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CONCEPT DEVELOPMENT OF A WATER HYDRAULIC ACTUATION SYSTEM

Faculty of Engineering and Natural Sciences
Master of Science Thesis
November 2019

ABSTRACT

Santeri Nuuttila: Concept Development of a Water Hydraulic Actuation System
Master of Science Thesis
Tampere University
Degree Programme in Mechanical Engineering
November 2019

European Union's need of mining inside its borders generates a demand for innovative mining machinery. The objective of the ROBOMINERS project's mining robot is to meet that demand. This kind of innovative mining machinery require innovative systems and procedures to solve different environmental, legislative and engineering challenges.

This thesis lays down the foundations of water hydraulic systems and water hydraulic actuators for the actuation system development of the mining robot prototype. Since mineral oil is more commonly used in hydraulics, the use of water as a hydraulic fluid is examined. After the examination of water hydraulic systems and its components, the aim was moved towards hydraulic artificial muscles (HAMs). The possibilities and challenges of this kind of actuators were studied, as they will be utilised in the mining robot. One type of commercial off-the-shelf (COTS) HAM was tested to ensure the findings of these studies and to start the development of the mining robot's actuating mechanisms.

The study indicates that water hydraulic systems are a viable drivetrain option for the mining robot. In addition, 3 European suppliers of water hydraulic components were found. COTS components from these suppliers will help in the building process of the actuation system. Furthermore, findings and testing of the HAMs gave some base information for the use of this kind of actuators. It was found, that the Festo's Fluidic Muscles should be suitable for the mining robot prototype, as they reach over 14 kN maximum force and allow 14 bars of overpressure. This thesis can also be used as an introduction to water hydraulic systems and water hydraulic actuators for the ROBOMINERS project group.

Keywords: Linear actuation system, water hydraulics, hydraulic artificial muscle, mining robot

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TIIVISTELMÄ

Santeri Nuuttila: Vesihydraulisen toimilaitejärjestelmän konseptisuunnittelu
Diplomityö
Tampereen yliopisto
Konetekniikka DI-tutkinto-ohjelma
Marraskuu 2019

Euroopan Unioni pyrkii löytämään innovatiivisia keinoja, joilla kaivostoimintaa pystyttäisiin toteuttamaan myös EU:n rajojen sisäpuolella. ROBOMINERS-projektin tehtävä on kehittää kaivosrobotti, joka olisi yksi keino tämän ongelman ratkaisuun. Uudenlaisen kaivosrobotin kehittäminen vaatii myös innovatiivisia järjestelmiä ja toimintoja, ratkaistakseen monia ympäristöystävällisyyteen, lainsäädäntöön sekä tekniikkaan liittyviä haasteita.

Kun EU:n sisäisen kaivostoiminnan haasteet ja kaivosrobotin tarve on esitetty, pyrkii tämä diplomityö luomaan perustan kaivosrobotin prototyypin vesihydraulisten järjestelmien sekä lihaksenkaltaisten toimilaitteiden suunnittelulle. Tämän perustan luominen alkaa vesihydraulisten järjestelmien ja komponenttien selvityksellä, sekä etsimällä veden ja nykyään hydrauliikassa yleisesti käytetyn mineraaliöljyn eroja. Kun vesihydraulisen järjestelmän ominaisuudet ja rakenne on esitetty, siirrytään tarkastelemaan vesihydraulisia lihaksenkaltaisia toimilaitteita. Kaivosrobotti tulee käyttämään näitä toimilaitteita erilaisten liikkeiden aikaansaamiseksi, minkä vuoksi tämäntyyppisten toimilaitteiden hyödyt ja haitat selvitettiin. Yhtä lihaksenkaltaista toimilaitetta testattiin, jotta selvityksen havainnot voitaisiin varmistaa ja kaivosrobotin prototyypin mekanismien kehitys pääsisi alkamaan.

Tämä diplomityö osoittaa, että vesihydraulisia järjestelmiä voidaan käyttää kaivosrobotin voimansiirrossa. Lisäksi selvityksessä löytyi 3 eurooppalaista vesihydraulisten komponenttien toimittajaa, joita voidaan hyödyntää prototyypin toimilaitejärjestelmien rakentamisessa. Vesihydraulisista toimilaitteista saatiin kerättyä hyvää pohjatietoa jatkotutkimuksia ja toimilaitejärjestelmien kehitystä varten. Feston lihaksenkaltaiset toimilaitteet osoittautuivat sopiviksi prototyyppiä varten, niiden saavuttaessa 14 kN maksimivoiman ja salliessa 14 barin ylipaineen. Tätä diplomityötä voidaan käyttää myös hyvänä lähtötietona vesihydraulisista järjestelmistä ja lihaksenkaltaisista toimilaitteista ROBOMINERS projektiryhmän jäsenille.

Avainsanat: Lineaarikäyttö, vesihydrauliikka, hydraulinen keinolihas, kaivosrobotti

PREFACE

As the author of this thesis I would like to thank my friends and family for the support and guidance in every part of my career. Secondly, I would like to thank my colleagues at Tampere University and Sandvik, as sometimes overlapping schedules have required flexibility from their side. Especially I would like to thank Tuomas Salomaa for helping with the testing setup. Lastly, I would like to thank every previous employer and teacher for educating me and helping me to reach my goals.

Tampere, November 2019

Santeri Nuuttila

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LIST OF SYMBOLS AND ABBREVIATIONS

AM	Artificial muscle
COTS	Commercial off-the-shelf (product)
DTH	Down-the-hole
EU	European Union
FMA	Test Fluidic Muscle A
FMB	Test Fluidic Muscle B
FREE	Fibre-reinforced elastomeric enclosure (actuator)
HAM	Hydraulic artificial muscle
PAM	Pneumatic artificial muscle
PEEK	Polyether ether ketone (material)
PTFE	Polytetrafluoroethylene (material)

C_1	Constant 1
C_2	Constant 2
D_0	Initial outside diameter [m]
$F_{elastic}$	Elastic force of the actuator membrane [N]
F_{fibres}	Force developed from the internal pressure [N]
F_{total}	Total axial force of the actuator [N]
L_0	Initial actuator length [m]
R_0	Initial outside radius [m]
t_0	Initial wall thickness [m]
θ_0	Initial wrap angle (°)
D	Current outside diameter [m]
E	Young's modulus [Pa]
F	Contraction force [N]
L	Current actuator length [m]
R	Current outside radius [m]
V	Actuator volume [m^3]
p	Applied pressure [Pa]
t	Current wall thickness [m]
ε	Contraction ratio
θ	Current wrap angle (°)

1. INTRODUCTION

New technology can be a great option for achieving goals which were before beyond reach. Creation of concepts might spawn a new way of doing things or even change what is achievable and what is not. These ideas are a possibility for European Union, which is finding ways to mine economically and ecologically inside its borders. One way to solve this problem is to develop an innovative and ground-breaking mining machine. This is also the way that EU has selected.

The mining robot gets its inspiration from the nature and will differ greatly from the conventional mining machinery. The aim of the ROBOMINERS project is to develop an autonomous small mining robot capable of mining in conditions where conventional mining machinery could not. This kind of innovative machinery require innovative solutions from the system and structure point of view.

The aim of this study is to lay down the foundations of water hydraulic systems and water hydraulic actuators for the actuation system development of the mining robot prototype. Water hydraulic systems and water hydraulic actuators are examined to understand better what to consider in the development of the prototype. In addition, some tests are executed to confirm the findings and to start the development of the mining robot's actuating mechanisms.

The study was accomplished for Tampere University's Mechatronics Research Group as a part of ROBOMINERS project. This project received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no 820971. Testing of the water hydraulic actuator was carried out in the Mechatronics Research Group's laboratory.

This work is divided into 6 main chapters including Conclusions. Chapter 2 provides an overview of the mining robot and mining in general. This chapter aims to introduce the operation environment of the mining robot in addition to the demand for this kind of machinery. Some key variables of the mining robot are also introduced. These are the boundaries, where the Chapter 3 will move when examining water hydraulic systems. In this chapter, water characteristics and water hydraulic components are studied. Chapter 4 provides information of muscle-like actuators and gives theoretical background for the tests of the water hydraulic actuator and for the use of this kind of actuators in general.

Chapter 5 combines the information of the two previous chapters and outlines the water hydraulic system of the mining robot. In addition, hydraulic artificial muscles and their use in the mining robot is defined. Chapter 6 concentrates solely into testing the actuator. In this chapter the test system, test methods and results of the tests are introduced. Chapter 7 contains the conclusions, where the findings are combined and examined to receive more clear understanding what was found. In addition, suggestions for future research are stated.

2. MINING OPERATIONS AND POSSIBILITIES OF THE MINING ROBOT

Large portion of everyday materials around us comes from different types of mines all around the world. In addition to the wide spread of mining sites, there are many ways to collect ore and transport it to the refinery. There could be also some ways that have not been tested yet.

