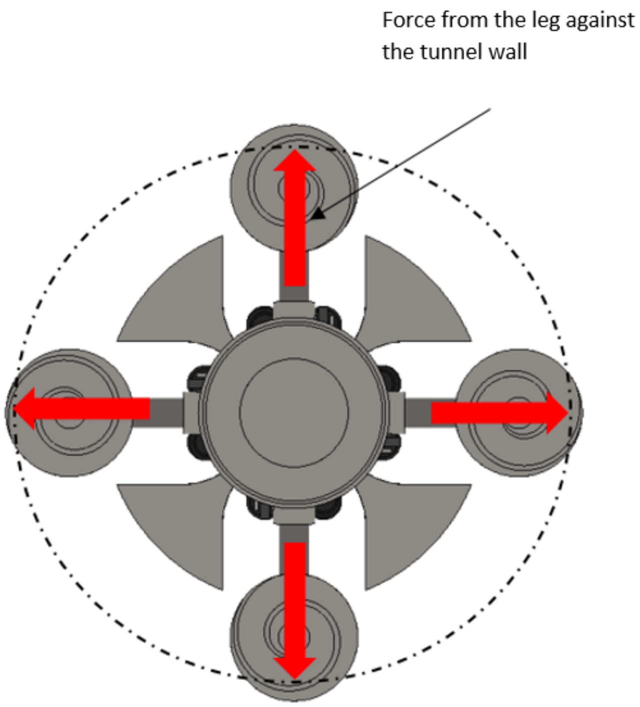


Figure 7 Screw's direction of the force when pressed against the tunnel’s wall

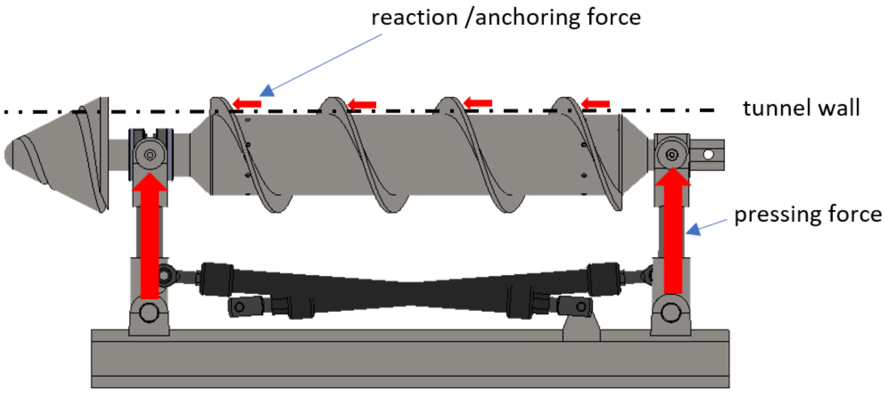


Figure 8 Anchoring force of the screw blade

The screw is powered by a water hydraulic motor and the leg movement is actuated by an artificial hydraulic muscle. When the hydraulic motors rotate the screws, the Robominer moves, and direction of movement depends on which direction the motors are rotated. The traction depends on friction between screw blade and the tunnels surface quality, rotation speed and screw pitch. Appendixes 3 and 6 present the calculated screw performance data.

Walking is realized by moving the legs one by one forwards or backwards while other leg is supporting the robot against the tunnel walls. For example (Figure 9) the robot releases and moves upper left screw (1) forward and then support it on the tunnel wall, then it releases and moves opposite (lower right) screw (2) forward and supports it on the wall. Then lower left (3) and after that upper right (4).

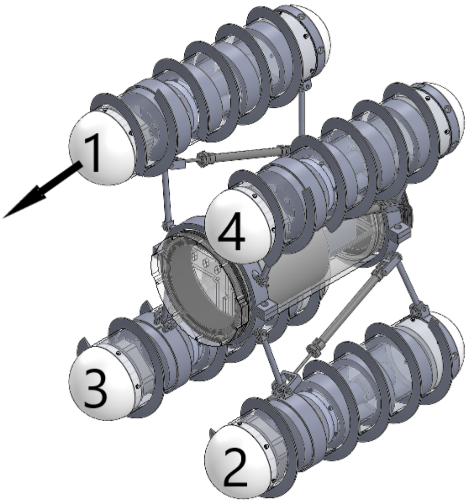


Figure 9 Laboratory scale model. Used to demonstrate the walking cycle

3.4.Actuation Principle

Multiple mechanisms have actuation needs in the Robominer to perform mining operations.

- Leg mechanisms, to lift the leg above an obstacle or push the leg against the mine wall for additional friction and to push screw back and forth axially
- Production tool manipulation mechanisms, to control the position of the production tool and to feed it
- Active module coupling mechanisms, to connect/disconnect the modules, articulated steering and to control the angle of the couplers during self-assembly.

The solution principle of actuation will be the same in each mechanism within the robominer. An open loop water hydraulic system will be used to power the robominers actuation needs. Using water as a pressure medium offer several important benefits

- High availability and low cost,
- Environmental friendliness,
- Non-flammability,
- High power-to-weight ratio.

As water will be used as the hydraulic medium, corrosion, low lubrication properties, and higher leakage flow between moving parts are drawbacks that must be considered when designing the actuation system.

To overcome some drawbacks of water as the pressure medium hydraulic artificial muscles (HAM) are used as linear actuators. Unlike conventional hydraulic cylinders, HAMs are single piece actuators. Pressure causes HAM’s elastomer body to expand, which shortens the actuator, hence exerting a pulling force. When compared to hydraulic cylinders, HAM also present a higher power-to-weight ratio, but lower displacements can be achieved. In addition, it must be noted that only a pulling force can be achieved with a HAM, whereas a conventional hydraulic cylinder can operate in both pulling and pushing direction.

A combination of HAM will be used as actuators, whenever possible to achieve the desired motion for each mechanism. Control of the actuators will be realized by fast digital hydraulic valves using digital hydraulic control principles /7/.

4. STRUCTURAL DESIGN CONCEPT OF ROBOTIC MINER

4.1.Body Module

The robominer has to be as small as possible in order to be able to operate in small diameter tunnels and deposits, such as old previously abandoned mines, and to be able to access mine through bore hole (Figure 10). Furthermore, small size is also a requirement for it to be able to mine efficiently small deposits and to operate with minimal environmental impact. Deliverable D 5.1 *Review document giving scope and examples of deposit types of interest* presents that in some cases efficient excavation of small ore veins require robominer to minimize extraction of waste rock. Minimizing the size of robominer is however kept on the level where miniaturization of components is not needed to enable using commercial of-the-shelf (COTS) components. Also, the harsh operation environment of the robot must be taken into consideration in robot design. Appendix 2 shows complete Robominer structure.

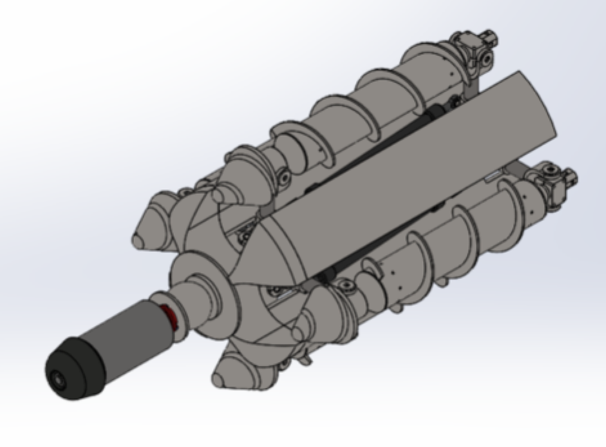


Figure 10 Robominer prototype design

The body module consists of the hull (Figure 10.), a nose dome and four screw-leg traction units. The hull consists of four separate compartments which are connected to the main structural beam Compartments are detachable to enable configuration changes in order to change robot’s capabilities (for example: Comminution, enhanced analysis etc.). Body modules diameter when the legs are fully retracted is Ø734 mm and the diameter of the hull is Ø600 mm (Figure 11.). The length of the body is 1300 mm (Figure 12).

Inside the hull there are (Figure 14.) bulkheads. These bulkheads are for supporting the structure and to give connection point for different components and wires which are going thru the module. There are mainly two different kinds of inner bulkheads, the other one is solid from the top for more support and the second one has an opening for easier wire (de-)assembly into the module.

Main structural beam is 100 x 100 x 10 mm square tube in the middle of the robominer. Beam carries all the loads in the structure, and it also acts as a cable duct for communication and power cables as well as water lines. Hull compartments are not water or pressure tight, but they merely offer mechanical protection for subsystems and components.

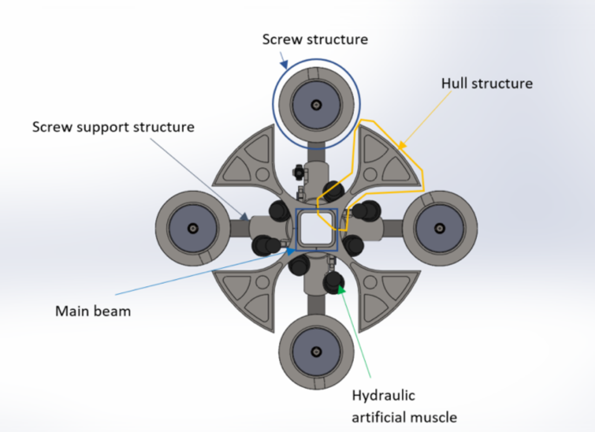


Figure 11 Longitudal cross-section of the robominer

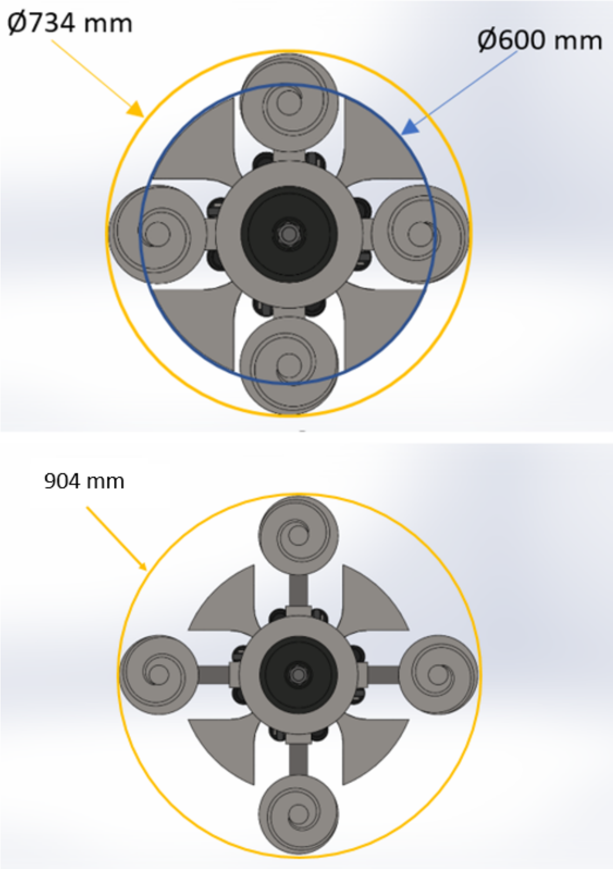


Figure 12 Robominer body module’s main diameters

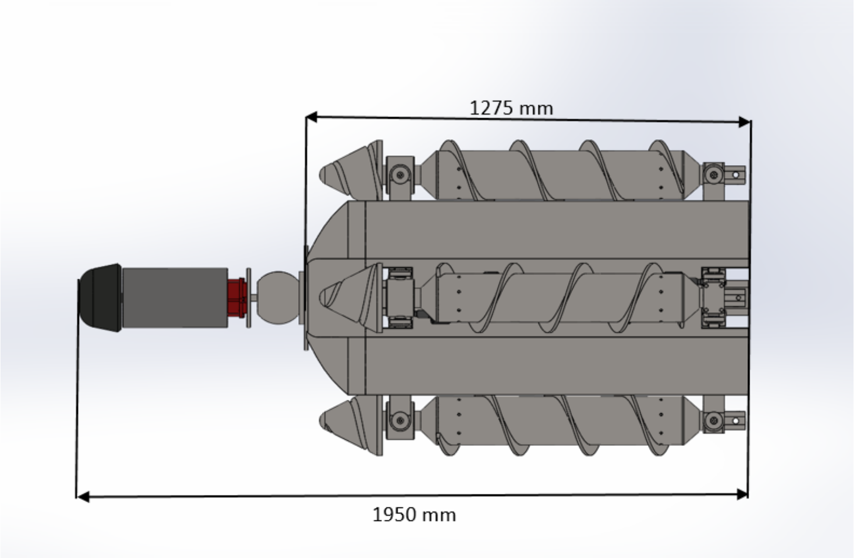


Figure 13 Length of robominer (body module and production tool)

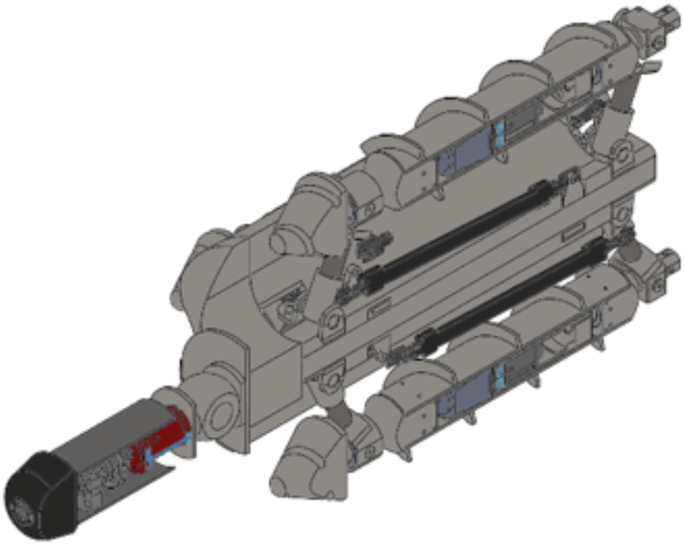


Figure 14. Body module's cross-section

Outer shell of compartments is supported with two bulkheads to increase rigidity and stiffness of the structure. The inner bulkheads (Figure 15.) are patterned with holes to allow piping and wiring and to attach subsystem components.

The fore end of the body module has a dome structure which acts also as a connection point for the production tool coupler. The dome is shell structure and will be designed to withstand the forces which the coupler and the attached production tool module generate.

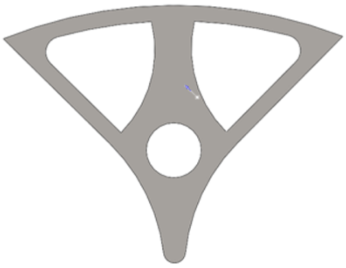


Figure 15 Bulkhead conceptual design

4.2.The Screw-Leg Locomotion System

The screw-leg locomotion system consists of the screw, screw support structure, two support struts (water hydraulic cylinders) (Figure 16) and two HAMs. The water hydraulic motor which is powering the screw through the gearbox is located inside the screw pipe. The gearbox lowers the motor's rotational speed to desired range (100-200 rpm) and increases the torque to 1000 Nm. (Figure 16). Batteries and other heavy components can be installed inside the screw. Inside the screw there is a wheel sensor which provides screws rotational speed, heading and slippage data to main computer.

Support struts are in principle water hydraulic cylinders (Figure 17). Cylinders move screws in radial direction of the body. Two HAMs are responsible of the longitudinal movement of the screw. The movement range of strut cylinders is 90 mm which means that the overall diameter of the robot can increase up to 904 mm (Figure 12.).

HAMs generate force only in one direction (retracting) and the force changes as a function of retraction following a logarithmic curve. Nominal length of HAMs is 550 mm. With 15 bar pressure and 10% contraction results in a force of 4000N. The HAM's calculations can be found on Appendix 5.

Front and rear strut cylinders have different designs (Figure 18). The front support includes screw front bearing. The end support connects directly to the shaft which is connected to the water hydraulic motor and gearbox which are driving the screw.

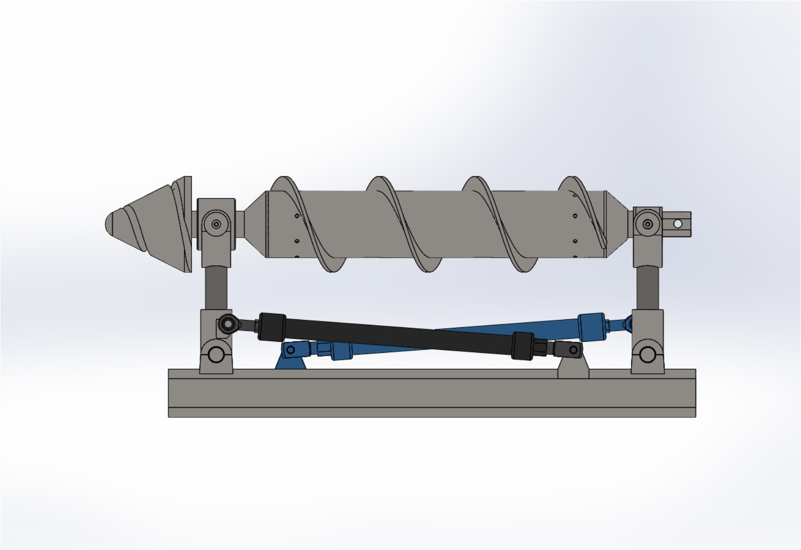


Figure 16 Screw-leg system conceptual design

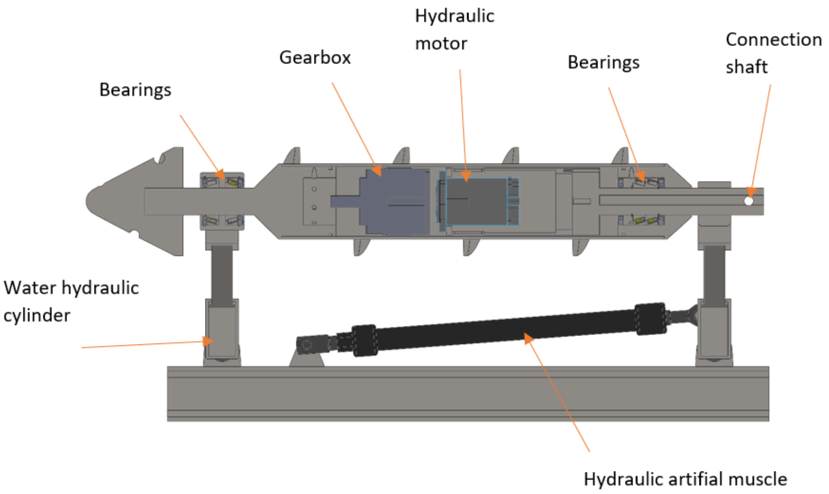


Figure 17 Lateral cross-section of the screw leg locomotion system

Figure 18 Support struts conceptual design.

Support struts can extend 90 mm, which means the robot diameter can change from 734 mm to 904 mm. The leg swivel to one direction is 30 degrees (half step 130 mm). This means the full step (from end to another) is 60 degrees and the step length is 260 mm. The movement of the screw-leg locomotion system (S-LLS) is shown in Figure 19. The movement range enables Robominer to step over obstacles, to adjust to various tunnel sizes, to have limited legged locomotion when needed and to keep traction when tunnel size varies.

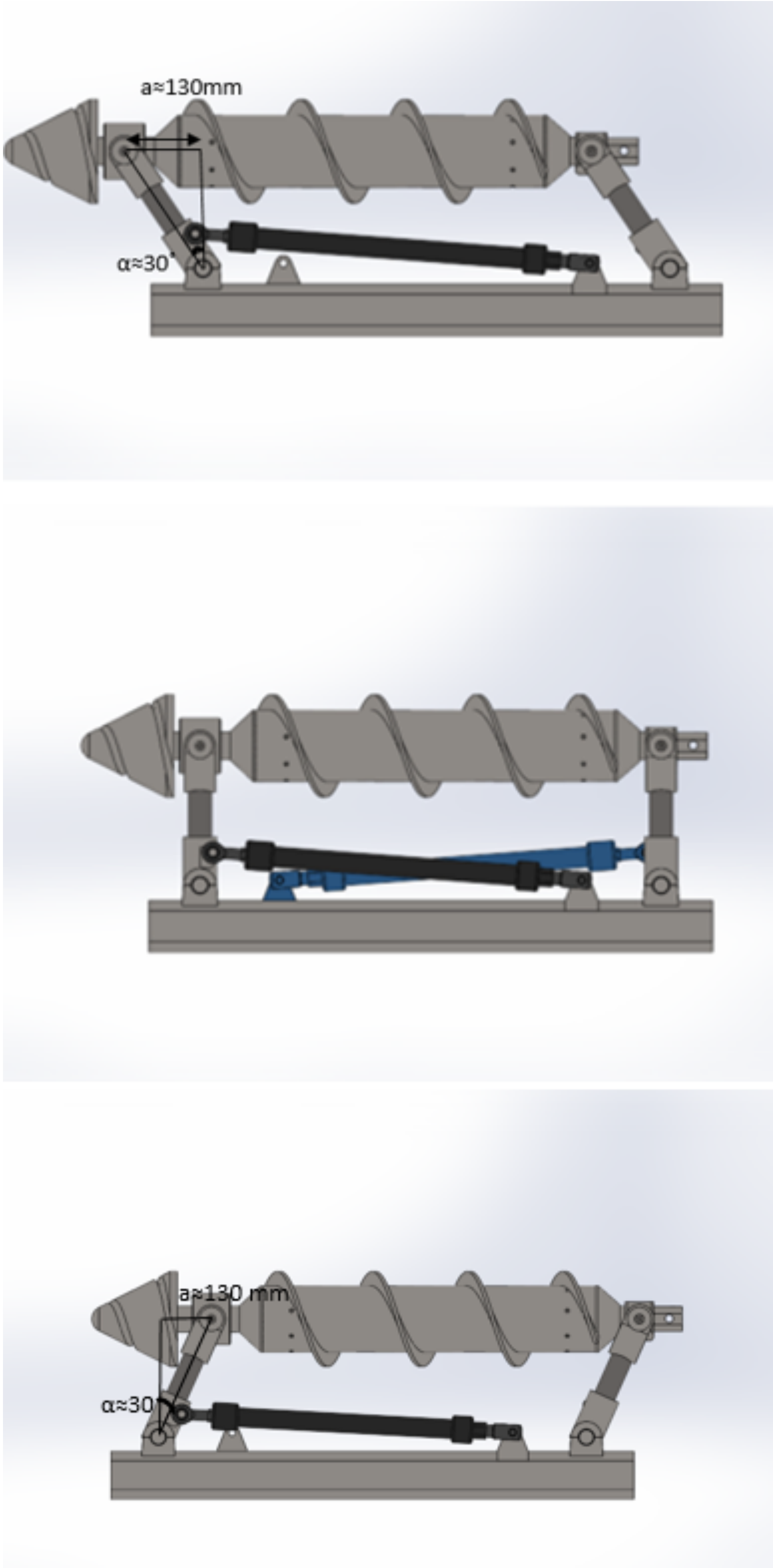


Figure 19 Screw-leg movement range

4.3. Production Tool System

The robominers production tool system includes an excavation, which extracts the material, and a material transportation system, which conveys the material from the rock face to the rear end of the robot.

4.3.1. Excavation

Tasks of the production tool are the extraction of rock and the excavation of tunnels for the robominer.

Excavation methods can be separated in drill and blast, mechanical, alternative and hybrid excavation technologies, whereas the first two listed are the most common in standard excavation engineering. The comparatively small weight and low available power are the most limiting factors. The interaction between an excavation tool and rock creates reaction forces, which the machine needs to be capable of handling. Those forces are depending on the rock strength (uniaxial compressive strength – UCS) to be excavated. The production tool needs to be adjusted to the desired excavation process. The material, environment, scope of application and the robot itself (power, weight) specify the boundary conditions for the excavation method. Important to mention is, that there is not a universally applicable excavation tool. Depending on the application scenario (dry, submerged, strength of rock) an appropriate excavation method is selected and afterwards dimensioned for the robominer. For the prototype and the accompanying field tests, the production tool unit will be a COTS product adjusted to the requirements.

Besides reasonable advance and excavation rates, the manoeuvrability of the excavation tool must be sufficient to ensure a flexible and mobile application.

Key parameters of the excavation unit are:

- Excavation rate / Advance rate
- Thrust force
- Selective mining ability

The robominer with given power of 30 kilowatts can mine up to 0,2 m^3 per hour and the production tools which is now under development is capable the excavate rock 0,5 to 2,0 m^3 per hour. This kind of rate is capable to achieved when the robot is giving all it power directly to drilling unit, but this is not plausible, because the robot also need to power on other components like rock transportation unit, muscles to move the drilling units boom and maybe also a crusher. That’s why the robominers excavating rate is smaller than the designed drilling units.

4.3.2. Excavated Rock Transportation

After the rock is excavated it must be transported to the rear end of the robot for further processing. For this reason, an appropriate conveying system needs to be implemented. Common rock / ore transportation is done with a track or track-less systems, mechanically or pneumatically / hydraulically. The excavation rate, particle size, particle size distribution, and layout of the mine are the deciding parameters for the selection of the transportation method.

After the rock has been excavated it might need to be crushed into smaller pieces to make transportation possible. The excavated material can be transported with a pumping unit which can be included in the robot. The excavated rock is sucked from under the robot or near the drilling head with a collar. these methods are shown in Figure 20. and 21. From this phase, the loose pieces of rock are fed to transportation pipe with the pumping unit which is in the robots one module or as a separated unit which is connected to robot’s main beam. The pumping unit cannot pump or move the loose pieces by itself so it might need a separate pumping unit/module to help it to move excavated rock to the surface.

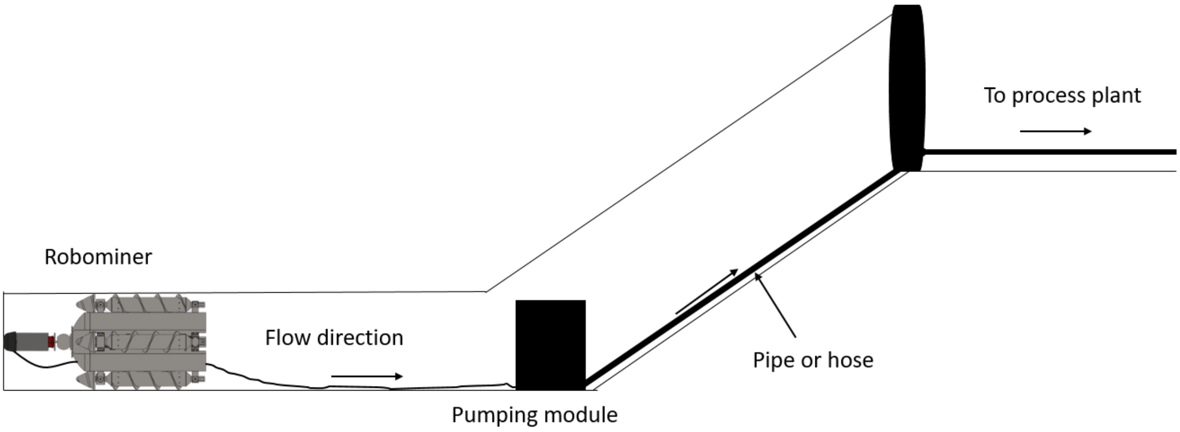


Figure 20 Excavated rocks/pieces transportation system directly from the cutting head with collar

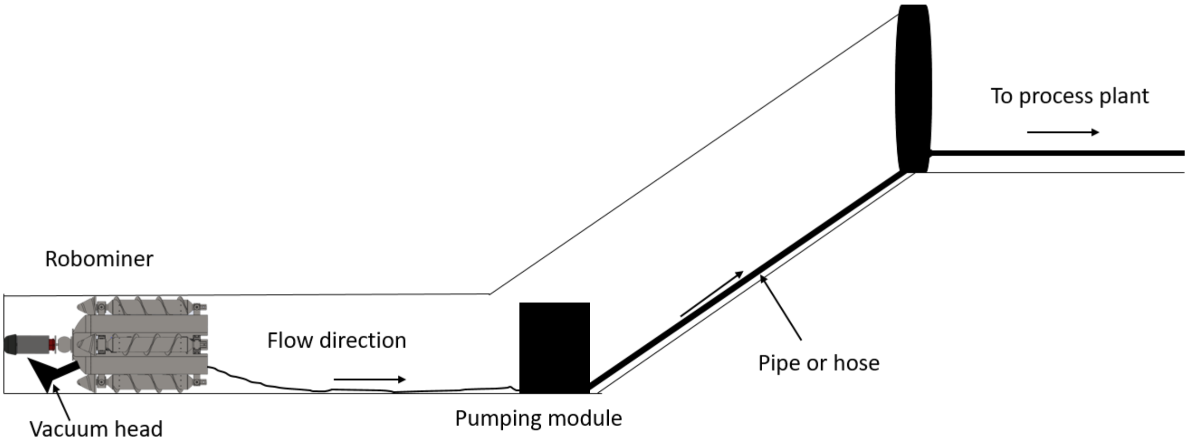


Figure 21 Vacuum head transportation system

The transportation system realized in the prototype used for demonstrations will be selected on the basis of demonstration site and its requirements.

4.4.Production Tool

The production tool needs to be small, but capable, to excavate small amounts of minerals for analysis and capable to selective mining. In the *WP6.5: Production tools conceptualization and research at TRL-3, Paper: Investigation on different excavation methods by M., Berner (2019)* is studied different mining methods how they fit in the robominer concept and answers to its various requirements. (Figure 22)

The production tool consists of the main production tool, gearbox, coupling to the water hydraulic motor, collar for the ore and the side rock collection in addition to a protection hull for the motor and gearbox. The production tool is connected directly to robot's body with active module coupling system which provides movement to all directions. The production tool is aimed to excavate 50 MPa hard rock. (Figures 23 and 24)

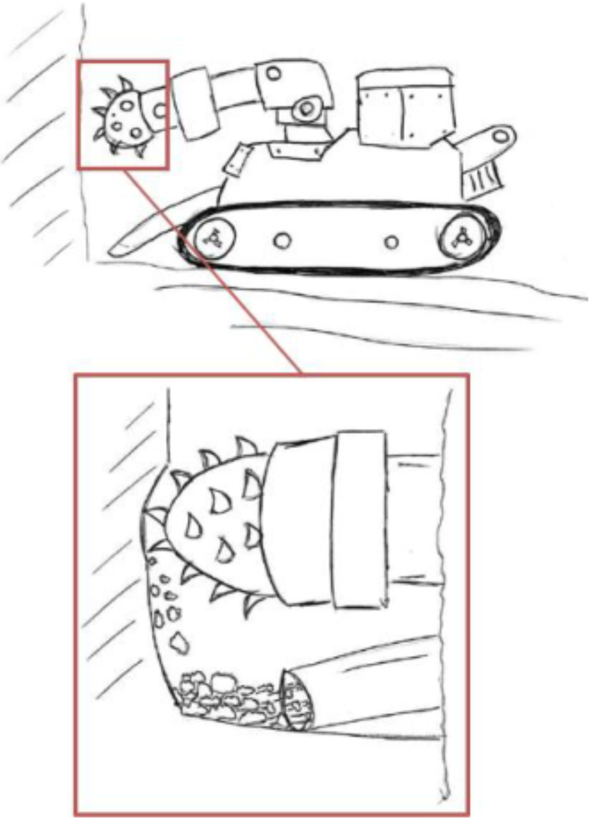


Figure 22 Sketch of the robominer with a cutter from WP 6.5: Paper: Investigations on different excavation methods.

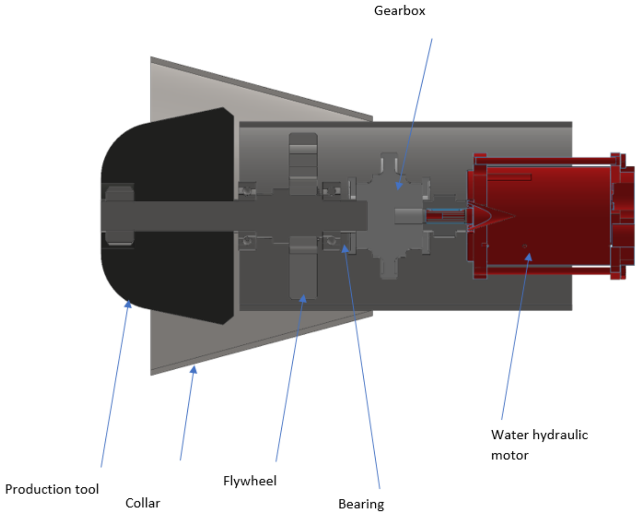


Figure 23 Longitudal cross-section of the production tool

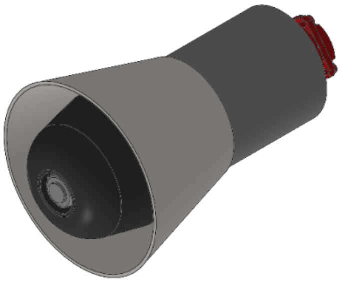


Figure 24 Production tool

4.5.Crusher and Slurry Management System

The size of the ground pieces can be estimated using the parameters of the production tool. In addition, the rock to be worked on can shatter and possibly drop during the excavation phase. This leads to a situation where rock size can be bigger than the slurry pumping system can tolerate. To overcome this, Robominer will be equipped with a crusher. The crusher provides even rock size after it. The crusher can replace one of the compartments on Robominer body module.

4.6.Active Module Coupling Unit

Concepts for the self-locking, self-aligning active module coupling unit are presented in Figure 25. The coupling unit will allow 3 rotational DOF to be precisely controlled through water hydraulic actuators. The coupling unit is self-aligning and self-locking because of its structural shape. In the D3.1 there was recommended that the coupler have 6 DOF, but in this design solution has only three. Other three are combinations of moving the modules and the coupler. With this change the design of the coupler can be simpler and more robust. The spring will push back the pivot link once the 2 parts are coupled and aligned.

The presented concepts consist of

1) Module n°1,
2) Pivot link,
3) Hydraulic artificial muscles,
4) Ball joint,
5) Automatic coupler body,
6) Spring/hydraulic artificial muscle actuator,
7) Pivot link,
8) Multi-connector device,
9) Module n°2.

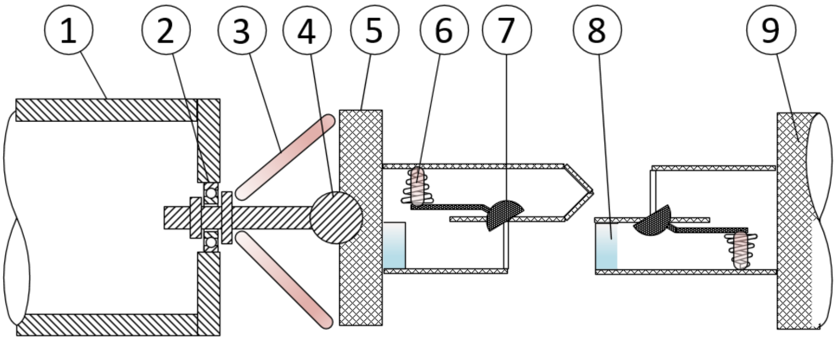


Figure 25 Concept for the active module coupling unit

Multi-connectors will be used to automatically connect and disconnect electric and hydraulic power lines, as well as communication lines for embarked electronics. Flushing will be necessary in order to clean dirt from the connectors and allow coupling.

A variant of the automatic coupler body is presented in Figure 26Figure 26. In this concept, the pivot link is replaced with spherical connections. The multi-connector device is not shown.

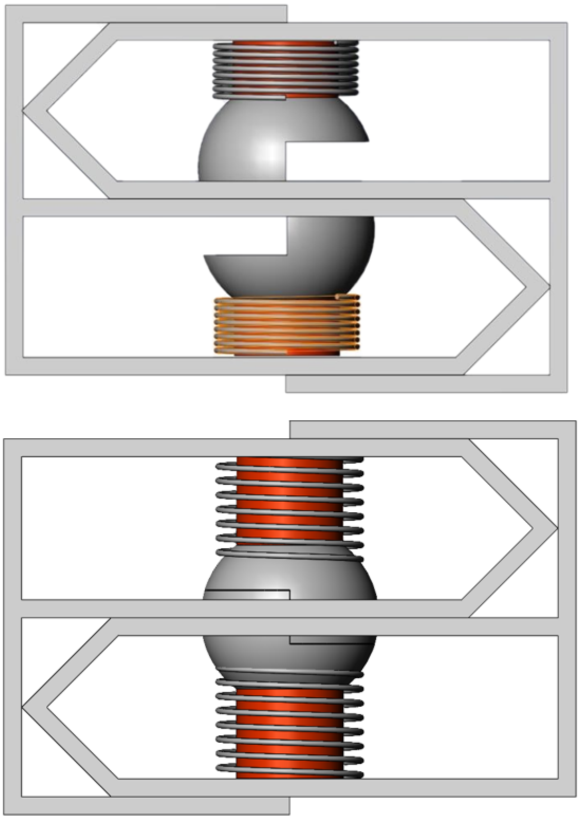


Figure 26 Automatic coupler body concept. Upper figure shows open position and bottom figure close position.

4.7.Hydraulic System

High-pressure water hydraulic system (Figure 27) is used to power all actuators (HAMs, hydraulic motors etc.) of the robominer. The system consists of a ground level station, underground substation, and the hydraulics in robominer module (Figure 28).