2.1 Mining inside the European Union

There are plenty of mines and opportunities for mining inside European Union borders, but still the EU is largely dependent on raw material imports. Today the imports are not intrinsically a problem, even though EU cannot benefit fully from the processing of the minerals. However, in the future the continuous and affordable supply of the raw material imports is not certain. This uncertainty and the 50-100% dependency of the raw material imports are pushing EU to find innovative solutions for increasing the domestic supply of the materials. [1]

There are still opportunities for increasing mining in Europe. On a longer time horizon however, there are only three potential mining operations in Europe:

- resume mining in abandoned underground mines
- ultra-depth mining
- mining selectively small and high-grade deposits.

Conventional mining operations are not capable of utilizing the potential in any of these operations. The conventional way in these cases would usually be uneconomical or technically impossible. In addition, the required infrastructure and environmental issues of the current operations would need public acceptance and permits to put into practice. In high population areas or when the mine's development affects cross-border regions, the permits are basically infeasible to achieve. [1]

As the three alternatives are representing the last major European mineral potential, an innovative solution that would tackle the problems of the conventional mining operations is a necessity. The new mining operation should be environmentally friendly, the miner should be capable of accessing the abandoned mines usually flooded with water, the ultra-depths should not disturb the miner and it should be able to mine selectively the small and high-grade deposit of the soil. [1]

To summarise, the need for the mining robot or other innovative way of gathering minerals inside EU is genuine. The robot, better introduced in a following chapter, could be a feasible solution for mining the raw materials from domestic sources. It could also be an alternative for the conventional operations worldwide, which usually include large infrastructure, Diesel powered machinery and the risk of spilling oil or other hazardous substances to the soil.

This new way of approaching the mining industry could also open or give information about new technologies which might benefit other branches of the industry. One example of this are the water hydraulic actuation system and actuators that will be examined in this study.

2.2 Challenges of conventional mining methods

As mentioned, conventional mining operations are not capable of achieving the future's mining opportunities in Europe. To overcome the difficulties included in the three potential mining alternatives, an innovative mining machine is needed. [1][2][3][4][5]

The conventional mining operation consists of five major stages: exploration; evaluation and development; design, construction and commissioning; production; and project decline and closure, remediation and restoration. The exploration stage might take up to 20 years and it continues also during the other stages. The time to production usually takes from five to 11 years. [6, pp. 112-114] Therefore, developing a new mine is not a rapid task.

One might ask, why the three Europe's potential mining methods are not implemented already. The reason is mostly due to difficulty of accessing the untapped and small ore deposits that are still found in Europe's abandoned mines and ultra-depths [1]. In addition, the underground mining in general is not an easy task even with the conventional methods.

2.2.1 Underground mining

Underground mining is one of the four major conventional mining methods [7]. Underground mining is practical, when the ore body is still at profitable depth and the grade of the ore is high enough to cover the additional infrastructural and caving costs. A lower ground footprint can also be achieved compared to surface mining methods. [8]

Galvin [9, p.14] generalises, that all underground mining methods are fundamentally the same, including some sort of excavations and pillars that hold the hanging rock wall. And for this reason, regardless the ore type, every underground mine has some common risks and difficulties. Easily over ten hazards caused by a different phenomenon can be defined when operating inside an underground mine, including but not limitied to roof falls, gas outbursts and frictional ignition [9, pp. 477-519]. And these hazards only consider the risks coming from the surroundings, excluding dangers from the machines and other alternating aspects. These dangers also vary depending on the mining method used.

The risks of operating inside an underground mine is not the only weakness of a conventional mine. Big part of the disadvantages considering the conventional mining methods inside EU's borders originate from the limited number of cost-effective operation methods and the large infrastructure needed. To better understand these, the basic concepts of underground mining must be conceived.

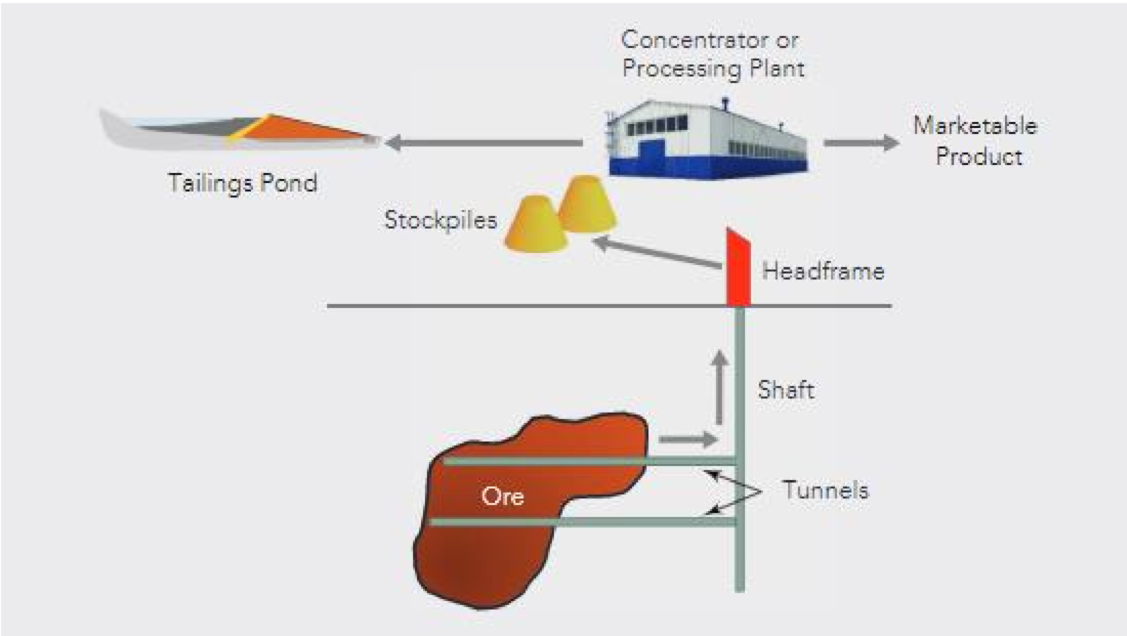

Figure 1. *Typical configuration of an underground mine [10].*

Figure 1 shows a typical underground mine and its main components. The mining process starts by ore mining. After the mining, the ore is moved through the tunnels, lifted along the shaft and then moved to stockpiles. From here, the ore is then processed or concentrated to marketable product. [10]

Compared to the surface mining where more waste rock must be moved, underground mines achieve a good waste rock-ore ratio [6, p. 134]. Practically only ore is extracted from the underground mines, which limits the amount of waste rock to the minimum of

5% and the maximum reaching only 30% [6, p. 134] [10, p. 43]. However, the underground mine still produces the tailing ponds from the ore processing like the surface mines do.

To achieve a good waste rock-ore ratio, the ore body must be known [11, pp. 44-45]. This enables accurate ore following and mine method selection. Ore geometry usually leads to complicated caving designs in underground mining as shown in Figure 2.