In the prototype robominer the high-pressure water hydraulic system is powered by a water hydraulic power pack which is in the ground level. The water hydraulic system has open loop system structure, which means that the pressure medium is not circulated back to power pack. Return flow of actuators is released to the mine and can thus be used for flushing various robominer components which may need to be cleaned from debris. The power pack takes in fresh water in through a filtration unit.

The purpose of underground substation is to make the tether more manageable for the robominer. Ground level station and underground substation are connected by a tether incorporating large diameter hydraulic hose and communication cables in the same bundle. In underground substation hydraulic hose diameter is decreased to reduce the moving tether weight and cables are routed inside the hose to protect cables. Underground substation will also include an automatic tether reel which keeps the length of tether between the robominer and the substation right for the distance in between them.

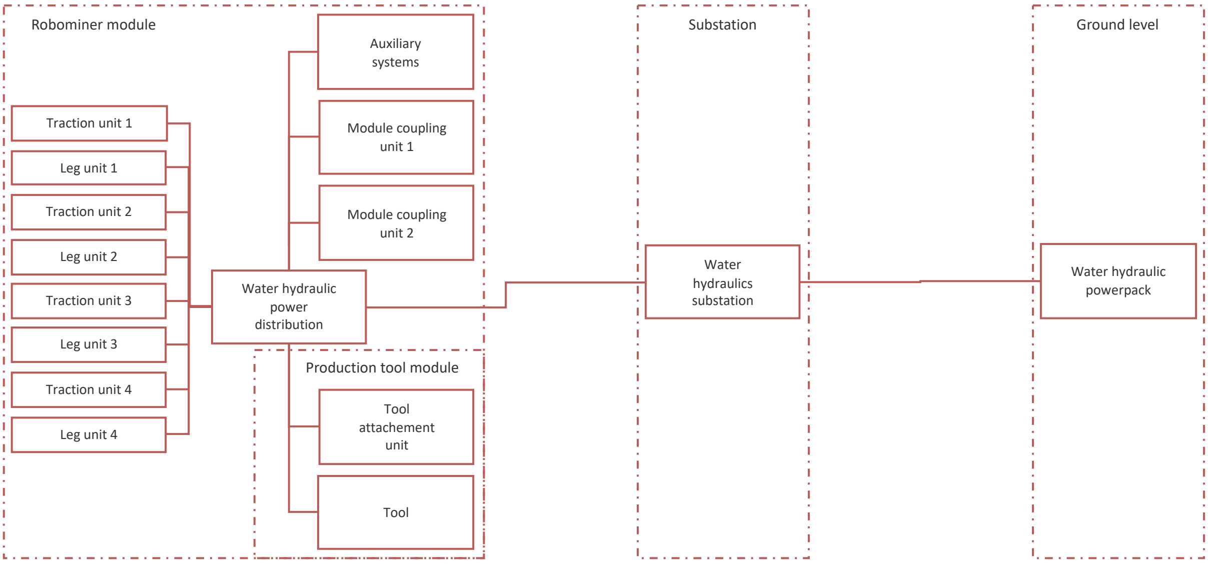


Figure 27 Hydraulic system

The robominer body module will include all active components of the hydraulic system. To increase reliability, the hydraulic system will be divided in independent and functional subsystem:

- Traction unit 1…4
- Leg unit 1…4
- Power distribution
- Tool attachment unit
- Tool
- Auxiliary systems
- Module coupling unit 1..2

Each subsystem includes actuators, control valves and auxiliary valves required for the operation. Subsystems will be integrated units incorporating control electronics and all valves in the same valve block which is located very close to actuators.

Power distribution unit has the safety valves required to prevent total power loss in case of hydraulic system failures and to control the division of available power in case of control system failures. Subsystems have different priorities according to their importance for the survivability of the robominer. Leg and traction units have the highest priority. Coupling units have the second highest priority. Tool and tool attachment are the third and auxiliary systems are the least important. During normal operation priorities are handled by the control system which will prioritize and sequence functions so that power limit is respected, for example prevent moving and drilling at the same time. Power division in case of control system failures are controlled by priority valves. Total loss of power is prevented by line rupture safety valves.

Low-pressure water system (*Figure 28*8) is the only hydraulic auxiliary system in the robominer. The system consists of pressure converter which uses high pressure water flow to create low pressure flow (for example centrifugal pump driven by water hydraulic motor). Low pressure water system can be for example used to supply drilling fluid to production tool or water flow for ore transport.

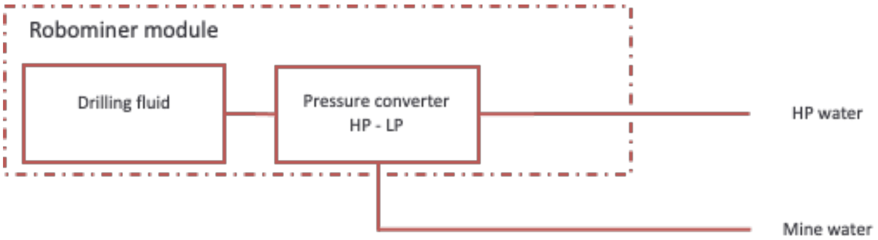


Figure 28 Low pressure water system

4.8. Electric system, electronics, and low-level control system

Robot, and modules working with it, will communicate via ROS2-messages over the Ethernet up to speed of one gigabit/s. Communication inside of the separate modules can be arranged as needed for best performance. Interaction between modules happen using ROS2.

Electricity will be supplied to the robominer via cable. In the context of prototype, voltage will be low enough to allow working with the system without special permission demand for the persons. Direct current 48 V is chosen due to general availability. For the general mobility cable can't be too big or heavy and better if it can be installed inside of the water hydraulic hose. For these reasons 4mm^2 was chosen to be cross sectional area of the conductor. Two conductors are needed. Voltage loss with 3 A current in 100m cable is shown in Table 1.

Table 1 Voltage and power losses of the cable

Temperature (°C)	Voltage loss (V)	Power loss (W)
0	2.4	7.0
20	2.6	7.6
85	3.2	9.6

Electric power will be used to charge battery pack which provides power for more demanding short-term needs, up to multiple kilowatts. As the constant power is smaller than expected peaks and robot is made of multiple modules, power distribution must be controlled. Every module, inside of the body module or outside of it, will get only small amount or current allowance (200mA) in the first hand. Modules can negotiate over the ROS-messaging with the main controller if they need more power. Modules must also respect the order to save power when controller decides.

Table 2 Available voltages and currents

Position	Connection	Voltage (V)	Current (A)
internal	Wired	48	100 (1 min)
internal	Wired	5	10
external	Wired	48	100 (1 min)
external	wireless, Qi	5	1 (limited by Qi)

Battery pack is made of 12 serial connected lithium-polymer batteries (LiPo). Voltage will be seen directly in 48Vdc connection, and it will fluctuate between 39.6V-50.4V. All modules must survive possible under voltage situations and recover without intervention. Internal 5V is regulated. External power of 5V is supplied with Qi-standard wireless power transmission. Wireless power is attenuated in the salt water in millimetres. Water in mines is always saline. For these reasons, the external module must have an antenna touching specific areas of body module.

Network inside the body module will connect with cables. Network for modules outside of the body module will connect with Wi-Fi 802.11n single antenna. Wi-Fi-signal is attenuated in the salt water in tens of millimetres. For that reason, external module must have antenna touching or very close to specific areas of the body module.

Figure 29 represents power and network interactions between robominer and its modules. Figure 30 shows the complete power system with its ground and underground support modules (Chapter **Error! Reference source not found.**).

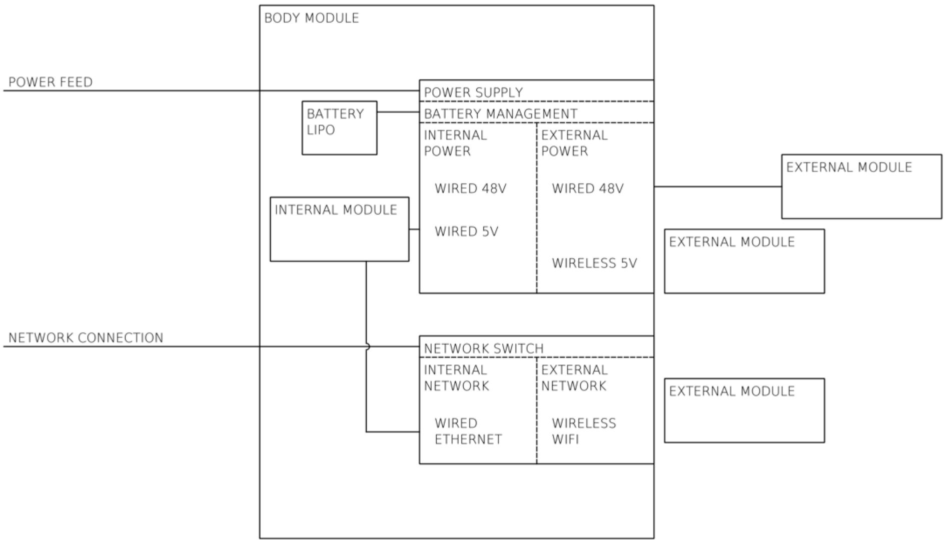


Figure 29 Network and power connections

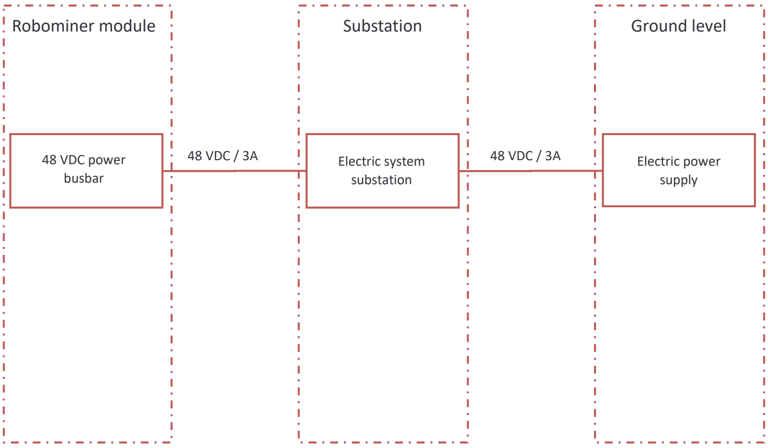


Figure 30 Electric power system

5. CONCLUSIONS

The robominer robot will have a modular structure which enables it to be configured to different tasks. This report presents a versatile and modular structure which consists of the production tool module and the body module. Body module can be fitted with various mining and sensing hardware which makes it possible to have body modules for different tasks and scenarios which can then be combined with different production tool modules. Also combining multiple body modules to form a snake-like structure is possible. This increases the traction capability of the robominer but also increases the number of capabilities which can be included in one robominer. The production tool module can be used as a carriage for the multitude of different production tools and sensors.

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APPENDIX 1 ROBOMINER TECHNICAL REQUIREMENT SPECIFICATION TABLE

Locomotion

Articulated screw propulsion with four screw units	High traction	All screws are pushed against tunnel walls
	Reliability and survivability	Simple compared to fully articulated legs, track or wheels
	Modular	

Production capability

Extraction capability	0,2 m^3/h solid rock
Rock transport capability	0,2 m^3/h
Excavation capability	Max. 100 MPa uniaxial compressive strength

Operational Case Scenarios

Three case scenarios	Operating abandoned mines with known remaining unfeasible 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, Cornwall

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 circulation 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 obstacle
		Capability to increase traction
Module coupling	Max 6 DOF active coupling	
	Capable to articulated steering between modules	
	Module docking function	Relative locating 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 module	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 Availability

Durability	System robustness	One year in mine conditions*
	System endurance	Robot has to be able to self-replace wear parts*
		Robot has to carry wear parts *
		One-year autonomous operation time *
Survivability	Robot must 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 fiber)
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

APPENDIX 2 SUPPORT METHODS

Hard-Rock Ground Control with Steel Mesh and Shotcrete

- Steel mesh and shotcrete supply *Surface Support*
    - Surface support was traditionally installed to stabilize wedges and blocks between internal reinforcement means that may fall as loose rock into opening
- Internal reinforcement holds or pins larger blocks
    - Surface support catches loose that fails
    - Surface support is also useful as a fallback in case subsequent mining in local areas cause stresses to increase in the opening
    - Stresses acting on opening (1) from another opening (2) within three opening diameters of opening (1) affects the stresses acting on the rock mass of opening (1)
- Systematic use of surface support is advisable in underground mines
    - Loose failing would increase the risk of damage to a robotic machine underground
    - Surface support catches smaller blocks of loose
    - Surface support is also handy in the circumstance when changing stresses in the mine cause loose rock to fail
    - In extreme circumstances, initial loose failure could be the precursor to a succession making underground areas inaccessible
- Steel mesh, straps, and shotcrete are surface support elements used for hard rock
    - Steel mesh catches pieces of loose rock
    - Steel mesh used in the mining industry includes welded-wire mesh (weld mesh) and chain-link mesh
    - Straps used to containing rock cross between reinforcement elements and distribute load between reinforcement elements
    - Shotcrete that is applied consistently on a surface provides a catching mechanism that can rely on the surrounding shotcrete to counteract

Welded-wire mesh

- Welded-wire mesh describes a mesh where the wires are welded together at each wire intersection as shown in Figure 31
    - It is available in sheet form. In Australia and North America, the sheet sizes are usually about two meters by three meters and 1.2 to 1.5 meters by three meters respectively.
    - The larger sheets entail that less sheets have to be installed and higher productivity
    - Smaller sheets in NA require more manual handling

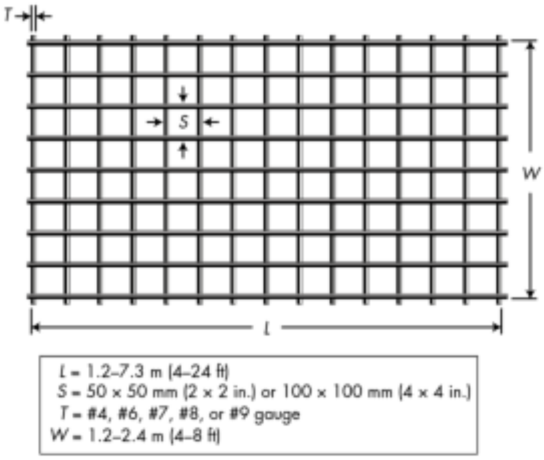


Figure 31 Welded Wire Mesh (typical dimensions) (Hadjigeorgiou & Potvin, 2011, p. 574)

- The space between the wire or mesh aperture is determined by the largest rock size that can pass through these holes
    - in North America, the aperture size is often standardized at 100 millimeters by 100 millimeters
    - when smaller aperture sizes of 50 millimeter by 50 millimeter and 75 millimeters by 75 millimeters are used, the blocks would have to be smaller in order to pass through.
    - Because more rock could potentially rest on the mesh, the sheets would have to be capable to bear greater loads
    - larger aperture sizes such as 150 millimeters by 150 millimeters can be used if shotcrete is sprayed over the mesh which allows more shotcrete to penetrate through the mesh
- Wire thickness is denoted by the gauge.
    - Common sizes used in North America are #4 gauge (approximately 5.8-millimeter thickness), #6 gauge (approximately 4.9-millimeter thickness) & #9 gauge (approximately 3.7 millimeter thickness)
    - The thinner wire meshes are more susceptible to damage by fly rock when blasting but as the wire gets thicker, it is more difficult to install the mesh around corners
- Welded wire mesh can be installed to threaded rock bolts
    - This is accomplished by installing it underneath pressure plates that are fitted over these installed rock bolts with threaded bars
    - It can support small blocks in the mesh
    - It can provide some control during rock bursts
    - When installing welded-wire mesh:
    - Effort must be made to ensure that the mesh sheets installed tightly against rock mass surface.
    - When the mesh is installed tightly, this would reduce the distance a rock would have to fall into the mesh which would increase the energy imparted from failed rock to the mesh.
    - It would also decrease the likelihood of rock collecting in one area increasing

    - the load on the rock mass
    - Overlap between mesh sheets decreases the likelihood of rock falling out the sides of the mesh
    - A standard practice is to overlap mesh by three squares
- Failures can occur at the weld point where the wires of the welded wire mesh overlap
    - Poor weld points could be the result of poor-quality welding or the heat used to weld the wires together to form the weld could weaken the wire
    - The weld capacity and the wire strength should be close to equal

Chain link mesh

- Chain link mesh involves a wire interlocking with one wire on one side followed by interlocking with another wire on the other side.
    - This interlocking pattern is repeated throughout the wire length
    - The other wires follow the same pattern and after interlocking with the central wire discussed they interlock with other wires on the other side of them

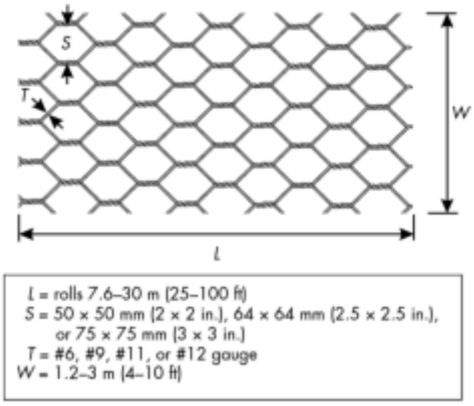


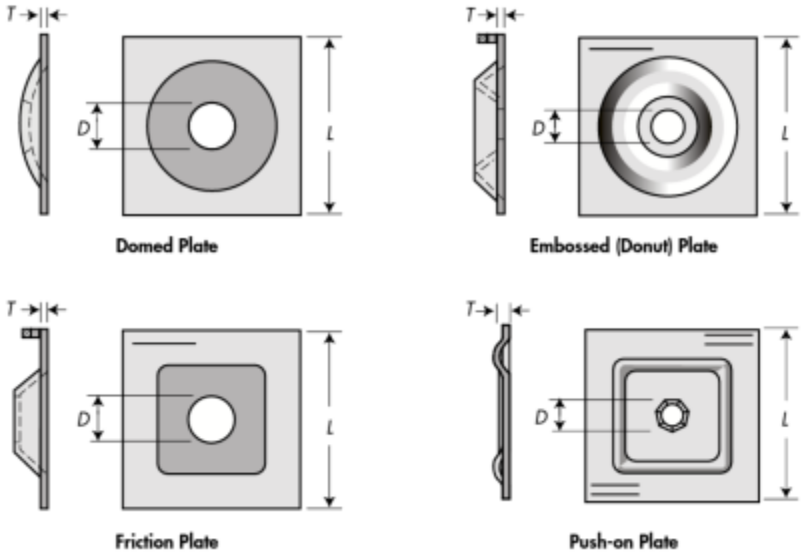
Figure 32 Chain-link mesh (typical dimensions) (Hadjigeorgiou & Potvin, 2011, p. 576)