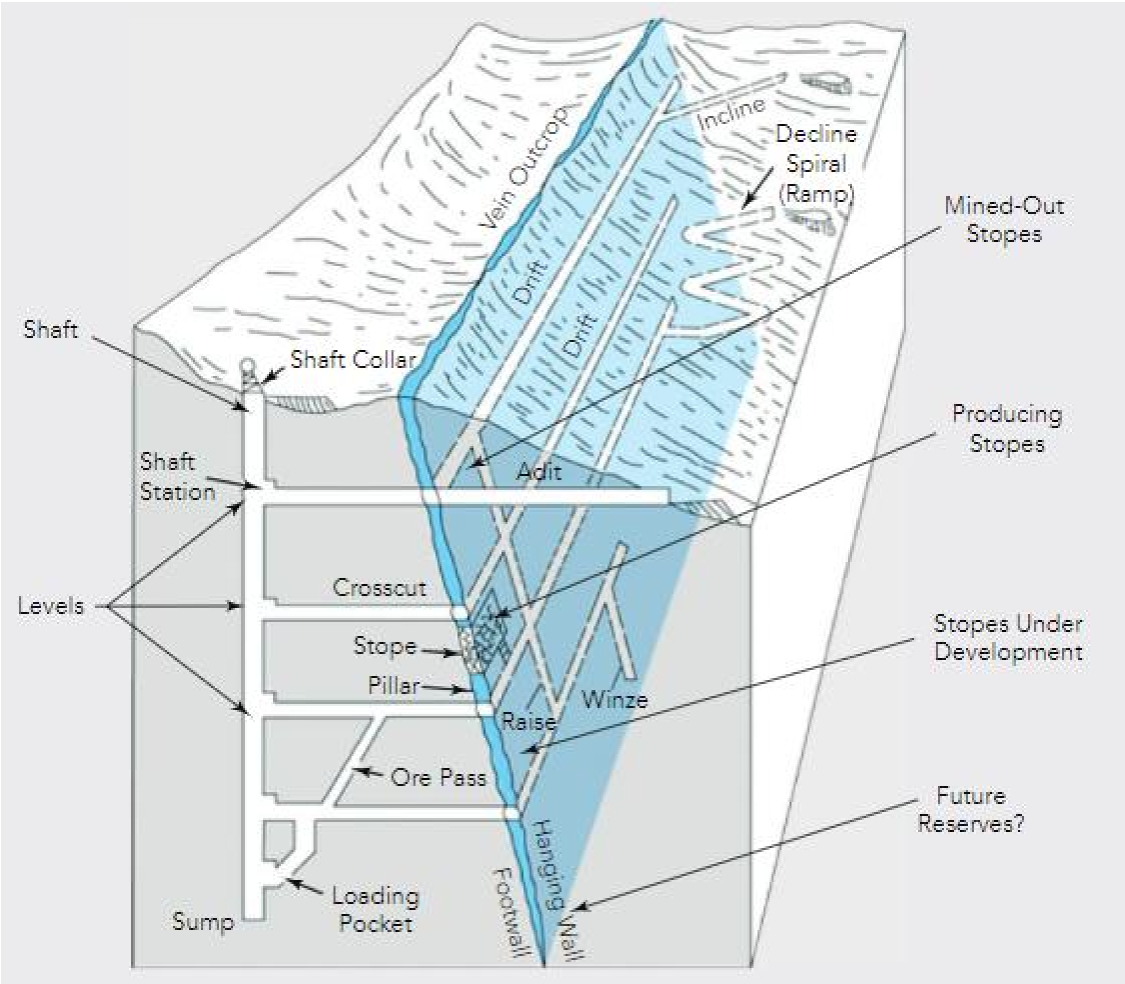

Figure 2. *Underground mine demonstration and vocabulary [10].*

The soil and ore veins are different in every mine, which affect the mining methods used and tunnel systems built. The mine can include multiple levels, many drifts, ore passes and declines. [10, pp. 13-66] This complexity of the tunnel systems and variation of the circumstances develop difficulties.

For example, the shaft construction requires several million-dollar costs and can take from months up to a year to execute. The shafts also need a ventilation system and a power supply before personnel and equipment can enter the mine. In addition, the strength of the rock is changing when advancing deeper or to different directions, which might lead to the need of stabilizing the rock with rock bolts or anchors. And even before executing any of these preparations, most of the water must be pumped out of the mine. risk [10, pp. 44-66]

In the Horizon 2020 call [1], costs of dewatering a mine was mentioned to be one of the reasons why some of the Europe's mines are abandoned. In addition, other execution related costs, environmental issues and technological challenges were the causes for most of the closures. Less frequently the closure was caused by depletion of mineral resources.

2.2.2 Surface mining

From the practicality point of view surface mining might seem more beneficial than underground mining. Even though the cycle of open-pit mining, shown in Figure 3, does not differentiate a lot from underground mining's usual drill and blast cycle, it is a lot simpler and much safer. There is no need for ventilation, substantial dewatering or operating in narrow openings on the surface. In addition, large volumes of rock can be moved in one go and the development of the mine is faster as there is no need for substantial caving. [8]

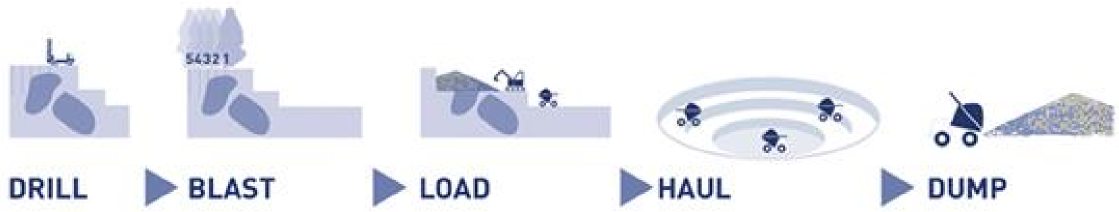

Figure 3. *Open-pit mining cycle [8].*

However, the practicality disappears, if ore-bodies are not located near to the surface or they are too small. In addition, surface mining has a big ground footprint and suffer from developing environmental issues just like the underground mining methods [1] [6, pp. 132-134] [8] [10, pp. 37-43]. Surface mining methods are also unreasonable, when trying to figure ways to accomplish the three potential mining operations in Europe [1].

2.2.3 Placer and in-situ mining

The two last major conventional mining methods, called placer mining and in-situ mining, have their own advantages and uses just like underground and surface mining [7].

In placer mining, ore or gems are basically sifted out from sediments in beach sands, river channels or in other environments which allows sediments to deposit [7]. Sediment is described as a matter that settles at the bottom of a liquid and thus can be found when liquid is present, and the material have had time to break down by different wearing processes [12]. Sediments can also be generated by other phenomena, for example by wind.

In-situ mining, practically used only to mine uranium, is a mining method which requires much less excavation compared to other mining methods. To summarize, in this type of mining solution is pumped down to injection wells where they start to dissolve the uranium. After the uranium is dissolved into the solution, it is pumped back to refinery where the uranium is collected. [13]

These two methods can be disregarded in this project due to their inability to obtain the potential of the three mining operations earlier mentioned [1]. In addition, the environmental issues, especially the danger of contaminating aquifers or other waters and the mineral one-sidedness of the methods make them ineligible for the future of Europe's mining operations [7][13].

2.3 Capabilities of the mining robot

Some of the difficulties regarding conventional mining methods will follow the mining robot, but big part of them should be non-existent hence the innovative mining capabilities of the mining robot [1].

The capabilities come from the robot's innovative structure and the way of mining. These topics are discussed more in the next chapters, where the structure of the robot is explained. The possibilities that come from these capabilities of the robot, is the main reason why the prototype is engineered. For this reason, the robot's way of achieving the three Europe's potential mining operations is examined thoroughly.

2.3.1 Mining in abandoned underground mines

Resuming mining in today's abandoned mines would be one of the potential ways for EU to lower the dependency rates of raw material imports [1]. Earlier, the costs and environmental risks of reopening the mines have blocked this alternative. The biggest environmental risks come from dealing with the acid mine drainage and from dewatering the mine, which also raise the costs significantly and forbids the mining operations in many locations [1] [10, pp. 44-66] [14] [15] [16].

The mining robot is trying to solve these problems by mining the ores without large infrastructure or full recommissioning, without dewatering the mine and doing it safely and environment in mind [1]. The result will be a possibility to turn the still ore containing abandoned mines into a profitable business.

The mining robot will face some challenges like conventional mining methods, for example the harsh and complex working conditions. In addition, there are some new challenges to be considered, like the ones that come from working fully or partially underwater. However, the possibilities coming from the fact that there is no need for humans and big machines to go into the mine at all, will set aside many of the sustained challenges.

2.3.2 Ultra-depth mining

When mining at great depth, there are economical, physical and technological challenges to overcome [1]. Even at 1000 m depth, now reached by over 100 different underground mines, the high in-situ stresses of the rock can result in severe risks of accidents and damages [17][18]. This high stress also rises the water pressures in the soil, which further changes the soil properties and increase mining risks. The great depths can also raise the rock temperature as high as 40 °C, which impacts the working conditions and influences the rock properties [17]. The high stresses and pressures alongside the changed rock properties mean that the amount of rock supports must be increased, which increases the costs of mining and decreases the profitability [19].

The deepest operating mine in EU is found in Finland, Pyhäsalmi and it is 1400 metres deep [1]. And this is not even half the way what is considered as ultra-depth, the border being 3000 m. The ultra-depths have been achieved however, the deepest mine on Earth being the Mponeng mine in Africa, which descend as low as 4350 m [17].

Despite the difficulties of mining at great depths, the underground mining is aiming deeper [19]. This is mostly due to the exhaustion of the mineral resources and coal at shallow depths. In addition, there is a mineral deposit with drastic lateral extension found at depth in North Central Europe, extending from England to Poland [1]. This formation also known as Kupferschiefer, with the continuous and horizontally extended deposit type, is one potential ultra-depth mining operation inside Europe. Finding an economic way of mining from couple kilometres deep would enable extensive benefitting of this formation.

The mining robot is trying to achieve the low-cost operation by downsizing its functions. The structure of the robot, further discussed in an upcoming chapter, is aimed to be small, lightweight and flexible compared to conventional mining machines. This enables the descend to ultra-depths through a large diameter borehole drilled from the surface. Compared to conventional mining machines using their weight, the mining robot will counter production forces by bracing its limbs and other body parts against the rock wall. In addition, this cycle will be achieved without a human entering the dangers of deep underground mine. [1]

2.3.3 Selective mining

Conventional mining methods alongside the large infrastructure and operational costs typically require a large deposit to be profitable and are usually commissioned to operate decades [1][10]. The grade of the ore is one of the key elements of the deposit, even though the large scale makes the limits more flexible. In addition to grading, conventional mining methods need to consider directions where the ore bodies distribute [1]. If the distribution of the ore body will lead to challenging mining operations, considering the tunnelling and other actions needed for conventional mining machines, even high-grade ores might not be mined.

Unfortunately, this has left many of the small mineral deposits in Europe untouched [1]. These deposits, the amount in Europe exceeding a thousand, have also high concentration of metals. By mining these small but high-grade deposits, EU could lower its dependency to raw material imports.

The mining robot is one viable option for gathering these small but high-grade mineral deposits. The type of operation executed in the ultra-depth mining could be used also in this scenario. First, the mining robot or its self-assembling modules will get close to the deposit through a large borehole without the need of mine infrastructure or other costly preparations. Secondly, the robot will self-assemble and mine selectively following the veins or other types of mineralisation. Exploiting its flexibility and small size, the robot has fewer constrains of mine layout designs compared to conventional mining machines, which is a big benefit when following the small deposits. After the deposit have been depleted, the mining robot will be removed through the borehole and deployed to another location. This continuous cycle might take only a year or even less depending on the size of the ore deposit. [1]

One great advantage of this operation compared to conventional mining methods is the small ground footprint and the fewer issues related to environment. Major leap to more ecological operation comes from ending the need for the large mine infrastructure including ventilation, dewatering and substantial caving. One evident benefit is also the safety improvement, which is result from the fact that there is no humans entering the underground mine.

2.4 Structure and system outline of the mining robot

It is good to knowledge that when discussing about mining robot the long-term goal is the target. When the discussion is about prototype of the mining robot, the four-year prototype build that will help the development of the future mining robot is in question.

Following ore veins, mining in abandoned mines or at great depths require a novel mining machine to operate cost-effectively and ecologically [1]. This means that the structure of the mining robot will differ greatly from the conventional mining machines. The innovative structure and operation methods lead also to novel actuation and controlling systems. A sketch of the mining robot is shown in Figure 4.

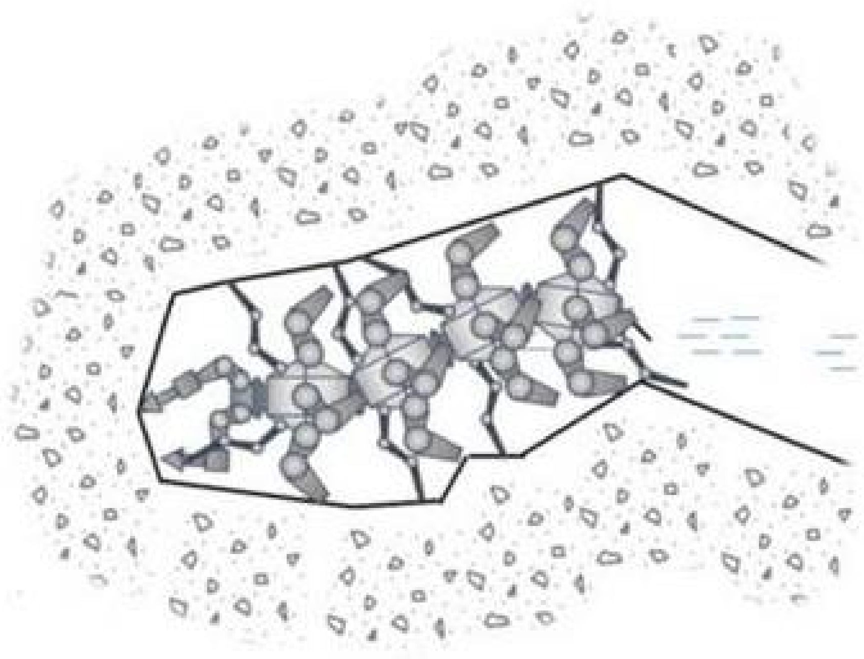

Figure 4. *Sketch of the mining robot [4].*

Despite the different mining operations, the harsh conditions of underground mining will still affect the mining robot. This means that the systems and structure need to be robust. The dust, dirt and moving rocks will wear the mechanical components and makes both controlling and navigating difficult. [19]

Working in slurry and in muddy conditions for an extended period and occasionally moving underwater or partly submerged is not an easy task. However, some hints have been received from the nature. For example, the limbs for moving could be adopted from the burrowing animals, which have great movement capabilities in earlier mentioned conditions [1]. This kind of bio-inspiration will also be exploited in some navigation systems and other structural aspects.

In order to keep the mining robot small and flexible, a modular structure is used. This allows the robot to be descended near the ore via a borehole. The modular structure also enables scalability, which means that the mining robot's reach, stability or effectivity could be increased by adding more modules. Modularity and self-assembly capabilities add structure requirements that conventional mining machines did not have. However, flexibility and scalability are some of the key factors for achieving the three potential mining methods inside Europe. [1]

The limbs and the modularity serve also another important purpose. The production forces of the mining are no longer countered by weight like in conventional mining methods. Instead, body parts will be tucked towards the walls of the cave to stay in place. Again, the modularity will allow the increase of the support by increasing the number of supporting modules. [1]

Working underwater or partly submerged require waterproofing the systems that use electricity. Corrosion will also be one of the problems when working near water. When the operations could last for years, robustness and redundant systems are also needed.

For moving the minerals to the surface, a pump for the slurry is used. The pump can be on the surface, but the structure will need to consider the pathway for the slurry. Some sensors will also be used to follow the mined minerals continuously for production control. In addition, many sensors are installed to follow the production route and method, for minimizing the wear and tear of the tool and the robot. [1]

This bio-inspired and modular structure with the amphibious and underground working environment achieving multiple mining procedures is a great engineering challenge. However, by achieving the functionality of the structure and the systems the last three potential mining operations in Europe can be put into practice.

2.5 Prototype of the mining robot

The first goal of the ROBOMINERS project is to construct a fully functional bio-inspired and modular robot miner prototype, which is capable of operating, navigating and performing selective mining in a flooded underground environment [1]. To achieve this goal, many of the structural and system related engineering goals must be fulfilled.

These engineering goals can be divided into seven different features [1]. The features that define the structure most are:

- biological inspiration for the Miner’s design
- heavy-duty actuation methods.

The prototype will not have all the features that the mining robot will eventually have, for example the capability of self-assembly, but the main aspects will be constructed. After the prototype is constructed, it is used to study and advance future research challenges of the mining robot [1].

The biological inspiration and the heavy-duty actuation methods lead to new structure designs and actuator selections compared to common robotics. Electric drivetrains and actuators, the usual applications for robotics, give a good controllability and are simple, but lack reliability in harsh and wet conditions. Another major problem in electric component usage is the power density, which is too low for the force and size requirements of the mining robot. [1]

With the use of hydrostatic drivetrains and hydraulic actuators, these problems can be solved. Water can be used as a fluid of the hydraulic system, which is more environmentally sustainable medium compared to oil. The water flowing inside drivetrain can also be used directly for hydrodemolition mining. The hydrodemolition will require high pressures, climbing as high as 800 bars or even higher [20]. Additionally, using high pressure all around the system can reduce the actuator diameters by 50-70 %. This could also lead to higher power density and reduce the system volume. [1]

In addition to drivetrain and production tools, actuators concerning movement will benefit from the water hydraulic system. The power density and durability achieved by a bio-inspired limb would give the mining robot reliable and robust movement and the ability to brace itself against the walls to give support during production. Limbs moved by artificial muscle based hydraulic actuators could be one viable solution for the movement. This kind of example system is shown in Figure 5. [1]

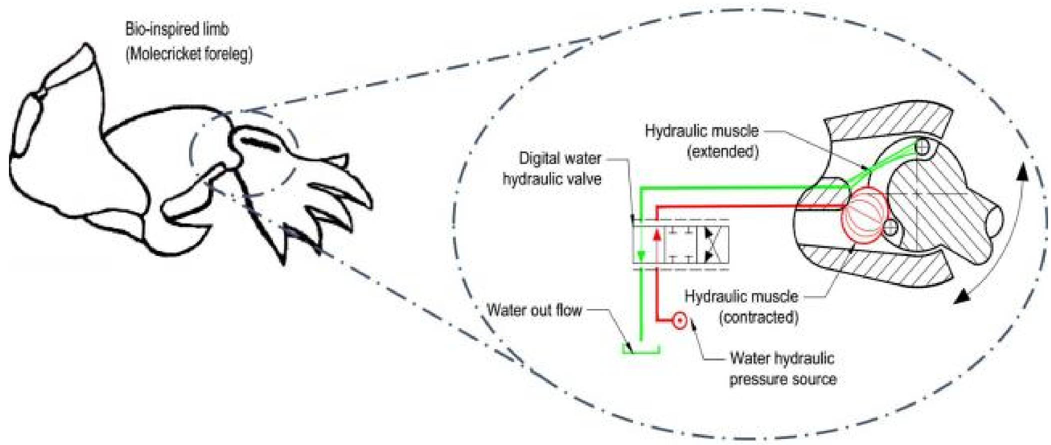

Figure 5. *Example of water hydraulic actuator-based limb and its system [1].*

Mining robot with design properties introduced above will have nearly the same performance and magnitude as a modern 1-ton excavator [1]. Preliminary specification of the mining robot structure is shown in Table 1.