- Can absorb a greater amount of energy than welded-wire mesh
    - This is related to its greater displacement capacity
    - The handling and installation of this mesh requires that the rolls need to be gradually and manually unrolled while it is being installed against the rock surface
    - This is labor intensive and it is difficult to mechanize
- it does absorb more energy than welded wire mesh
    - This is linked to its greater displacement capacity due to the fact that the rigidity is lower
    - In Canada, #9-gauge wire (approximately 3.7 millimeter) is commonly used
- high-tensile, light steel chain link mesh can be used when extra load-bearing capacity required

Load transfer between mesh and reinforcement

- A standard is for bolts to be spaced about 1-1.5 meters apart

  - Therefore, the maximum weight that would fall between the bolts is approximately 2 tons
  - These blocks of rock put a weight on the mesh
  - This force transmits through the mesh to the bolt plate
  - It then transmits to the bolt
  - The force in the bolt transmits back to the plate
- The bolt plates can cut the wire mesh
  - This can be rectified by ensuring the force from the bolt is transmitted over a larger area by using larger plates
  - Other means to rectify this is to use plates that are shaped, thin, deformable or flexible
  - Common types of bolt plates used to install mesh are shown in Figure 33



Domed Plate
Embossed (Donut) Plate
Friction Plate
Push-on Plate

Figure 33 Common Types of Bolt Plates Used to Install Mesh (Hadjigeorgiou & Potvin, 2011, p. 577)

- Mesh displaces as it is loaded
  - The bolts that support it if grouted allow only a few millimeters before failure but have a load capacity in the range of 150-200 kilo Newtons
  - The mesh has a load capacity of only 20-40 kilo Newtons
  - However, it can displace 100-350 millimeters
  - If either of these are exceeded, the mesh is incapable of transmitting the load to the bolts
  - This can be precluded by using tighter bolting patterns which would ensure that the rock bolts would be smaller before they fail

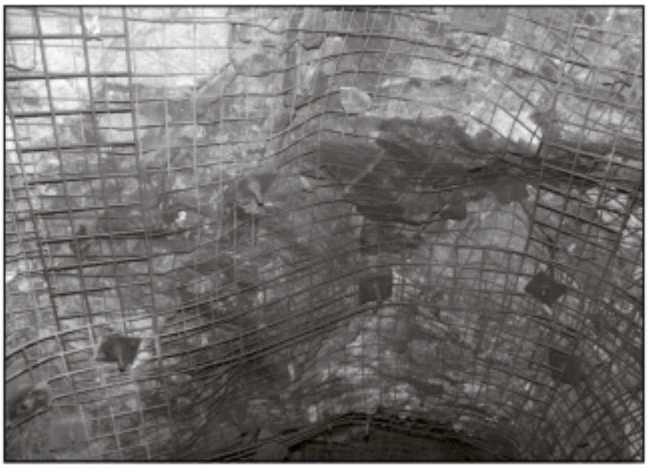
Straps

- Straps usually not part of a support system design
- They can be installed against the rock surface or over mesh
- It is in close contact with the rock mass
  - Extra strength and stiffness is provided to the surface support
  - Support blocks of rock between bolts

  - Monitoring essential to ensure that the straps support rock that is part of the *in situ* set
  - If the rock loosens and fails, the strap may no longer have a good contact
  - In this instance, it will probably no longer be effective
- Types of straps are steel straps, mesh straps and Osro straps
- ***Steel Straps*** are long and rectangular
  - They are fixed in place by rock bolts being inserted into holes already present
  - These preperforated holes may not be in ideal locations for rock bolt holes to be collared and drilled due to the irregular rock mass surface
  - If the holes cannot be collared and drilled within a designed range, they may not be tight to the rock mass

Figure 34 Plain Steel Strap (Hadjigeorgiou & Potvin, 2011, p. 578)

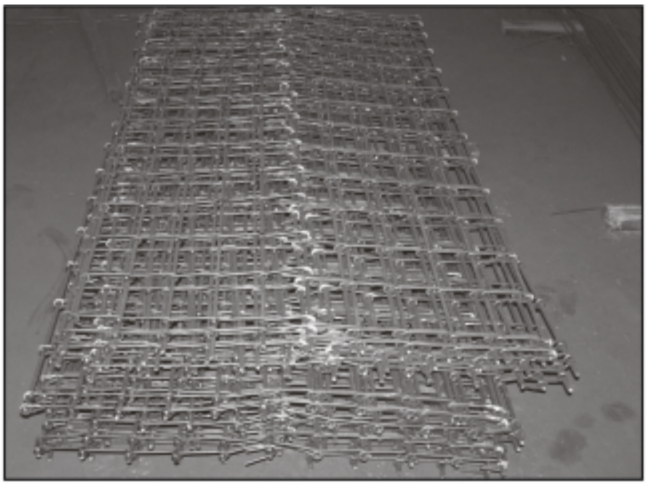
- ***Mesh Straps*** are bands of welded wire mesh of #0 gauge (approximately 7.8 millimeters thickness
  - Bolts can be installed at convenient locations through the mesh because not constrained to drilling through pre-perforated holes



Courtesy of the Australian Centre for Geomechanics.

Figure 35 Mesh Straps Installed over Mesh (Hadjigeorgiou & Potvin, 2011, p. 578)

- ***Osro (Oslo) Straps***
  - These consist of a set of longitudinal, parallel, round and smooth set bars
  - These bars are attached with strapping crossbars tag are loosely twisted around the set bars
  - This allows free movement of the set bars
  - These bars have a high ductility and energy absorption capacity which means they support they provide continues even if there in larger deformation or more dynamic events than for steel straps and mesh straps



Courtesy of ATM Components Republic of South Africa.

Figure 36 Osro Straps (Hadjigeorgiou & Potvin, 2011, p. 579)

- ***Cable Lacing***
  - Shown in Figure 37
  - Destranded & degreased hoisting cable bolts is put over wire mesh or shotcrete
  - This forms a cable web
  - This cable web has a high load bearing capacity and allows for deformation in the rock mass
  - This method is practiced in rock-burst prone areas in South African mines
  - This technique is labor-intensive
  - Rarely used in countries practicing mechanized mining

Courtesy of the Australian Centre for Geomechanics.

Figure 37 Cable Lacing in a South African Mine (Hadjigeorgiou & Potvin, 2011, p. 579)

Shotcrete

- Concrete applied to rock surface at high velocity
    - Conducted with specialized equipment that pneumatically shoots the concrete
    - When it is first applied, much of the shotcrete does not stay on the rock but ‘rebounds’
    - As the shotcrete gets thicker, the rebound decreases
    - When estimating the quantity of shotcrete required, the roughness factor must first be determined
    - The roughness factor can be estimated using Table 3
    - After the roughness factor is determined, this number is used in Table 4
    - It does depend on the thickness of shotcrete desired and some interpolation is required
    - Note that thicknesses of shotcrete desired is directly related to the roughness factor
    - Therefore, thicker layers of shotcrete are needed for poorer ground

Table 3 Determination of the roughness factor based on ground condition and drill-and-blast process (Hadjigeorgiou & Potvin, 2011, p. 583)

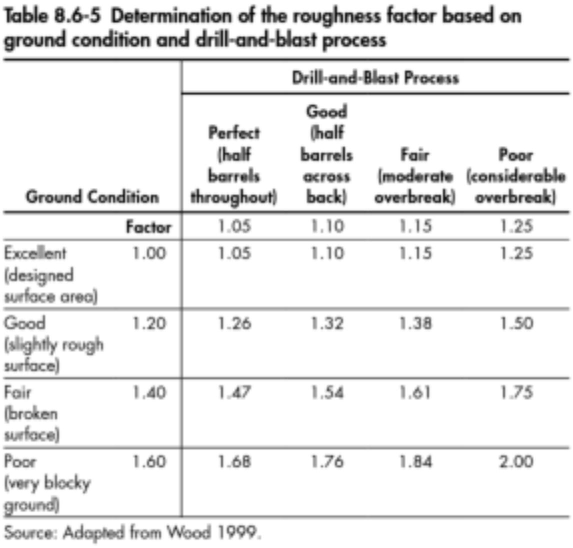


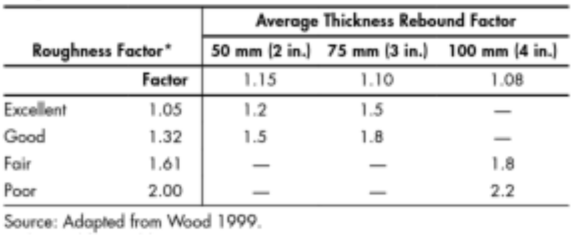
Table 8.6-5 Determination of the roughness factor based on ground condition and drill-and-blast process

Ground Condition		Drill-and-Blast Process Perfect (half barrels throughout)	Good (half barrels across back)	Fair (moderate overbreak)	Poor (considerable overbreak)
	Factor	1.05	1.10	1.15	1.25
Excellent (designed surface area)	1.00	1.05	1.10	1.15	1.25
Good (slightly rough surface)	1.20	1.26	1.32	1.38	1.50
Fair (broken surface)	1.40	1.47	1.54	1.61	1.75
Poor (very blocky ground)	1.60	1.68	1.76	1.84	2.00

Source: Adapted from Wood 1999.

- As the
    - Concrete comprised of 15-20% cement, 30-40% coarse aggregates, 40-50% fine aggregates, and 2-5% additives (Hadjigeorgiou & Potvin, 2011, pp. 580-581)
    - Clean water that is free of chemicals that are detrimental to the reaction is added to the concrete mix
    - The water hydrates the cement & starts the curing process that gives the concrete strength

Table 4 Determination of the volume factor based on roughness and thickness rebound factors – note * is obtained from Table 1 (Hadjigeorgiou & Potvin, 2011, p. 584)



Roughness Factor*		Average Thickness Rebound Factor		
		50 mm (2 in.)	75 mm (3 in.)	100 mm (4 in.)
	Factor	1.15	1.10	1.08
Excellent	1.05	1.2	1.5	—
Good	1.32	1.5	1.8	—
Fair	1.61	—	—	1.8
Poor	2.00	—	—	2.2

Source: Adapted from Wood 1999.

- Shotcrete provides more protection from rock if it can bond with the *in situ* rock mass
  - this is accomplished by preparing the surface
  - removing or scaling loose rock
  - both these actions can be accomplished with high pressure water jets
- Once the shotcrete is applied, it has a glue-like effect on the broken rock mass
  - If the shotcrete is applied correctly, a uniform surface is created
  - Therefore, blocks that have to be caught do not detach from the shotcrete
- The shotcrete can be applied in-cycle immediately following a blast
  - Deterioration over time is prevented by shotcrete application
  - Bolts can pin the shotcrete to the wall after the shotcrete is applied
  - However, geomechanical data cannot be collected from the rock that is blasted
- Shotcrete can be mixed with water directly before it is applied or at a mixing station that is away from where shotcrete is applied
  - These two times to mix the shotcrete are referred to as the dry-mix technique and the wet-mix technique respectively
  - If the dry mixing technique is used, the concrete does not begin curing before it is applied
  - However, this will mean more dust is generated
  - The main concern for Robominers in this instance is that visibility would be restricted
  - With guns used for dry-mixing are batch-single chamber, batch double chamber, or rotary continuous feed guns

1. Batch single chamber: chamber stocked with shotcrete, the chamber is pressurized, and the shotcrete is applied until the chamber is empty, shotcreting stops, and the chamber is recharged.
2. Batch double chamber gun: one chamber below the other; both chambers are air locked; while the lower chamber is mixing dry shotcrete with water and discharging to the rock outside, the upper chamber is being filled with dry shotcrete; when the two chambers are equal in pressure, the contents of the upper chamber is transferred to the lower chamber; this leads to continuous operation
3. Rotary continuous feed gun:

- When using the wet-mix technique, there is a time constraint in ensuring the shotcrete arrives at the working face before work is conducted

  - It would be easier to mechanize
  - Not as much dust would be generated
  - Logistics is important to ensure it does not cure too much before application
- Wet mix is conducted by slugs of material added at the delivery hose
  - Compressed air ensures the slug flows out to the delivery hose
  - Shotcrete is pushed into the hose in a continuous stream by mechanical, air, or hydraulic pressure
  - Air is injected at the nozzle
  - This breaks the stream and increases exit velocity
- Shotcrete is brittle
  - It has a high compressive strength
  - Tensile and flexural strengths markedly lower
  - This can be countered by reinforcing the shotcrete
  - In mining, two common means of reinforcement is to use mesh-reinforced shotcrete and fiber-reinforced shotcrete

Mesh-Reinforced Shotcrete

- When shotcrete started being commonly used, it was applied over the mesh as a response to deteriorating ground conditions
  - This served to control ground falls
  - It is now used where difficult ground conditions are anticipated
- When ground conditions were particularly friable: shotcrete is applied first.
  - This is then followed by mesh
  - Finally, another layer of shotcrete is applied over the mesh
  - This maintains much of its load capacity after the shotcrete cracks
  - The shotcrete cracks when the shotcrete deformation causes it to move more than 10-20 millimeters
  - This results in the wires being subjected to point load by the shotcrete crack causing them to fail in tension

Fiber-Reinforced Shotcrete

- Steel or synthetic fibers with high tensile strength can be added to the shotcrete
  - These fibers do not effect shotcrete resistance to deformation
  - When the strength of the concrete is exceeded and the shotcrete starts to crack, the fibers bridge the cracks and prevent further opening of the cracks
  - These enhance the flow resistance of the fibers within the concrete
  - This act of bridging allows the yielding shotcrete to maintain its load-displacement capacity

Courtesy of the Australian Centre for Geomechanics.

Figure 38 Fibre-reinforced Shotcrete, Showing Fibres Bridging Cracks (Hadjigeorgiou & Potvin, 2011, p. 581)

- The bridging action is augmented by hooks or cavities in the shotcrete fibres
  - ➢ Bridging is more effective the higher the length/diameter aspect ratio
  - ➢ It is more likely that cracks will be bridged if the amount of fibres within the concrete increases
- Testing: EFNARC Test – RDP Test

Shotcrete stresses

- Shotcrete provides surface support
  - ➢ The effectiveness of this support depends on the adhesion and shear strength between the rock and the shotcrete
  - ➢ The effectiveness is also influenced by the flexural strength of the shotcrete
  - ➢ Finally, how effectively does the load transfer to the rock reinforcement

Shotcrete failure

- Shotcrete can fail if the adhesion to the rock mass is strong
  - ➢ This can be accomplished through preparing the rock mass as described ****
  - ➢ It can also fail if the rock mass deforms enough to exceed the shotcretes' flexural strength
  - ➢ The flexural strength can also be exceeded due to dynamic loads imposed by blasting