Table 1. *Mining robot prototype structure specification.*

Main variable	Value
Weight	1000 kg (4-5 main body sections)
Power	20 - 30 kW
Power input	Electric cable
Drivetrain	Water hydraulics
Production main tool 1	Hydrodemolition
Production main tool 2	Mechanical cutter head
Production auxiliary tool	Hydraulic hammer

These values are important foundations for the prototype. In every category, minor or major engineering is needed to achieve the durability, functionality and profitability needs of the mining robot. Some of the biggest challenges for the robot will be energy consumption of producing the ore, wear rate of the tools and production capacity [1]. However, these are not the main problems that are concerning the design of the prototype.

The new systems and actuation methods will probably be one of the biggest challenges of the prototype. There is no extensive industrial scale experience from the systems and structure of the robot and some innovations could be completely new. [1]

One aim of this study is to examine and test a water hydraulic actuator because it could be used as a part of the water hydraulic system in several different actuation needs. These actuators could be a major part of the mining robot's water hydraulic system.

Before diving into the water hydraulic actuator, now that the mining robot is introduced, water hydraulic systems will be introduced. This is done to gather the information which will be needed when examining and testing the actuator. Like a hydraulic cylinder in a hydraulic system, the water hydraulic actuator is a part of a bigger water hydraulic system, which without it cannot operate.

3. WATER HYDRAULIC SYSTEMS

Hydraulics is a way of transferring mechanical work from one source to another, which is done by binding and releasing the energy of a transfer liquid. The energy is bound either to pressure or to movement of the liquid [21]. This divides hydraulic systems into hydrostatic or hydrodynamic systems, respectively. The mining robot's hydraulic system might be hydrostatic in the energy transfer point of view, but hydrodynamic in some actuation methods (hydrodemolition, water jetting) [1][22].

Hydraulic systems can also be divided by the application where they are used. As we are investigating hydraulic systems used in robotics, the area is known as industrial hydraulics [23]. The industrial hydraulic viewpoint will be used through this chapter.

In drivetrain use hydraulics has many advantages. One of the most important is the fact that hydraulic systems have freedom of many design limitations compared to conventional gear and drive shafts [22]. The power can be routed freely with pipes and hoses and then used in the needed location [21]. As important is the good power to weight ratio of the hydraulic systems [21][22]. In addition, electronic control systems can be integrated to the hydraulic system, which will enhance the already good controllability of the hydraulics.

Hydraulic systems have many benefits also in other fields of mechanics. One crucial advantage when considering the mining robot is the previously mentioned additional actuator options. In addition, possibility to use water as a transfer liquid will open an environmentally friendly way of actuating the mining robot.

3.1 Water as a hydraulic fluid

Water is not a new medium for hydraulic systems, in fact it is the fluid used in the first hydraulic pump in 200 BC [23]. It was the medium that pioneered the hydraulics from the industrial revolution all the way to the start of 20s century [21][23]. During the Second World War the use of hydraulics rose rapidly, but the main medium of hydraulic systems was changed from water to oil, which saw the first use as a hydraulic medium in 1906. To this day, the oil has been the main medium of hydraulics. However, the rising environmental awareness and the issues with the use of oil are starting to change the distribution.

Certain disadvantages of water as a hydraulic fluid have restricted its usage in the industry, but it has had a few special areas covered a long time already. Food processing, mining equipment and paper processes are good examples of this [24].

The change of medium from one to another in the hydraulic system might seem trivial. However, as it will be discovered in the next chapters, the medium will affect the hydraulics significantly.

3.1.1 Benefits of using water as a medium

The main reason why medium changes the hydraulic system so much comes down to characteristics of the liquid. First, the benefits of water as a medium will be discovered. In the latter chapter the reasons and characteristics behind these benefits will be explained.

The three most important benefits of using water as a medium in the hydraulic system are [21][23]:

- water is cheap and easier to obtain compared to other fluids
- water is environmentally friendly
- water is non-flammable.

The fact that water is present technically all around the world, makes its availability eminent compared to other hydraulic fluids like mineral oil. Other important factor what makes water cheap and easy to obtain, is the fact that water does not need large scale refining like other nowadays used hydraulic fluids do [21][23]. Bypassing refining lowers the energy used in the production significantly, which shows in the price and makes the production ecological.

Toxicity of the nowadays used hydraulic fluids, for example mineral oil containing additives, makes leakage situations dangerous for the environment and organisms [21][23]. Water on the other hand does not affect the surroundings this way, as it is non-toxic and will evaporate.

The non-flammability of water makes it safe to use. Water flowing inside the hydraulic system can be also seen as a safety system in case of a fire. If the fire will tear down pipelines or hoses of the hydraulic system, the water inside those will put down the flames. This increases safety compared to the possibility of explosion and inflaming, which mineral oil and other nowadays used fluids have in similar situation.

Some drawbacks of using water as a hydraulic fluid can be seen, for example worse lubrication properties and narrow operating temperatures due to freezing and low boiling point [21][23]. Water to oil emulsions have been used to overcome these challenges, but this would lead to same environmental issues as the nowadays commonly used fluids, which is not acceptable. However, vegetable oil could be one answer to these problems because it would have minimal impact to environment and still have the lubrication and other benefits of oil [23]. The flammability of vegetable oil is considered high, but this might be a problem that could be accepted.

There are also more benefits that might not be as apparent as the price, non-flammability and environmental friendliness of water. At least many function specific advantages can be found having a source of water besides the hydraulic system. For example, with the down-to-hole drills water can be used instead or air to gain better efficiency [25, pp. 753-754]. In addition, the water used to operate the drill can be injected inside the drilling hole to capture the drilling dust. This kind of advantages will be found also in the mining robot's hydraulics, which will be covered in a latter chapter.

3.1.2 Characteristics of water in a hydraulic system

The change of medium of the hydraulics will change the system in many ways. This change can be explained with the characteristics of the fluid. Compared to today commonly used hydraulic fluids, water have surprisingly different properties.

One big change compared to oils is water's low viscosity, which is over 10 times smaller compared to mineral oil in 20°C [21, pp. 446-447] [23] [25, pp. 725-742]. For this reason, if water would be used in the same system that was earlier used by oil, the more freely flowing water would lead to major leakage and lubrication issues. This would lead to loss of efficiency and even to malfunction of the system as the components would wear down due to lack of lubrication. The lower viscosity of water will require tighter gaps inside the hydraulic components to achieve the same lubrication and in order to maintain the leakage level of oil.

Even 0,26-0,40 times smaller gaps would be necessary [21, pp. 446-447]. This would require very small surface roughness levels. To get this smooth surface, even finer than Ra 4 (average surface roughness of 0,1 μm), very accurate manufacturing is needed. The possibility of heat expansion and the difficulty of manufacturing as fine components combined to relatively poor lubrication properties of water would make this approach infeasible.

This is the reason why lubrication with the fluid should be secondary practice and the major friction between the surfaces should be dealt with wear resistant and low friction material pair [21, pp. 447-448]. PEEK (polyether ether ketone) combined with carbon fiber, PTFE (polytetrafluoroethylene) and graphite is one of the typical material compounds for water hydraulic applications. Coated metals can also be used. However, dissolution to water and electrochemical corrosion between the materials must be considered with the metals. Suitable metals are stainless steel and some of the copper and aluminum alloys, as they are not as sensitive to corrosion as other metals.

Another way to prevent wear of the moving surfaces is to disregard hydrostatic lubrication and move towards components that does not have as strictly dimensioned moving surfaces [21, p. 447]. For example, seat valves should be used instead of slide valves, where the spool fitted inside the valve body requires strict tolerances. Hydrostatic lubrication could be replaced with the use of bearings. Hydrodynamically lubricated sliding bearings are the only viable option because water lubricated roller bearings have too short lifetime for this kind of application.

The lower viscosity of water can be a benefit in some situations. For example, flow losses of the hydraulic system will be smaller compared to system using oil [21, p.448]. In addition, small viscosity will lead to more turbulent flow, which is great for cooling systems. However, this turbulence can increase the wear of the components.