APPENDIX 3 COMPLETE ROBOMINER ASSEMBLY

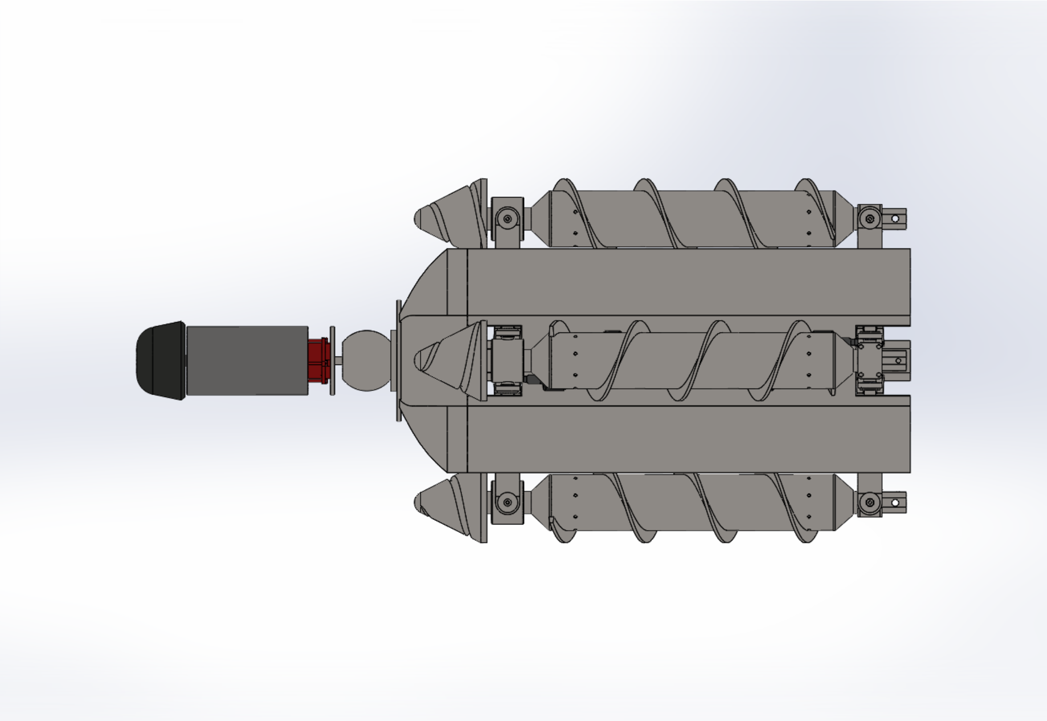


Figure 39 Side view with extended S-LLS

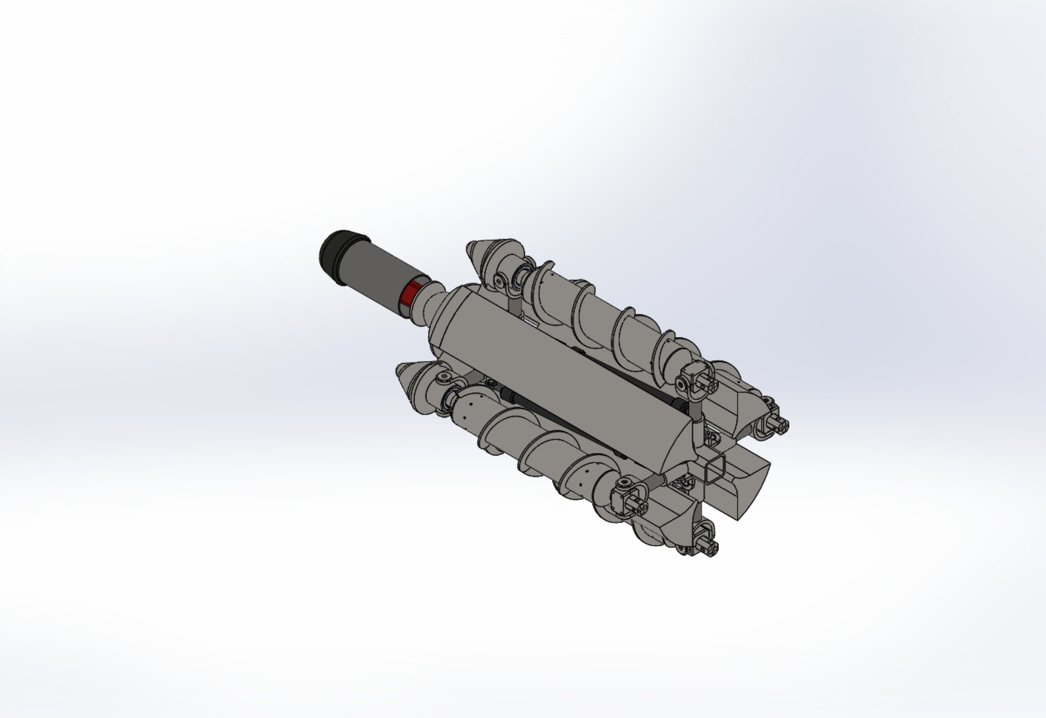


Figure 40 Isometric view from left back

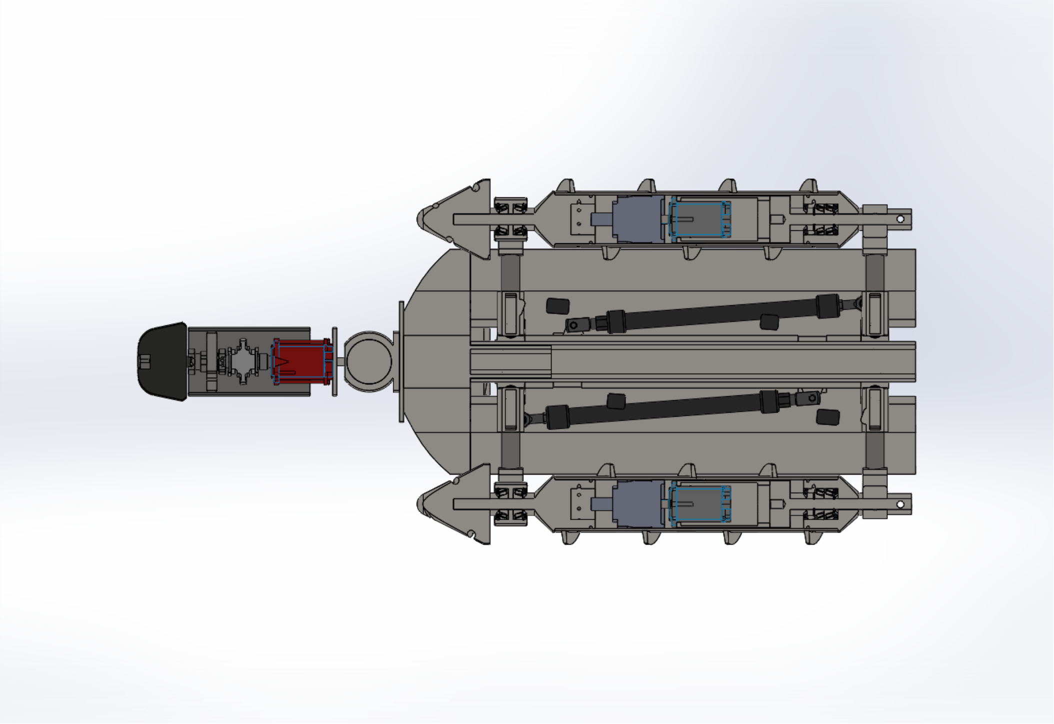


Figure 41 Lateral cross-section

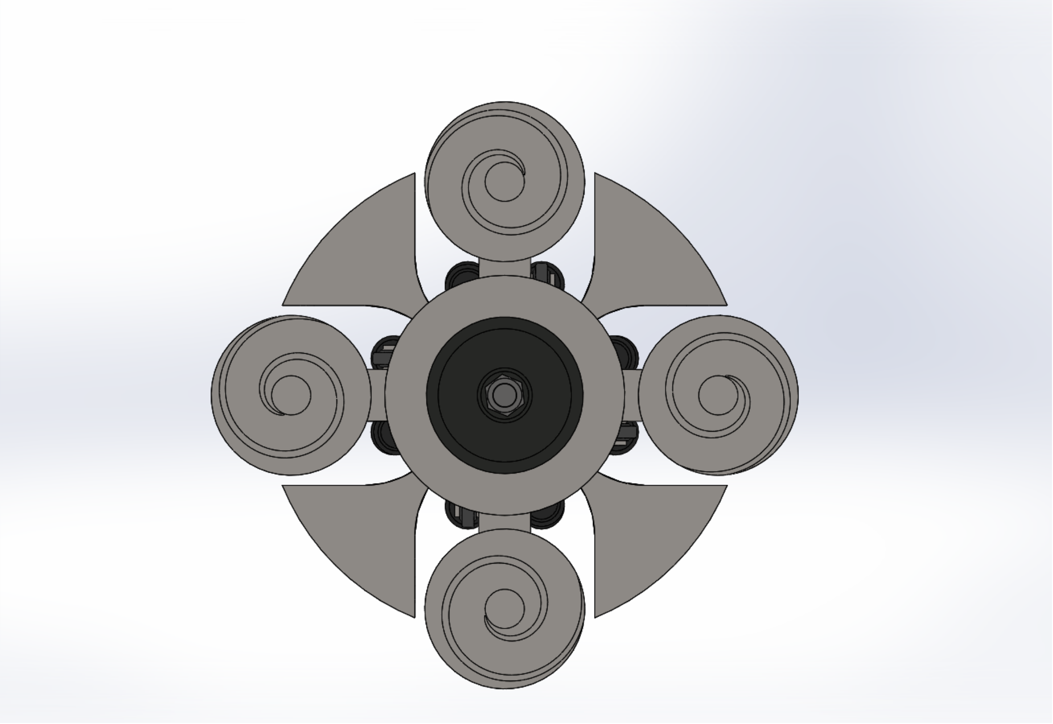
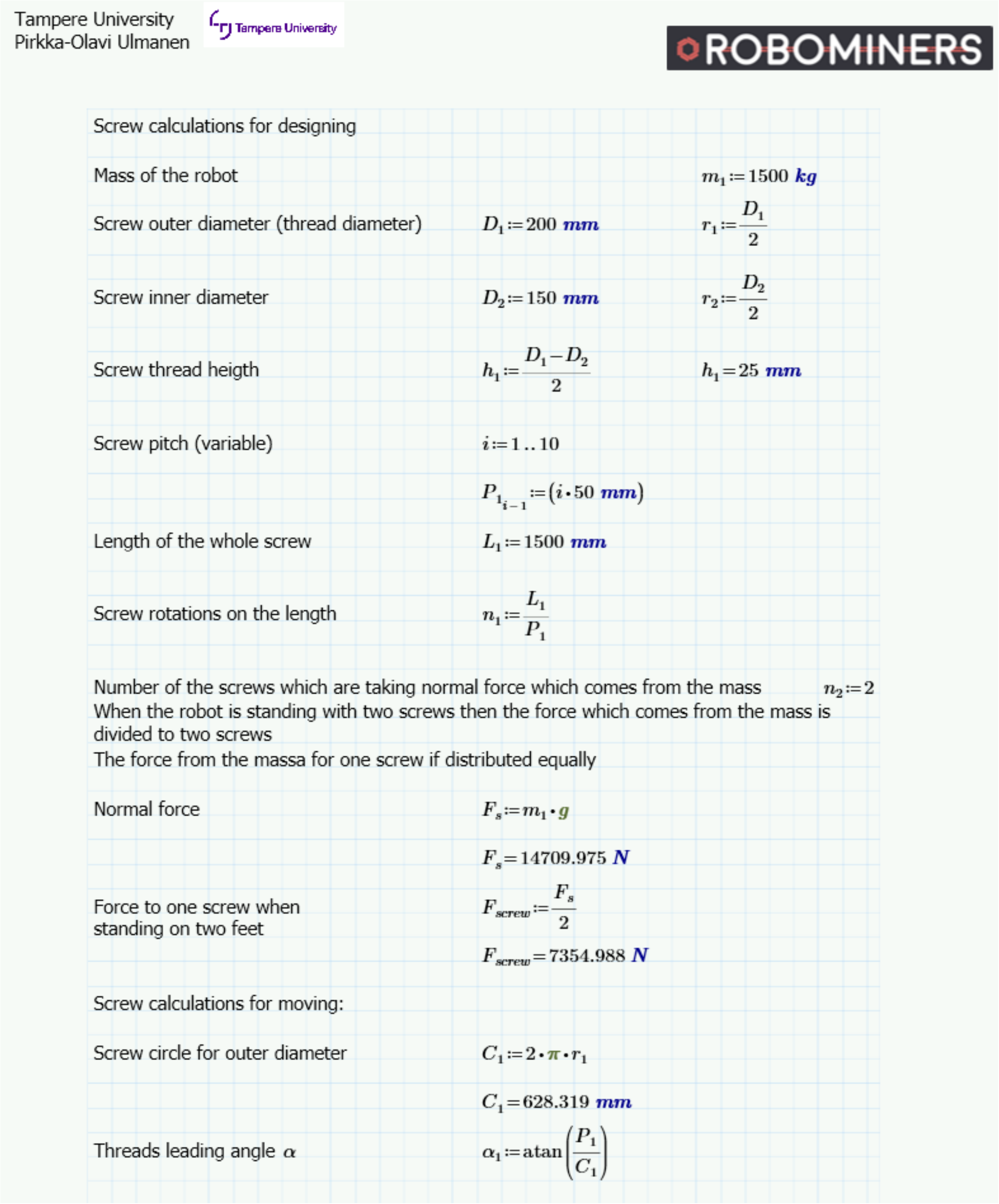


Figure 42 Front view of the Robominer with retracted S-LLS

APPENDIX 3 ROBOMINER'S SCREW DESIGN CALCULATIONS



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Screw calculations for designing

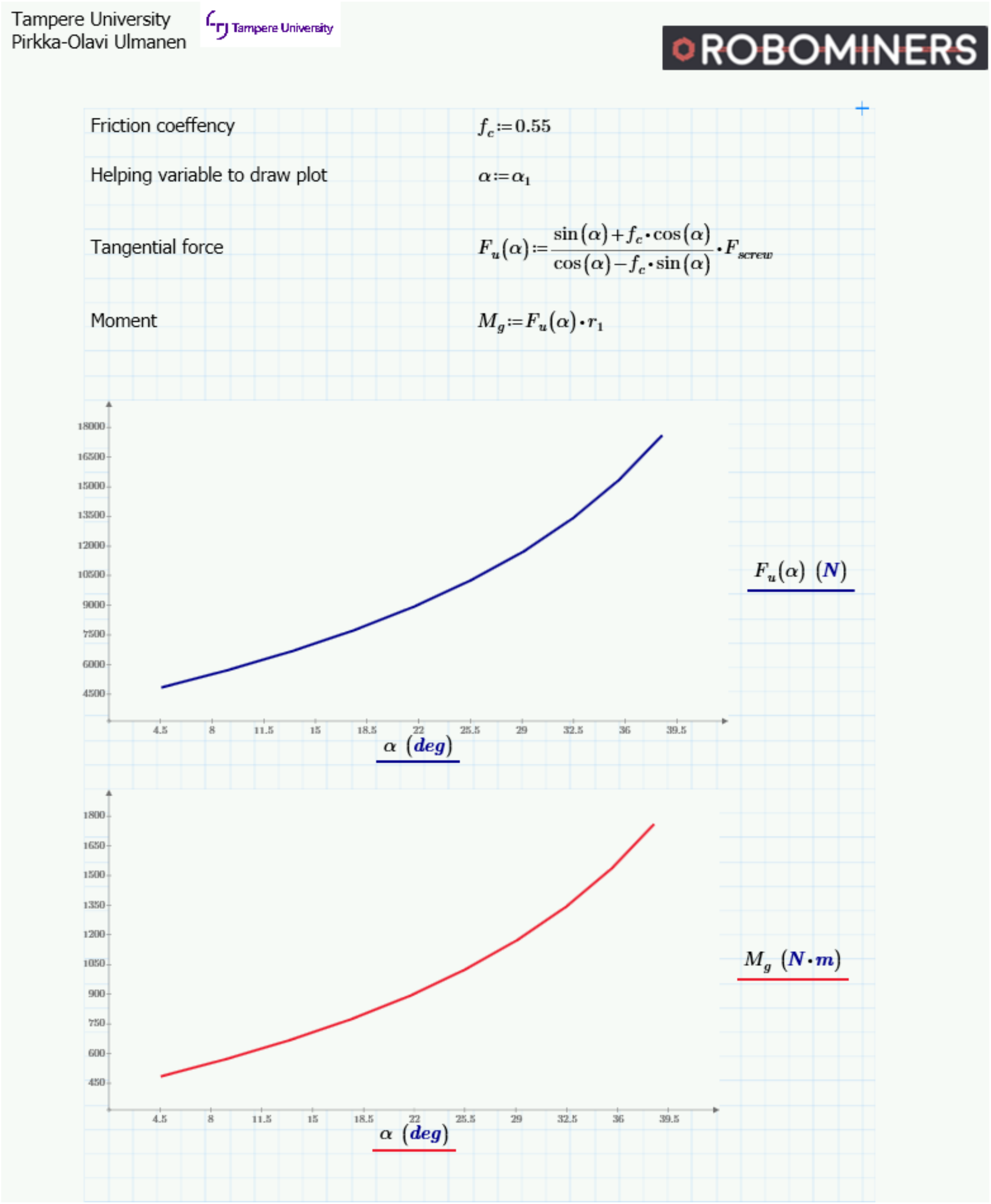
Mass of the robot		$m_1 := 1500\ \mathbf{kg}$
Screw outer diameter (thread diameter)	$D_1 := 200\ \mathbf{mm}$	$r_1 := \frac{D_1}{2}$
Screw inner diameter	$D_2 := 150\ \mathbf{mm}$	$r_2 := \frac{D_2}{2}$
Screw thread heigth	$h_1 := \frac{D_1 - D_2}{2}$	$h_1 = 25\ \mathbf{mm}$
Screw pitch (variable)	$i := 1 .. 10$	
	$P_{1_{i-1}} := (i \cdot 50\ \mathbf{mm})$	
Length of the whole screw	$L_1 := 1500\ \mathbf{mm}$	
Screw rotations on the length	$n_1 := \frac{L_1}{P_1}$	

Number of the screws which are taking normal force which comes from the mass $n_2 := 2$
When the robot is standing with two screws then the force which comes from the mass is divided to two screws
The force from the massa for one screw if distributed equally

Normal force	$F_s := m_1 \cdot g$
	$F_s = 14709.975\ \mathbf{N}$
Force to one screw when standing on two feet	$F_{screw} := \frac{F_s}{2}$
	$F_{screw} = 7354.988\ \mathbf{N}$

Screw calculations for moving:

Screw circle for outer diameter	$C_1 := 2 \cdot \pi \cdot r_1$
	$C_1 = 628.319\ \mathbf{mm}$
Threads leading angle α	$\alpha_1 := \text{atan}\left(\frac{P_1}{C_1}\right)$



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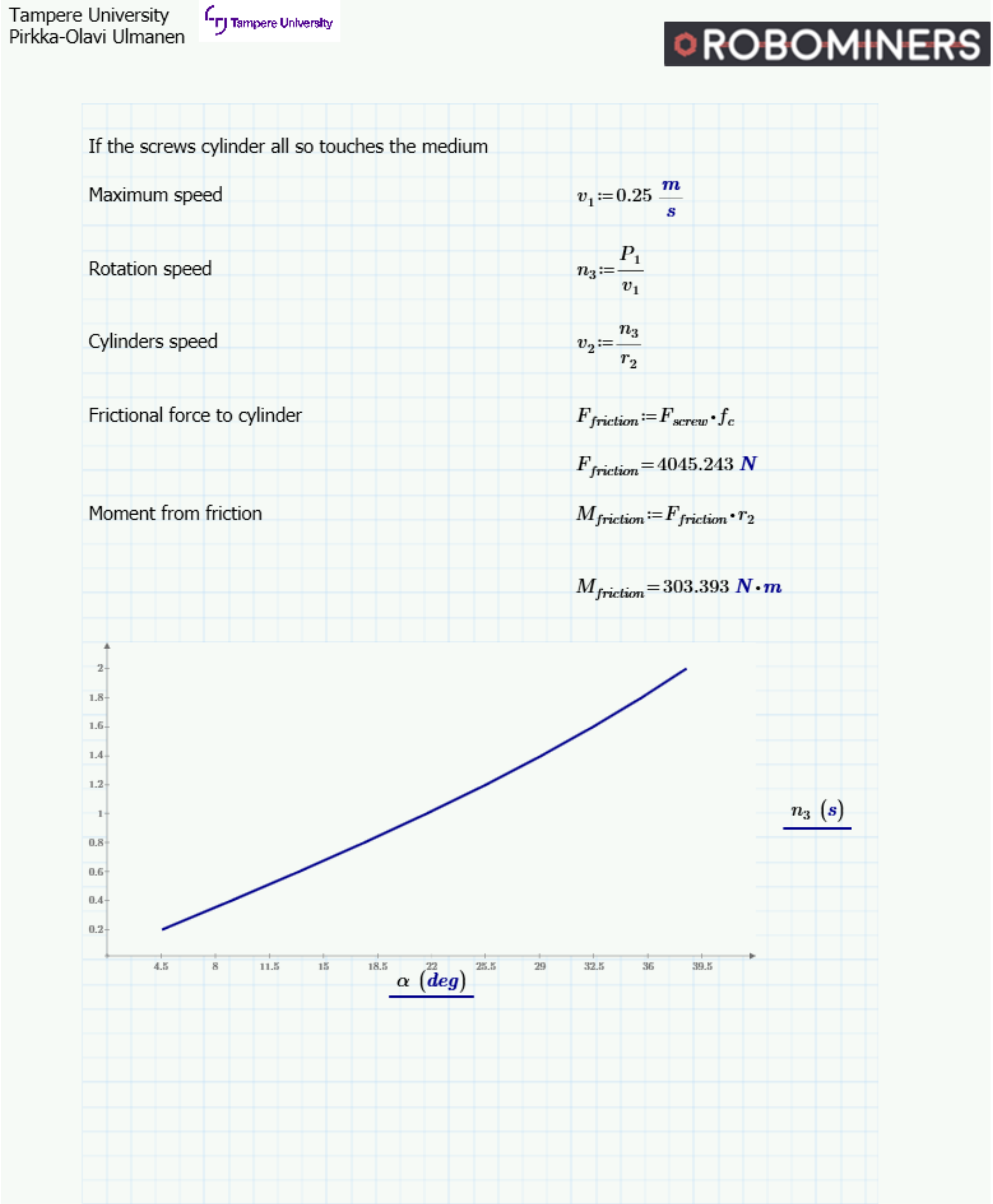
Friction coeffency $f_c := 0.55$

Helping variable to draw plot $\alpha := \alpha_1$

Tangential force $F_u(\alpha) := \frac{\sin(\alpha) + f_c \cdot \cos(\alpha)}{\cos(\alpha) - f_c \cdot \sin(\alpha)} \cdot F_{screw}$

Moment $M_g := F_u(\alpha) \cdot r_1$



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If the screws cylinder all so touches the medium

Maximum speed $v_1 := 0.25\ \frac{m}{s}$

Rotation speed $n_3 := \frac{P_1}{v_1}$

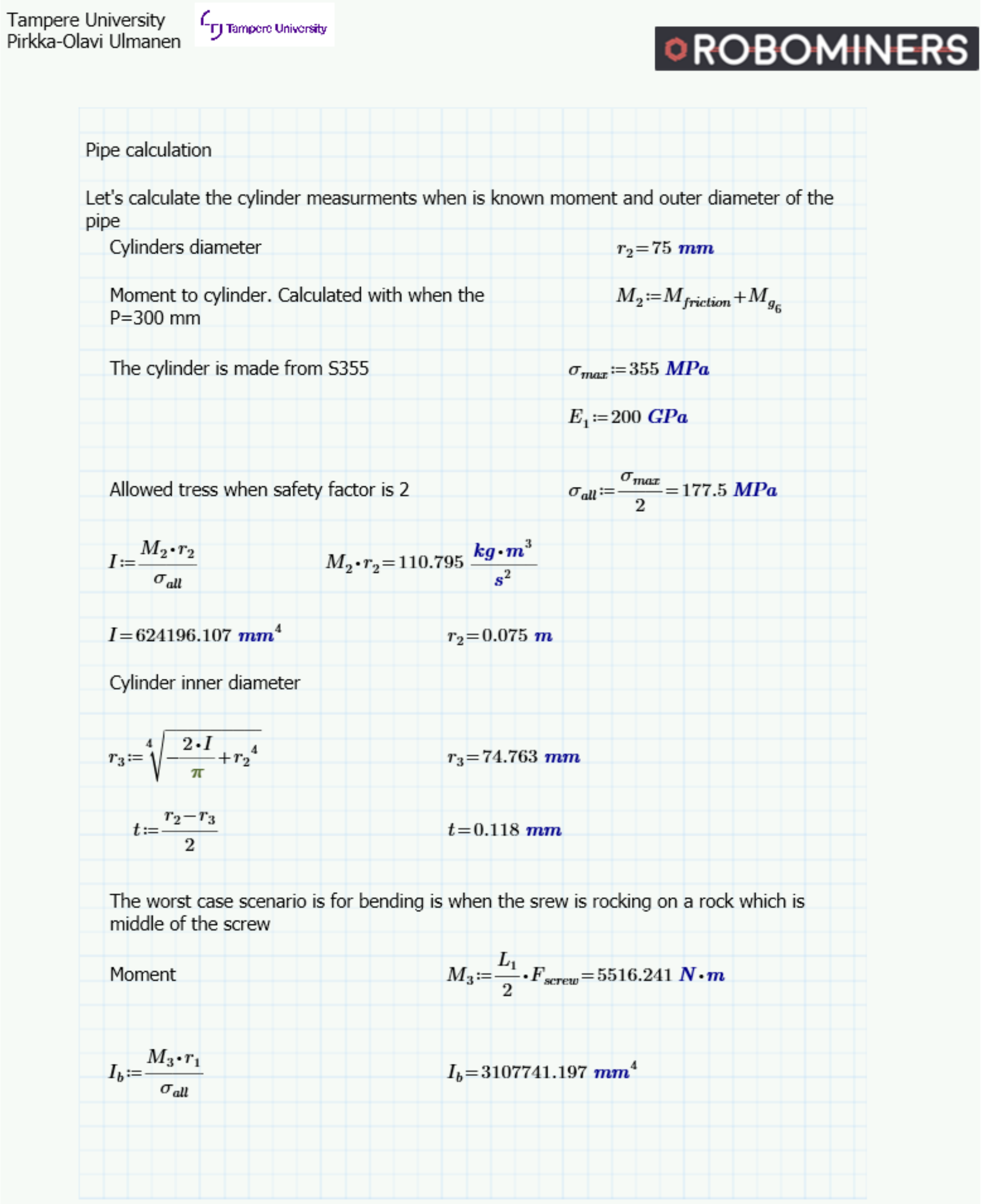
Cylinders speed $v_2 := \frac{n_3}{r_2}$

Frictional force to cylinder $F_{friction} := F_{screw} \cdot f_c$

$F_{friction} = 4045.243\ N$

Moment from friction $M_{friction} := F_{friction} \cdot r_2$

$M_{friction} = 303.393\ N \cdot m$



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Pipe calculation

Let's calculate the cylinder measurments when is known moment and outer diameter of the pipe

Cylinders diameter $r_2 = 75\ mm$

Moment to cylinder. Calculated with when the P=300 mm $M_2 := M_{friction} + M_{g_6}$

The cylinder is made from S355 $\sigma_{max} := 355\ MPa$

$E_1 := 200\ GPa$

Allowed tress when safety factor is 2 $\sigma_{all} := \frac{\sigma_{max}}{2} = 177.5\ MPa$

$I := \frac{M_2 \cdot r_2}{\sigma_{all}}$ $M_2 \cdot r_2 = 110.795\ \frac{kg \cdot m^3}{s^2}$

$I = 624196.107\ mm^4$ $r_2 = 0.075\ m$

Cylinder inner diameter

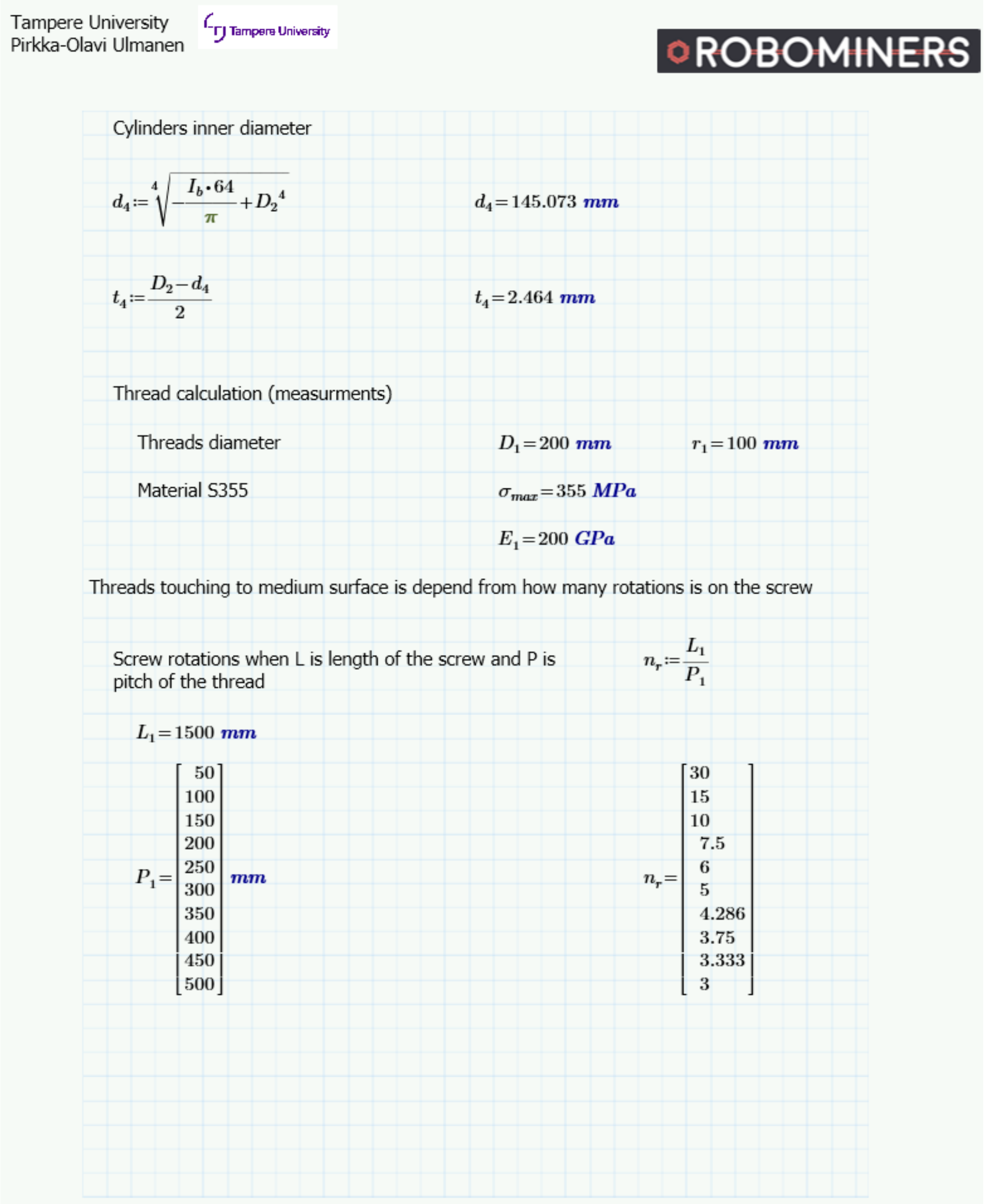
$r_3 := \sqrt[4]{\frac{2 \cdot I}{\pi} + r_2^4}$ $r_3 = 74.763\ mm$

$t := \frac{r_2 - r_3}{2}$ $t = 0.118\ mm$

The worst case scenario is for bending is when the srew is rocking on a rock which is middle of the screw

Moment $M_3 := \frac{L_1}{2} \cdot F_{screw} = 5516.241\ N \cdot m$

$I_b := \frac{M_3 \cdot r_1}{\sigma_{all}}$ $I_b = 3107741.197\ mm^4$



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Cylinders inner diameter

$$d_4 := \sqrt[4]{\frac{I_b \cdot 64}{\pi} + D_2^{\,4}} \qquad d_4 = 145.073\ mm$$

$$t_4 := \frac{D_2 - d_4}{2} \qquad t_4 = 2.464\ mm$$

Thread calculation (measurments)

Threads diameter $D_1 = 200\ mm$ $r_1 = 100\ mm$

Material S355 $\sigma_{max} = 355\ MPa$

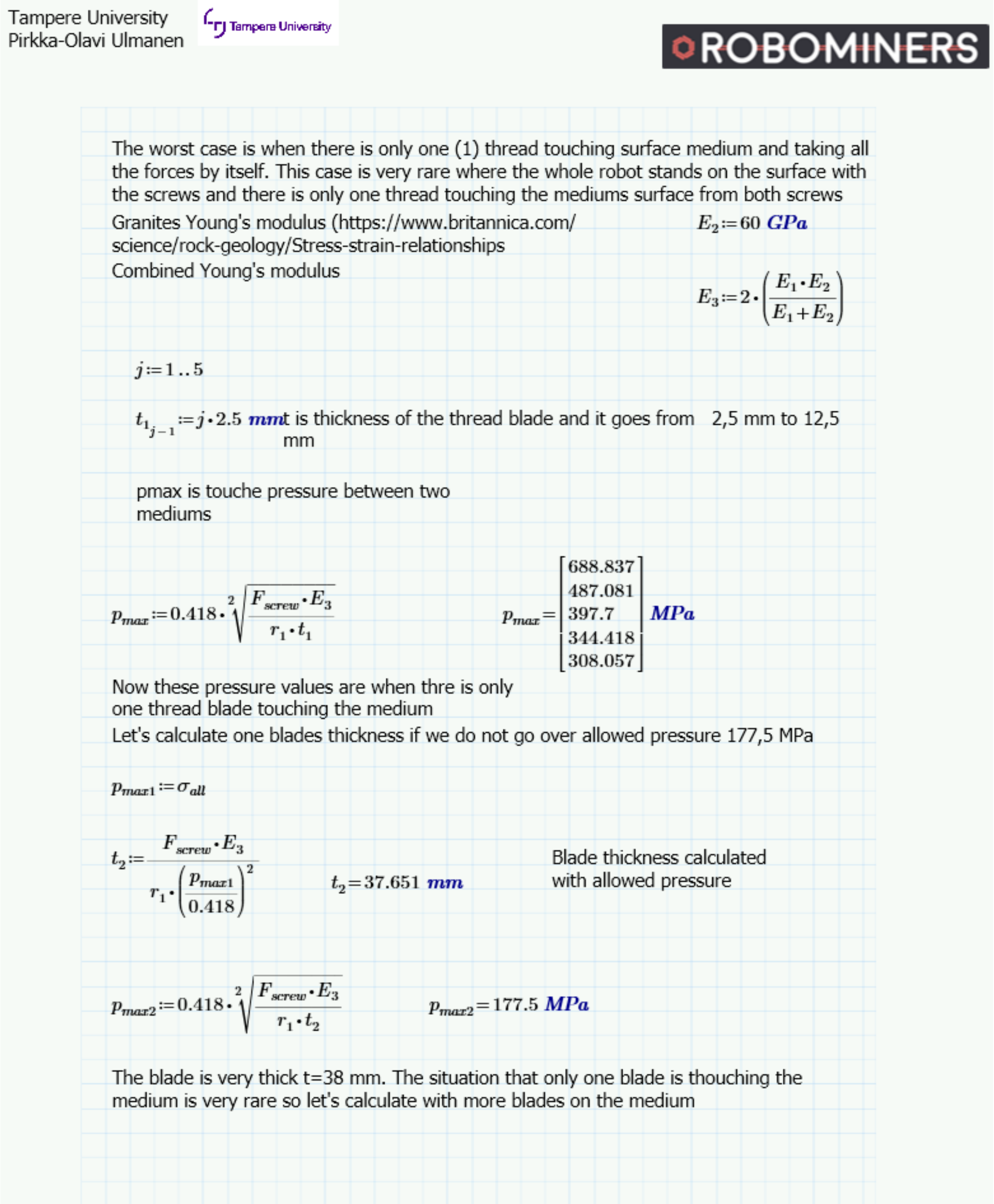
$E_1 = 200\ GPa$

Threads touching to medium surface is depend from how many rotations is on the screw

Screw rotations when L is length of the screw and P is pitch of the thread $n_r := \frac{L_1}{P_1}$

$L_1 = 1500\ mm$

$$P_1 = \begin{bmatrix} 50 \\ 100 \\ 150 \\ 200 \\ 250 \\ 300 \\ 350 \\ 400 \\ 450 \\ 500 \end{bmatrix} mm \qquad n_r = \begin{bmatrix} 30 \\ 15 \\ 10 \\ 7.5 \\ 6 \\ 5 \\ 4.286 \\ 3.75 \\ 3.333 \\ 3 \end{bmatrix}$$



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The worst case is when there is only one (1) thread touching surface medium and taking all the forces by itself. This case is very rare where the whole robot stands on the surface with the screws and there is only one thread touching the mediums surface from both screws

Granites Young's modulus (https://www.britannica.com/science/rock-geology/Stress-strain-relationships $E_2 := 60\ \mathbf{GPa}$

Combined Young's modulus

$$E_3 := 2 \cdot \left(\frac{E_1 \cdot E_2}{E_1 + E_2} \right)$$

$$j := 1 \,..\, 5$$

$t_{1_{j-1}} := j \cdot 2.5\ \mathbf{mm}$t is thickness of the thread blade and it goes from 2,5 mm to 12,5 mm

pmax is touche pressure between two mediums

$$p_{max} := 0.418 \cdot \sqrt[2]{\frac{F_{screw} \cdot E_3}{r_1 \cdot t_1}} \qquad p_{max} = \begin{bmatrix} 688.837 \\ 487.081 \\ 397.7 \\ 344.418 \\ 308.057 \end{bmatrix} \mathbf{MPa}$$

Now these pressure values are when thre is only one thread blade touching the medium

Let's calculate one blades thickness if we do not go over allowed pressure 177,5 MPa

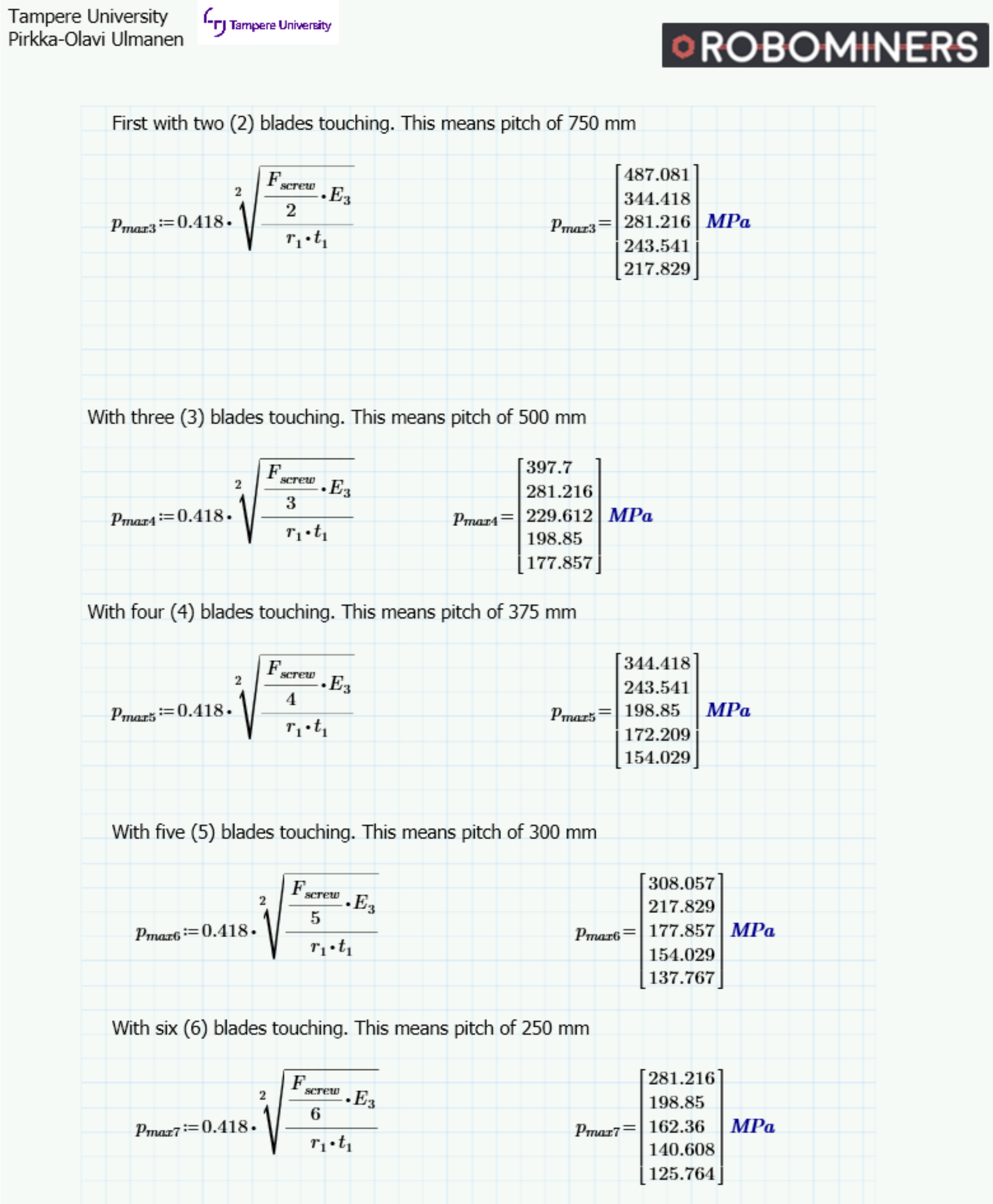
$$p_{max1} := \sigma_{all}$$

$$t_2 := \frac{F_{screw} \cdot E_3}{r_1 \cdot \left(\frac{p_{max1}}{0.418} \right)^2} \qquad t_2 = 37.651\ \mathbf{mm}$$