The working temperature of water is another major difference compared to oil. Due to freezing at 0°C and high vapor pressure of water making it prone to cavitation in suction lines, the working temperature must be limited to minimum of 3°C and to maximum of 50°C [21, p. 229] [23, pp. 46-48] [25, pp. 725-742]. However, there is possibility to pressure the suction lines to increase the maximum temperature allowed. The pressure compensation of the water hydraulic system might also be needed, as the mining robot will be operating underwater bearing high external pressures [1]. This will lead to high internal pressures, which might produce additional cause of cavitation [21].

Temperature will also affect the density and viscosity of water [21, pp. 446-448] [23, pp. 48-50] [25, pp. 725-742]. However, the density does not change significantly at the introduced temperature range. The change of density is also smaller compared to oil. Change of viscosity of water can be detected at the introduced temperature range, but the change is half as big as the viscosity change of oil.

Another variable is the pressure of the fluid. Viscosity of the fluid will increase when the pressure is raised with almost every liquid [23, pp. 50-51] [25, pp. 725-742]. The change of viscosity will be greater also at cold temperatures. However, the change is not major if the system pressure is under 200 bar. If this pressure is exceeded, the change becomes significant and must be considered when designing the system.

Figure 6 shows the viscosity's dependency to temperature and pressure of the water. As can be seen, the viscosity of water will increase as the temperature decreases. Increasing the pressure will also increase the viscosity and this effect is amplified if the temperature is low.

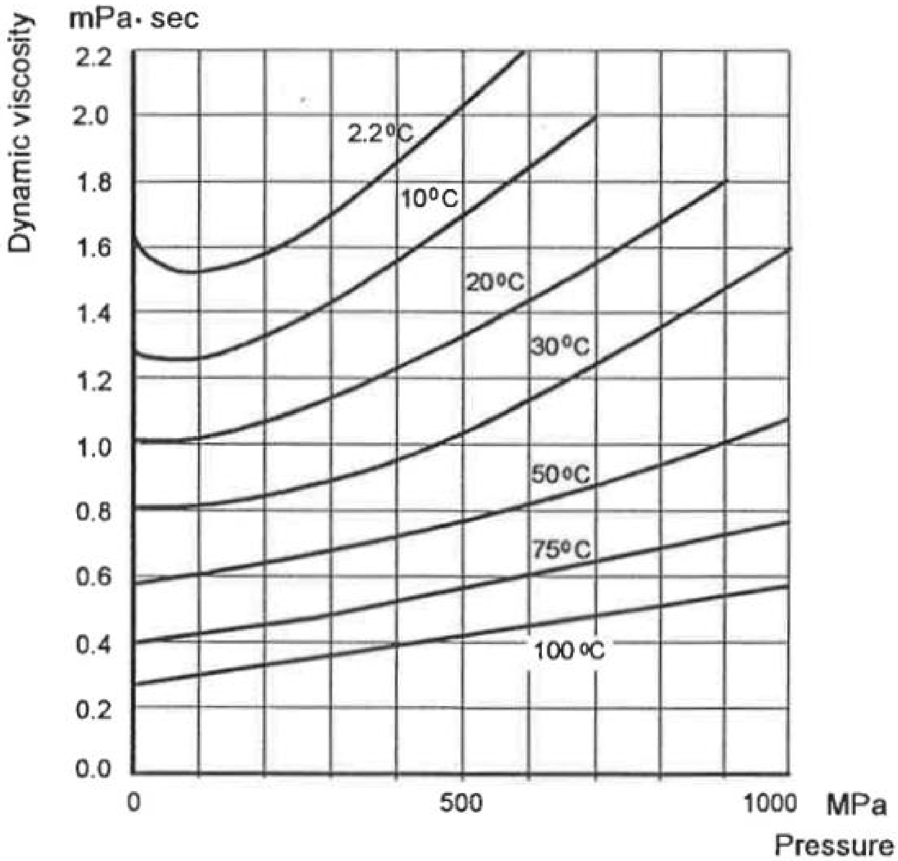

Figure 6. *Viscosity's dependency to temperature and pressure of the water [23].*

In addition to the corrosion issues that is recognized when using water near metal components, is the difficulties generated by bacteria and fungi [21, pp.450-451] [23, pp.53-54]. This issue can be solved by using filtered water and by having the right components of sustaining the cleanliness of the water. The water can also be refined, or it could contain bacteria stopping additives. However, that could serve against the environmental advantages of the use of water as the fluid. In addition, the system can be flushed with or without cleaning agent, which will remove the growth and revive the system [21, pp. 450-451].

Different concentrates can also be used to change the characteristics of the water. For example, lubrication properties can be increased by adding certain polymers increasing the viscosity of the water by 30-45% [26]. Corrosion protection is another major possibility of the concentrates. This way some of the difficulties originating from the use of water in a hydraulic system can be reduced. In these systems, the concentration of the blend must be monitored. Environmental impacts of the concentrates must be considered before the selection as well.

The use of tap water is possible, but some precautions must be done. Firstly, even the tap water must be filtered to get to satisfactory level of cleanliness [21, pp. 450-451]. In addition, pH and hardness values and content of chloride ions must be monitored because the tap water properties will change from region to region [21, pp. 450-451] [23, pp. 52-53]. The pH value range is, depending on the source, between 5,8-8,6 or 6,5-8,5. The right hardness level is between 5 and 10 °d ("German" degree of hardness). Content of chloride ions must be under 25 mg/l, although higher values might be usual [23, p. 53]. If these values are monitored and kept inside the limits, lime and corrosion should not be major problems. However, if for example content of chloride increase to 200 mg/l, severe corrosion problems might occur also with stainless steel [23, p. 53].

Concise tables of hydraulic fluid's ISO-codes, descriptions and characteristics can be found in Appendix A [23]. The first table is a collection of mineral oils (petroleum-based fluids), second is for fire-resistant hydraulic fluids and third for environmentally friendly hydraulic fluids. From the 4th table it can be seen, how water is the best hydraulic fluid in environmental impact, flammability and cost point of view. However, the working temperature, lubrication properties, corrosion protection and the fact that water will cavitate easily are the aspects that have to be considered when designing a water hydraulic system.

3.2 Components of water hydraulic systems

A hydraulic system requires many components in order to function. In addition, same actions can be achieved with completely distinct components. This results to various hydraulic systems with diverse actions and features. However, every hydraulic system has some similarities regarding the function and components of the system.

This chapter combines information of water hydraulic components and their differences to mineral oil systems' components. Some water hydraulic component suppliers are introduced in a latter chapter, as the availability of these components are scarce [21, p. 452].

3.2.1 Example of a hydraulic system

In the Figure 7 a simple hydraulic system is shown. Even though many real-life systems are more complex, the main components of a hydraulic system are included.

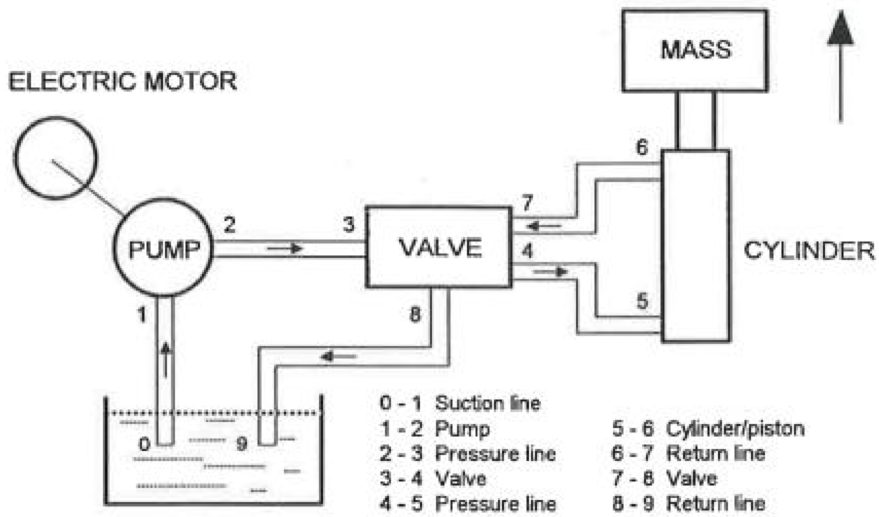

Figure 7. *A simple hydraulic system and its components [23].*

The cycle of hydraulic fluid starts from the tank, where the fluid is sucked through suction line towards the hydraulic pump. Here, the pump will push the fluid towards the valve. In hydrostatic systems, the pump is only a source of flow and the fluid is pressurised by actuators or other components of the systems [22, p. 5]. The fluid will then flow through a valve or valves, which will channel the fluid towards the desirable actuator through pressure lines. At the actuator, for example in the hydraulic cylinder, fluid will push the piston and mechanical work is achieved. From here, the fluid from other side of the piston will be pushed towards the tank through the return line. In the return line, cooling, filtering or other maintenance related actions are usually executed.

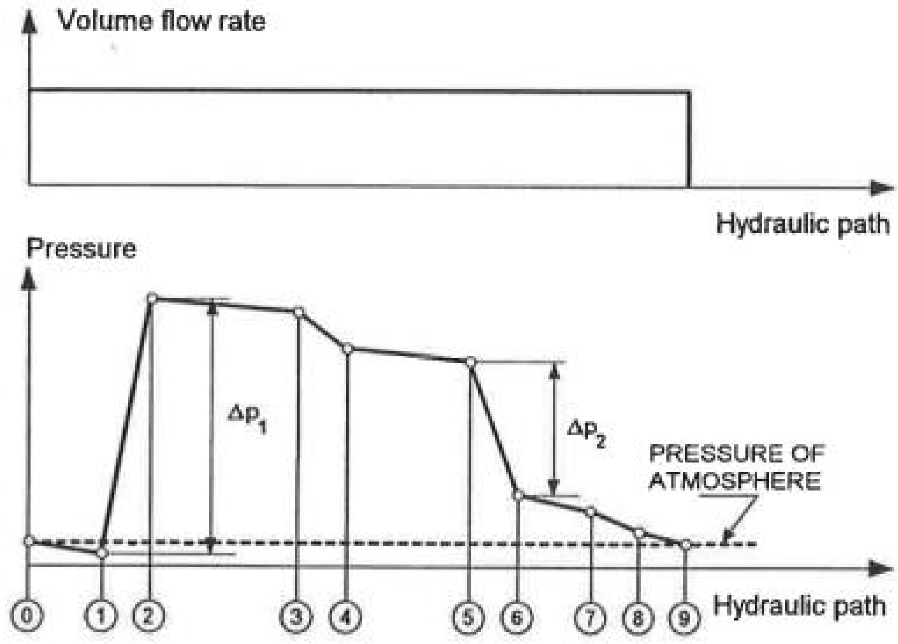

Figure 8. *Volume flow rate and pressure of the hydraulic system [23].*

Figure 8 shows the volume flow rate and pressure of the same system over the hydraulic path. The volume flow is constant through the cycle. However, the pressure will fluctuate depending on where the fluid is in the system. First, the fluid is pressurised to p_1 because the mass of the hydraulic cylinder is pushing against the flow that the pump is generating. Before the cylinder, some pressure drops are noticed due to the efficiency of the valve and the lines. Finally, the p_2 is the pressure that will push the piston of the cylinder, causing the mass to move. After the cylinder, the leftover pressure will drop inside the return lines and level to atmospheric pressure.

This cycle is the basis of a hydrostatic hydraulic system. The system can be divided into three parts. The first distinct part of the system, so called primary side, houses the pump and its components [21, p. 6] [23, p. 6]. The second part might not be so distinct, but it includes control and maintenance components like valves and filters, respectively. The third distinct part of the hydraulic system is called secondary side. It includes the actuators of the system. These three parts are examined more closely in the next chapters.

3.2.2 Generating the hydraulic power

Primary side of the hydraulic system is responsible of generating the hydraulic power which the system uses. Usually, the mechanical work is delivered by electric motor or internal combustion engine [21, p.137]. Rotational motion is usually the form what is used to transfer the energy from the motor to the pump. Linear motion can be used too, but the usage limits to small power applications. One example of linear motion usage are hand pumps.

The energy delivered can be transferred to hydrostatic or hydrodynamic power depending which kind of pump is used. Hydrostatic pumps are called positive displacement pumps and hydrodynamic non-positive displacement pumps [23, p. 59]. The major difference between these two is the fact that positive displacement pump will neglect the internal leakage of the fluid, concealing the fluid inside a pump chamber. This means that the flow will be constant even if the pressure fluctuates, which is not the case with non-positive displacement pumps. In usual hydraulic systems, positive displacement pumps are used.

There are several positive displacement pump types, but they can be divided into four categories, which are gear pumps, screw pumps, vane pumps and piston/plunger pumps [21, p. 137] [22, pp. 6-12]. The principle is same for all of these, but the properties and benefits will vary depending on the type.

The division can also be made to fixed displacement pumps and to variable displacement pumps [21, p. 137] [22, pp. 6-12]. The flow rate can be determined only by speed with fixed displacement pumps whereas the variable displacement pumps allow flow rate adjustment with the ability to control the displacement of the pump.

To positive displacement pumps it is important, that there is no leakage between the high-pressure port and low-pressure port [23, p. 68]. Due to the low viscosity of water, this might be challenging task for the traditional pumps and seals. This is the main reason, why the water hydraulic pumps are mainly piston pumps rather than gear or vane pumps. In-line, axial and radial piston pumps are all viable options for water hydraulics.

In addition to the pump, usually the primary side includes also the hydraulic fluid reservoir, pressure relief valve and check valve [21, p. 6]. These ensure, that the suction line is always full of fluid, the pump will not go over maximum pressure and that the fluid flow cannot return to the pump, respectively.

3.2.3 Transfer of the hydraulic power

After the hydraulic power has been generated, it will be transferred to the wanted direction. Valves are one of the most important components in this section of the hydraulic system. They can regulate pressure or flow of the fluid and change the direction where the fluid is going [23, pp. 97-112]. These three actions divide valves into three main groups. The first is pressure-control valves, second flow-control valves and third directional control valves [21, p. 224]. In addition to these clearly distinct valve types, proportional, servo and cartridge valves form their own groups. These valves can again be used to control the pressure, flow or direction of the fluid.

The low viscosity of water compared to mineral oil develops some challenges for the valve designs too [23, pp. 98-99]. Higher velocity through restrictions, greater kinetic energy, increased leakage through clearances, damaging friction to surfaces with relative motion and high perpendicular load are the properties to be considered in the water hydraulic valve design. Furthermore, the higher energy density of the pressurised fluid flow in the hydraulic system and the higher vapor pressure of water might develop more challenges. The higher vapour density might lead to cavitation and abrasion in the leakage flows of functioning valve. Water-hammering problems due to the higher energy density might occur, causing high transient pressure peaks, noise and resonance. Lastly, the valve materials must be corrosion resistant.

The use of seating type valve rather than spool type valve is a way to avoid these problems [21, p. 447] [23, p. 99]. Built-in damping of the valve member is also an important factor to consider in order to avoid the water-hammering problems.

Control of the valves can be achieved by mechanical, electric or hydraulic signals [21, p. 239]. The control methods can also be used parallelly. Control systems can be open or closed, depending on which kind of regulation is needed.

When transferring fluid from one component to other, if sandwich bodies are not used, pipes or hoses are needed. Pipes are used when the components are stationary and dampening properties of hoses might lead to unwanted flexibility [21, pp. 418-423]. Hoses are used when components are moving, since pipes would be hard to mount, and when the dampening properties of hoses are wanted. The corrosion resistance of these must be considered when using the lines in water hydraulic systems. Compared to systems using oil, smaller diameter pipes and hoses for the water hydraulic system can be used [23, pp. 146-147].

In addition to the valves and lines, accumulator is a component that can be used between the hydraulic power generation and exploiting. It is not a mandatory component, but it has many applications for hydraulic systems. Accumulator can be used as supplementary pump delivery, for maintaining pressure over a certain period, absorbing shocks of the system and for dampening the delivery pulsations of pumps [21, pp. 212-220] [23, p. 128]. Accumulators store energy in the form of hydraulic fluid volume under pressure. The fluid pressure in which the energy storage is based, is preserved by gas pressure, loaded weight or spring. The water does not affect significantly the operation of accumulators. If corrosion resistance is considered, accumulators can be used also in water hydraulic systems.

Another component branch that belongs to this section of the hydraulic system, is the maintenance components. These are the filters and heat exchangers of the system [21, pp. 377-401] [23, pp. 120-125]. Filters are always used in hydraulic systems and they can be found around the system, for example before the pump, in the pressure line or even in a separate filter loop.

There are also different types of filters, which can be roughly divided into surface and depth filtering [23, pp. 120-125]. Depth filtering uses thicker filter element to catch the impurities, when the surface filtering use flat filter element. For both types, the important factor is the filter capacity. This defines the flow volume through the element per unit time, which should be as a rule of thumb two times the pump delivery.

Another important factor is the filtration rating of the filter [23, pp. 120-122]. There are different ways of rating a filter, but the absolute filtration rating should be used. This rating specifies the diameter of the largest hard and spherical particle that will go through a filter under specified test conditions. The rating is basically an indication of the filter elements largest opening.