Blade thickness calculated with allowed pressure

$$p_{max2} := 0.418 \cdot \sqrt[2]{\frac{F_{screw} \cdot E_3}{r_1 \cdot t_2}} \qquad p_{max2} = 177.5\ \mathbf{MPa}$$

The blade is very thick t=38 mm. The situation that only one blade is thouching the medium is very rare so let's calculate with more blades on the medium



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First with two (2) blades touching. This means pitch of 750 mm

$$p_{max3} := 0.418 \cdot \sqrt[2]{\frac{\frac{F_{screw}}{2} \cdot E_3}{r_1 \cdot t_1}} \qquad p_{max3} = \begin{bmatrix} 487.081 \\ 344.418 \\ 281.216 \\ 243.541 \\ 217.829 \end{bmatrix} \, MPa$$

With three (3) blades touching. This means pitch of 500 mm

$$p_{max4} := 0.418 \cdot \sqrt[2]{\frac{\frac{F_{screw}}{3} \cdot E_3}{r_1 \cdot t_1}} \qquad p_{max4} = \begin{bmatrix} 397.7 \\ 281.216 \\ 229.612 \\ 198.85 \\ 177.857 \end{bmatrix} \, MPa$$

With four (4) blades touching. This means pitch of 375 mm

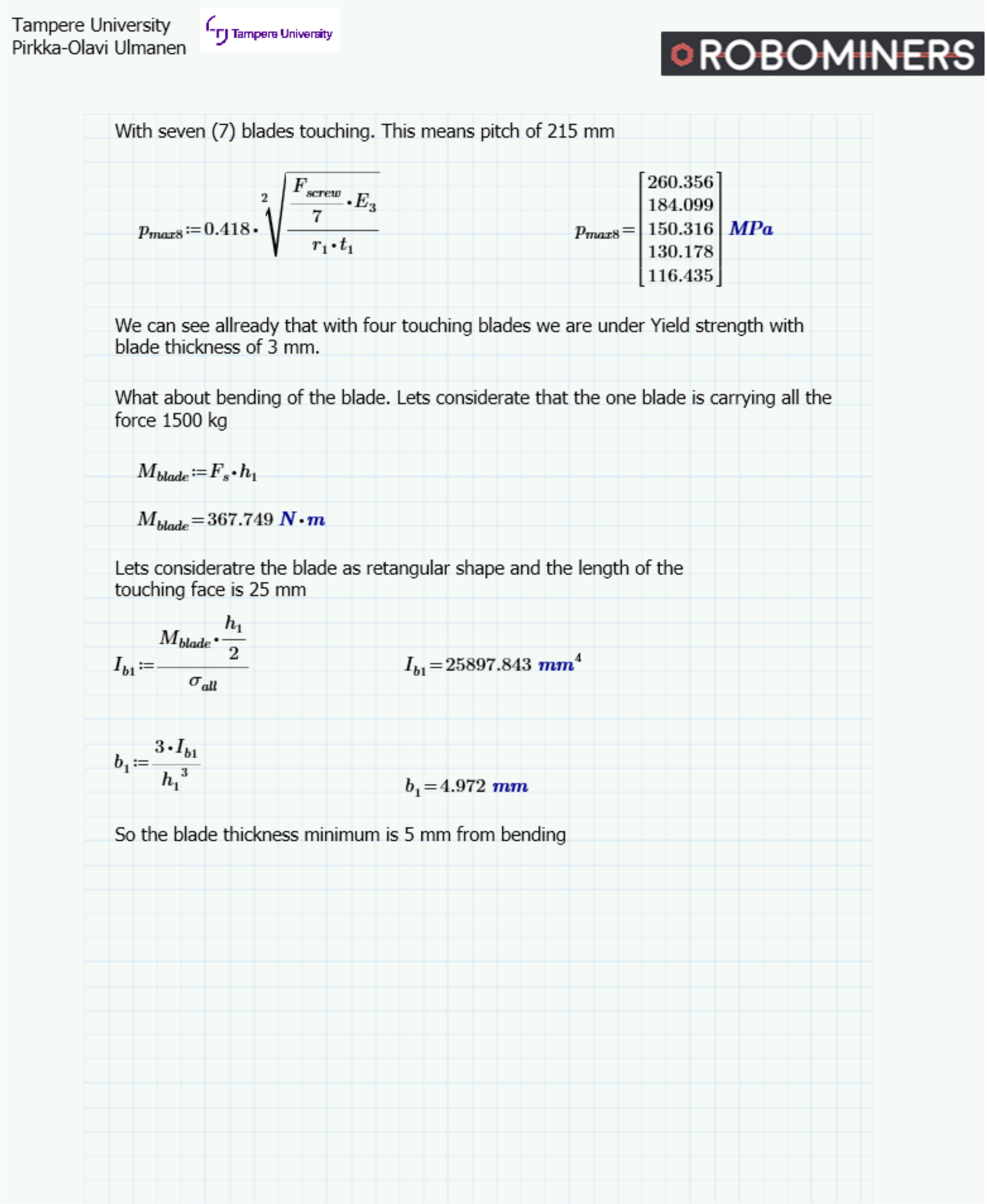
$$p_{max5} := 0.418 \cdot \sqrt[2]{\frac{\frac{F_{screw}}{4} \cdot E_3}{r_1 \cdot t_1}} \qquad p_{max5} = \begin{bmatrix} 344.418 \\ 243.541 \\ 198.85 \\ 172.209 \\ 154.029 \end{bmatrix} \, MPa$$

With five (5) blades touching. This means pitch of 300 mm

$$p_{max6} := 0.418 \cdot \sqrt[2]{\frac{\frac{F_{screw}}{5} \cdot E_3}{r_1 \cdot t_1}} \qquad p_{max6} = \begin{bmatrix} 308.057 \\ 217.829 \\ 177.857 \\ 154.029 \\ 137.767 \end{bmatrix} \, MPa$$

With six (6) blades touching. This means pitch of 250 mm

$$p_{max7} := 0.418 \cdot \sqrt[2]{\frac{\frac{F_{screw}}{6} \cdot E_3}{r_1 \cdot t_1}} \qquad p_{max7} = \begin{bmatrix} 281.216 \\ 198.85 \\ 162.36 \\ 140.608 \\ 125.764 \end{bmatrix} \, MPa$$



With seven (7) blades touching. This means pitch of 215 mm

$$p_{max8} := 0.418 \cdot \sqrt[2]{\frac{\frac{F_{screw}}{7} \cdot E_3}{r_1 \cdot t_1}} \qquad p_{max8} = \begin{bmatrix} 260.356 \\ 184.099 \\ 150.316 \\ 130.178 \\ 116.435 \end{bmatrix} MPa$$

We can see allready that with four touching blades we are under Yield strength with blade thickness of 3 mm.

What about bending of the blade. Lets considerate that the one blade is carrying all the force 1500 kg

$$M_{blade} := F_s \cdot h_1$$

$$M_{blade} = 367.749 \; N \cdot m$$

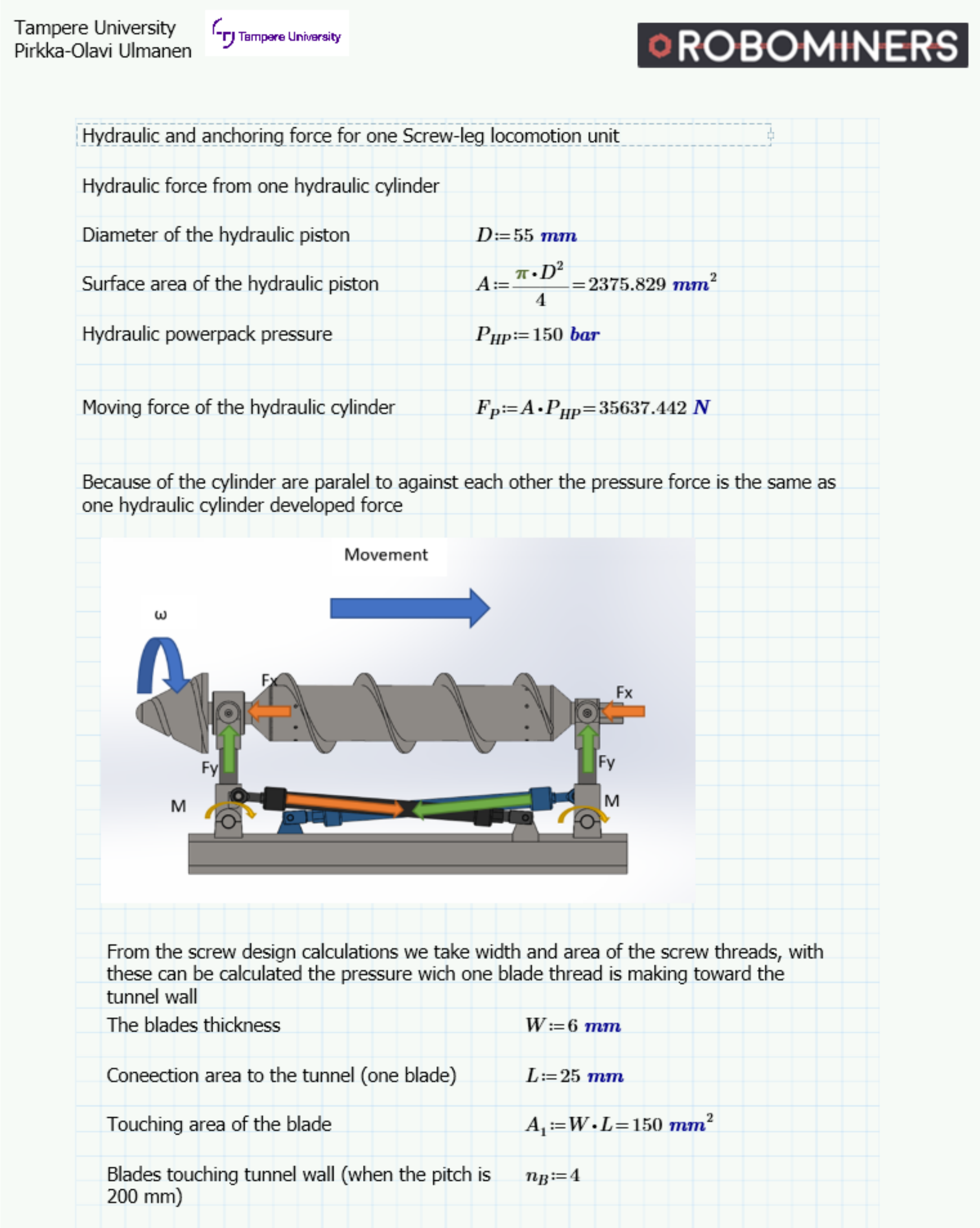
Lets consideratre the blade as retangular shape and the length of the touching face is 25 mm

$$I_{b1} := \frac{M_{blade} \cdot \frac{h_1}{2}}{\sigma_{all}} \qquad I_{b1} = 25897.843 \; mm^4$$

$$b_1 := \frac{3 \cdot I_{b1}}{{h_1}^3} \qquad b_1 = 4.972 \; mm$$

So the blade thickness minimum is 5 mm from bending

APPENDIX 4 SUPPORT STRUT HYDRAULIC CYLINDER AND THE ANCHORING FORCE



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Hydraulic and anchoring force for one Screw-leg locomotion unit

Hydraulic force from one hydraulic cylinder

Diameter of the hydraulic piston $D := 55\ mm$

Surface area of the hydraulic piston $A := \frac{\pi \cdot D^2}{4} = 2375.829\ mm^2$

Hydraulic powerpack pressure $P_{HP} := 150\ bar$

Moving force of the hydraulic cylinder $F_P := A \cdot P_{HP} = 35637.442\ N$

Because of the cylinder are paralel to against each other the pressure force is the same as one hydraulic cylinder developed force

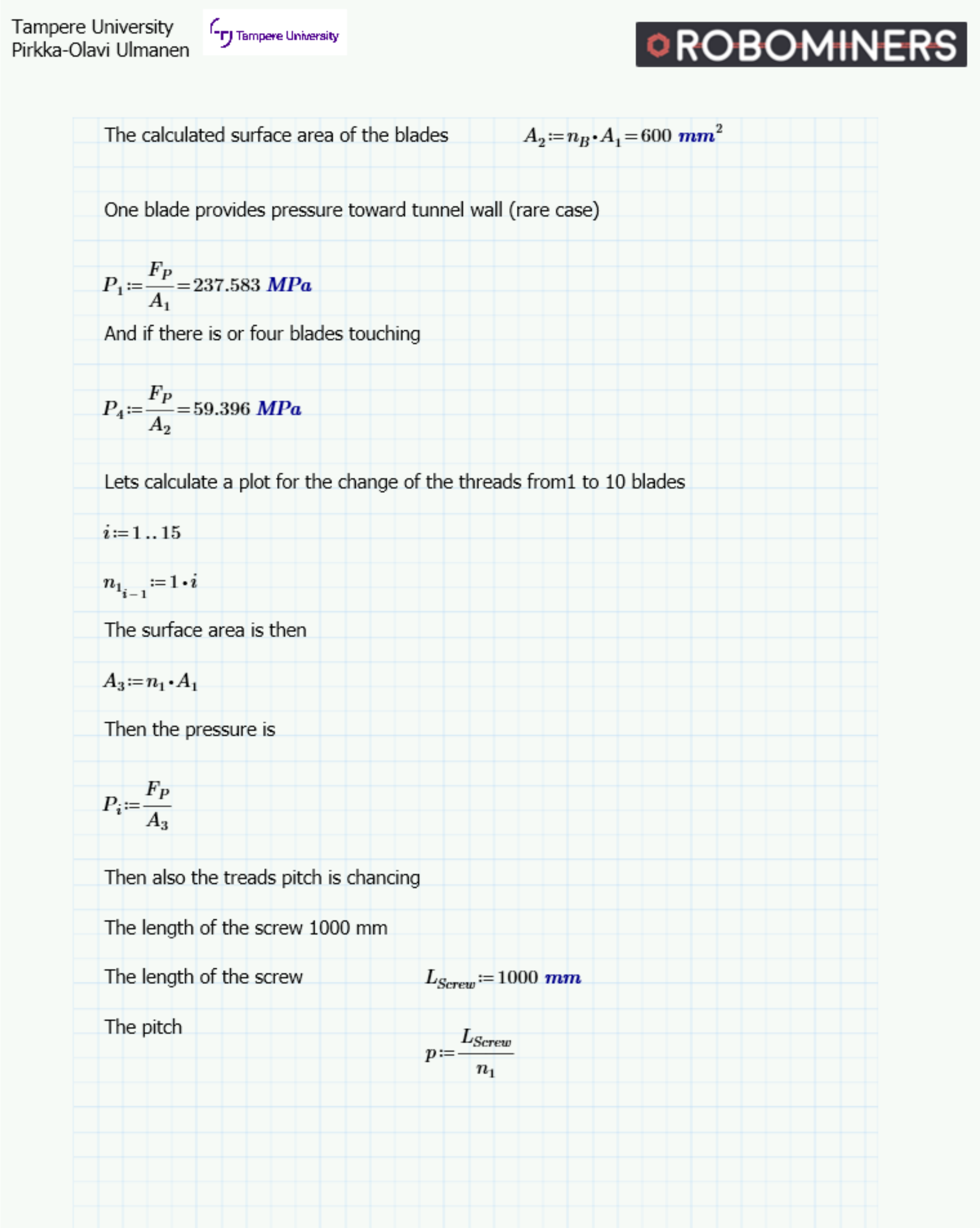
From the screw design calculations we take width and area of the screw threads, with these can be calculated the pressure wich one blade thread is making toward the tunnel wall

The blades thickness $W := 6\ mm$

Coneection area to the tunnel (one blade) $L := 25\ mm$

Touching area of the blade $A_1 := W \cdot L = 150\ mm^2$

Blades touching tunnel wall (when the pitch is 200 mm) $n_B := 4$



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The calculated surface area of the blades $A_2 := n_B \cdot A_1 = 600\ \mathbf{mm}^2$

One blade provides pressure toward tunnel wall (rare case)

$$P_1 := \frac{F_P}{A_1} = 237.583\ \mathbf{MPa}$$

And if there is or four blades touching

$$P_4 := \frac{F_P}{A_2} = 59.396\ \mathbf{MPa}$$

Lets calculate a plot for the change of the threads from1 to 10 blades

$i := 1..15$

$n_{1_{i-1}} := 1 \cdot i$

The surface area is then

$A_3 := n_1 \cdot A_1$

Then the pressure is

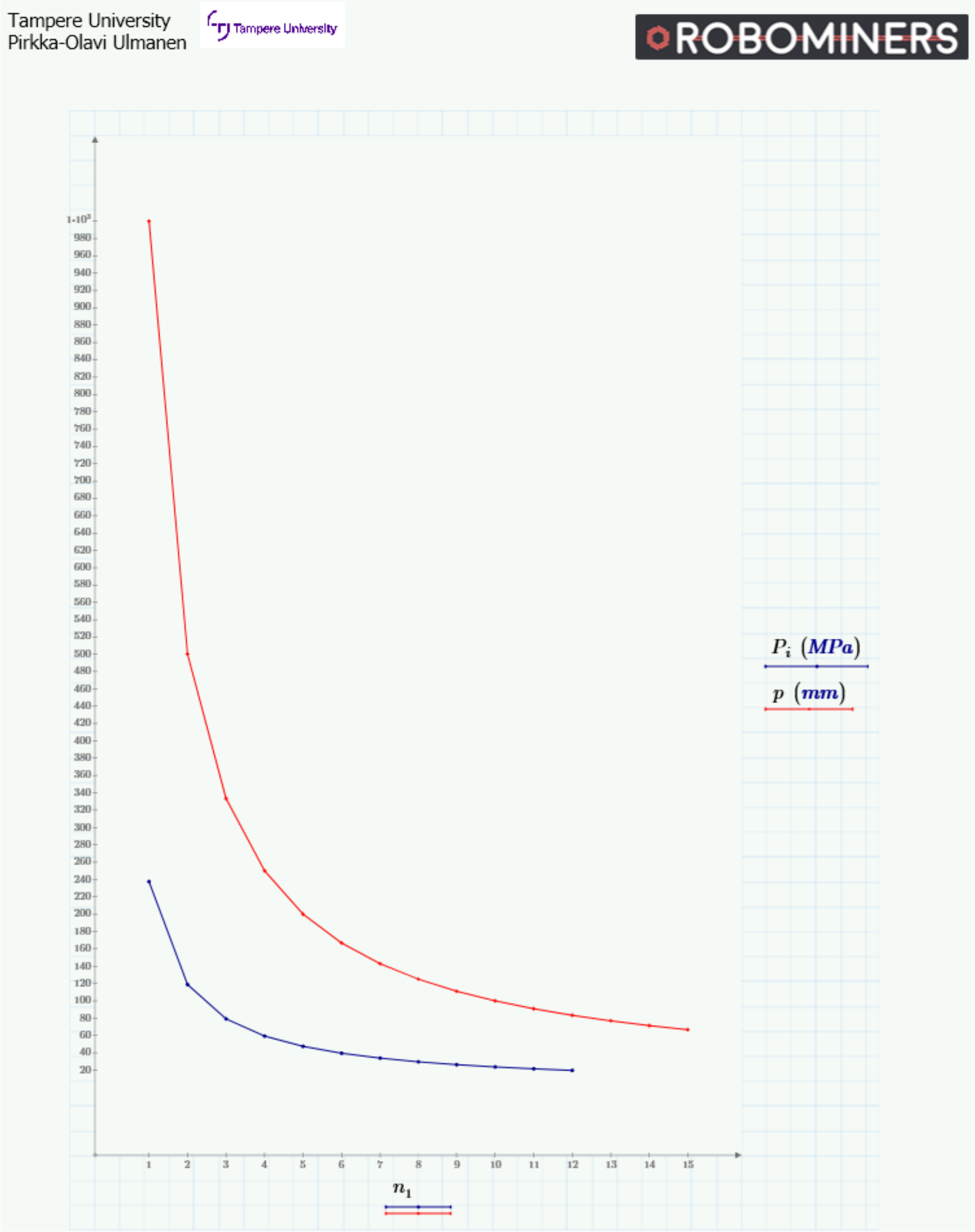
$$P_i := \frac{F_P}{A_3}$$

Then also the treads pitch is chancing

The length of the screw 1000 mm

The length of the screw $L_{Screw} := 1000\ \mathbf{mm}$

The pitch $p := \frac{L_{Screw}}{n_1}$



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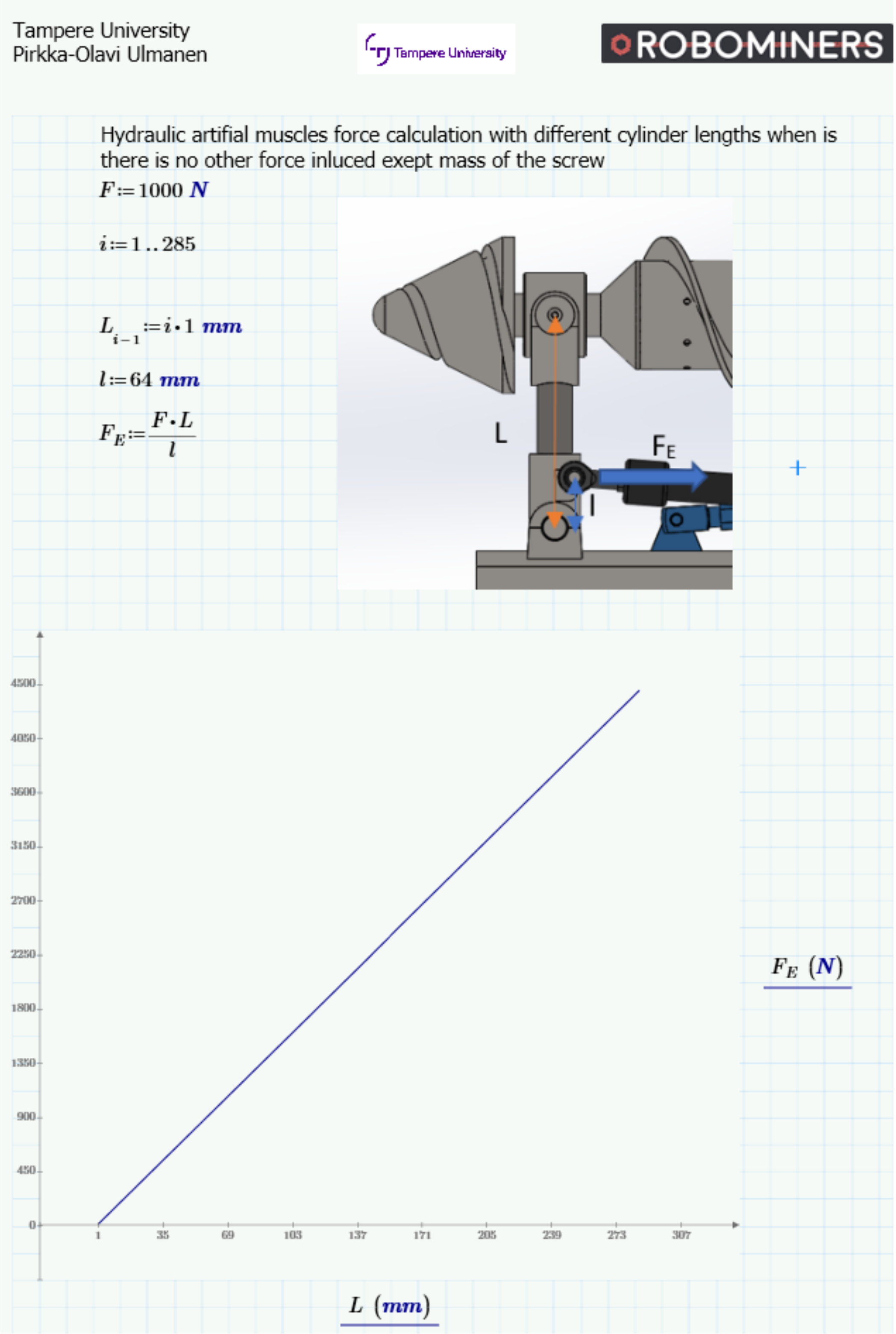
APPENDIX 5 S-LLS HYDRAULIC ARTIFICIAL MUSCLES CALCULATION



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Hydraulic artifial muscles force calculation with different cylinder lengths when is there is no other force inluced exept mass of the screw

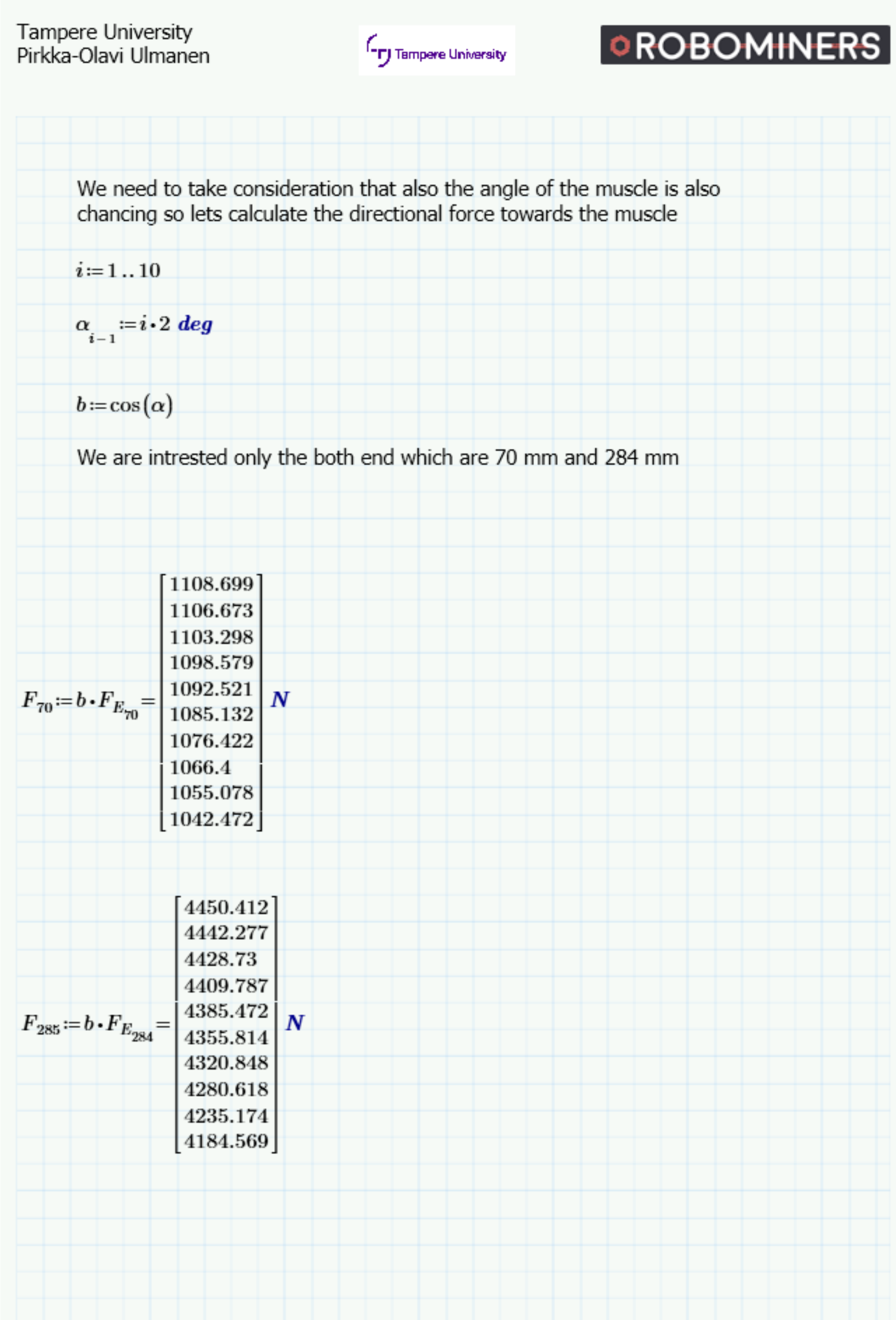
$F := 1000\ N$

$i := 1..285$

$L_{i-1} := i \cdot 1\ mm$

$l := 64\ mm$

$F_E := \frac{F \cdot L}{l}$



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We need to take consideration that also the angle of the muscle is also chancing so lets calculate the directional force towards the muscle

$i := 1 .. 10$

$\alpha_{i-1} := i \cdot 2\ deg$

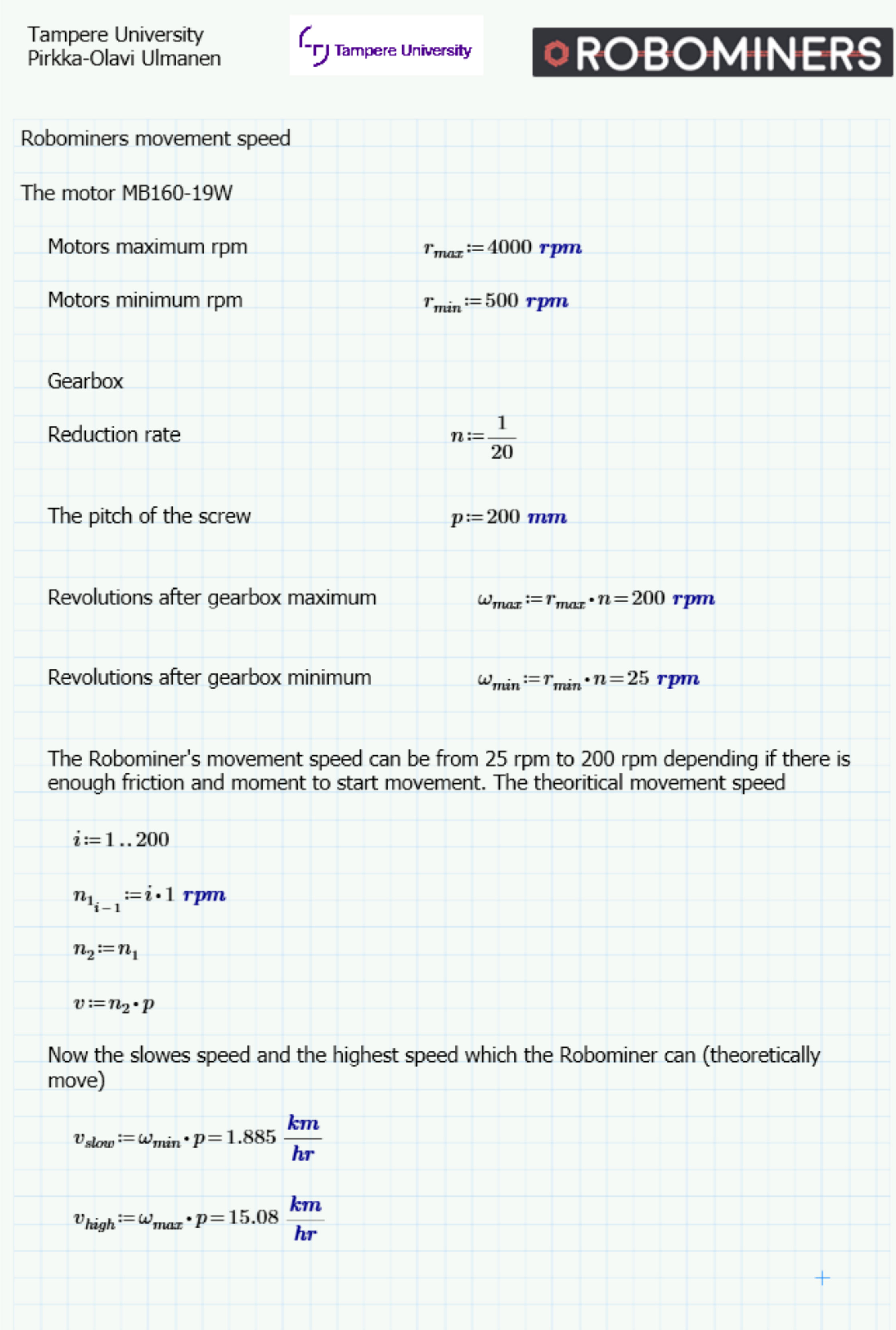
$b := \cos(\alpha)$

We are intrested only the both end which are 70 mm and 284 mm

$$F_{70} := b \cdot F_{E_{70}} = \begin{bmatrix} 1108.699 \\ 1106.673 \\ 1103.298 \\ 1098.579 \\ 1092.521 \\ 1085.132 \\ 1076.422 \\ 1066.4 \\ 1055.078 \\ 1042.472 \end{bmatrix} N$$

$$F_{285} := b \cdot F_{E_{284}} = \begin{bmatrix} 4450.412 \\ 4442.277 \\ 4428.73 \\ 4409.787 \\ 4385.472 \\ 4355.814 \\ 4320.848 \\ 4280.618 \\ 4235.174 \\ 4184.569 \end{bmatrix} N$$

APPENDIX 6 ROBOMINER MOVEMENT SPEED



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Robominers movement speed

The motor MB160-19W

Motors maximum rpm $r_{max} := 4000\ \mathbf{rpm}$

Motors minimum rpm $r_{min} := 500\ \mathbf{rpm}$

Gearbox

Reduction rate $n := \frac{1}{20}$

The pitch of the screw $p := 200\ \mathbf{mm}$

Revolutions after gearbox maximum $\omega_{max} := r_{max} \cdot n = 200\ \mathbf{rpm}$

Revolutions after gearbox minimum $\omega_{min} := r_{min} \cdot n = 25\ \mathbf{rpm}$

The Robominer's movement speed can be from 25 rpm to 200 rpm depending if there is enough friction and moment to start movement. The theoritical movement speed

$i := 1 \,..\, 200$

$n_{1_{i-1}} := i \cdot 1\ \mathbf{rpm}$

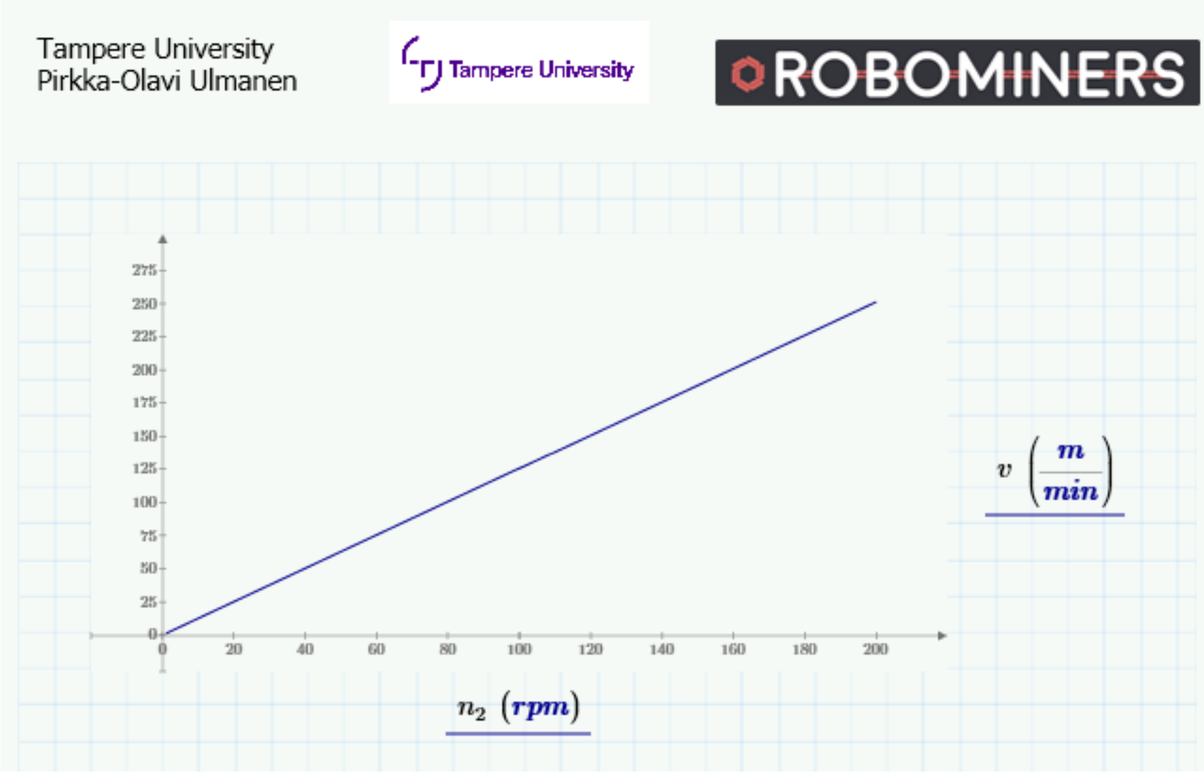
$n_2 := n_1$

$v := n_2 \cdot p$

Now the slowes speed and the highest speed which the Robominer can (theoretically move)

$$v_{slow} := \omega_{min} \cdot p = 1.885\ \frac{\mathbf{km}}{\mathbf{hr}}$$

$$v_{high} := \omega_{max} \cdot p = 15.08\ \frac{\mathbf{km}}{\mathbf{hr}}$$



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