The heat exchangers might be excluded from a hydraulic system, if the heat exchange of the system is small and carried out by the reservoir and other components [21, pp. 401-408]. However, to keep the fluid temperature optimum for stable properties of the fluid, heat exchange might be needed. Usually, coolers are used to keep the temperature under the maximum, which without the fluid might start to cavitate or lead to other problems. Furthermore, heater might be used to keep the temperature and viscosity of the fluid at the wanted level.

3.2.4 Exploiting the hydraulic power

The part of the hydraulic system that is responsible for the actuation is called secondary side. Secondary side of a hydraulic system includes every actuator, for example a hydraulic motor or a cylinder. The hydraulic energy that primary side of the system has delivered, will be transformed to mechanical work in the actuator [23, p. 81].

The actuators are divided into two depending on the way of motion [23, p. 81]. Rotary actuator, which transforms the hydraulic power into rotary motion, is basically a hydraulic pump running backwards. Linear actuator, usually a hydraulic cylinder, is a great way of achieving straight-line movement. The motor term is commonly referring to the rotary actuator.

Conventional design of hydraulic cylinders is a viable option in the water hydraulics [23, pp. 90-96]. However, when the hydraulic cylinder is functioned with water, corrosion resistance, smaller leakage clearances and lubrication achieved by the surface materials must be considered. The worse damping properties of water must be considered too, which can be achieved with the use of end-stroke cushioning. As the mining robot will be using muscle-like actuators instead of conventional hydraulic cylinders, detailed explanation of the hydraulic cylinders is disregarded [1]. The muscle-like actuators are examined thoroughly in a following chapter.

Motors on the other hand could be used in the mining robot. There are two type of motors, the ones that carry out continuous angular motion and semi-rotary motors, which are only capable of rotating limited angular motions, for example only one revolution [23, p. 81]. Continuous motor is basically a hydraulic pump, with some differences [22, p. 6]. For example, all pumps are not reversible because of their sealing arrangements. In addition, pumps are usually efficient at high speeds and lack the efficiency at start-ups. Furthermore, the motors must support big shaft side loads, which could break the structure of a hydraulic pump.

The main variables to consider when designing a motor are torque, speed, volume flow rate and pressure [23, p. 81]. In addition, cost, level of noise, suction performance, contaminant sensitivity and weight should be regarded [22, p. 6]. When these values are discovered, the correct pump type and features can be selected.

When using water as the medium in the hydraulic motor, same precautions as with the pumps must be considered [23, pp. 85-90]. For example, the higher leakage is again the reason why majority of water hydraulic motors are piston type. Corrosion resistant materials is also required for the motor structure.

4. MUSCLE-LIKE ACTUATORS

A part of the water hydraulic system of the mining robot will be muscle-like actuators. Even though the use of these actuators is not yet known, the basics and properties of the actuators can be examined.

There are a few different types of muscle-like actuators available today. The differences and features of these will be examined.

4.1 Background of artificial muscles

This chapter will address the history and definition of the artificial muscles, or AM. The mining robot will use the water hydraulic system to power the hydraulic artificial muscles, which means that the further examination of pneumatic or other type of artificial muscles can be disregarded.

Despite the actuation mechanism of HAM being close to the pneumatic counterpart, the studies have been concentrating more in the pneumatic side [27]. Similarity of these two is apparent, but some differences of features and functions can be found.

4.1.1 History of artificial muscles

There has been interest in muscle-like actuators, also referred as artificial muscles, from the start of the 20th century [28]. The first patent associating artificial muscles, was De Levaud's "Apparatus for Generating an Over-or-Under Pressure in Gases or Liquids", which was awarded in 1929. A few patents followed in the following three decades, including the McKibben pneumatic artificial muscle. This patent is the reason why PAMs are often referred as "McKibben actuators", even though the correct attribution could be given to the foundational work by De Levaud, Morin, Woods and Gaylord.

However, the McKibben's aim to bring motion to his daughter's polio-paralyzed hands in 1950s, was the first attempt of using muscle-like actuator in prosthetic applications [29][30]. In addition, the first use of term "artificial muscle" took place. Figure 9 shows the components of the McKibben Artificial Muscle System.

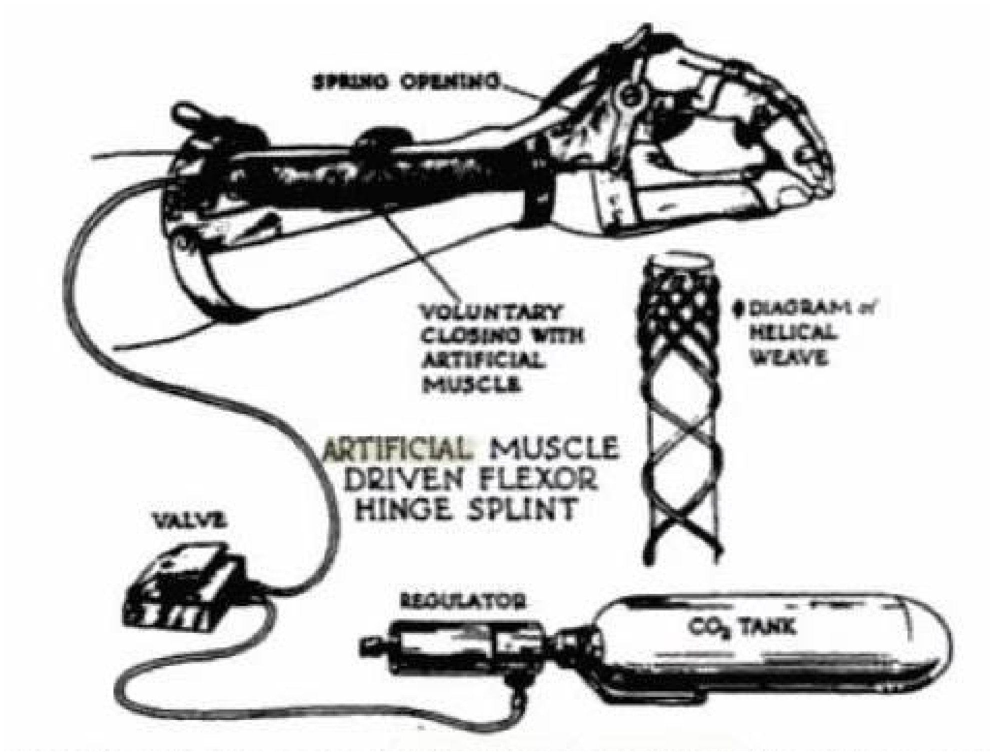

Figure 9. *Joseph Laws McKibben's Artificial Muscle System [29].*

The commercialization of the PAMs was executed by Dynacycle in 1970s and Bridgestone in 1980s [28]. Figure 10 shows the artificial muscles and their operation principle developed by Bridgestone in 1980s [31].

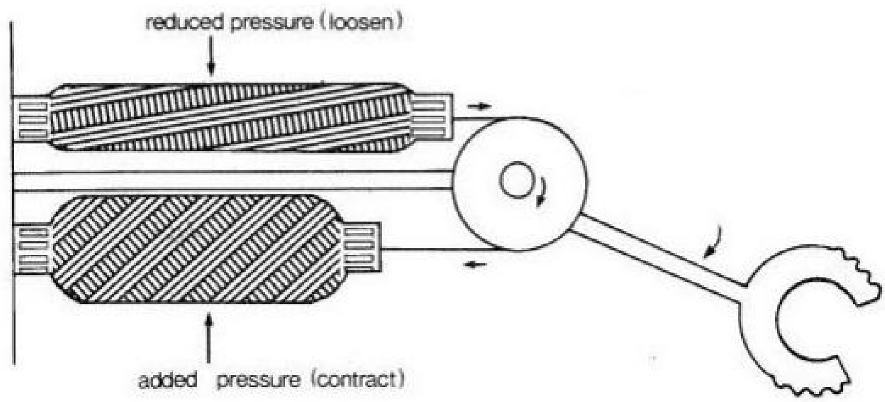

Figure 10. *Bridgestone's artificial muscles and their operation principle [31].*

The movement mechanic is basically the same as in the human body [27][32]. There are pair of muscles that are connected to joints at the ends. The movement is achieved by rotating the joint by loosening one of the muscles and by contracting the other one. The contraction or loosening of the muscle inside the human body is achieved by alternating the amount of blood inside the muscle. In the AMs contraction and loosening is achieved likewise by altering the amount of fluid, air or other medium inside the actuator.

This mechanic can be used to achieve large variety of motions, if multiple muscle pairs and different kind of joints are used. Bridgestone's and Hitachi's pneumatically used hydraulic arm used a series of muscles, wire ropes and pulleys to achieve human-arm-like maneuverability in 1980s [31]. The arm, shown in Figure 11, was capable of rotation around 7 axes.

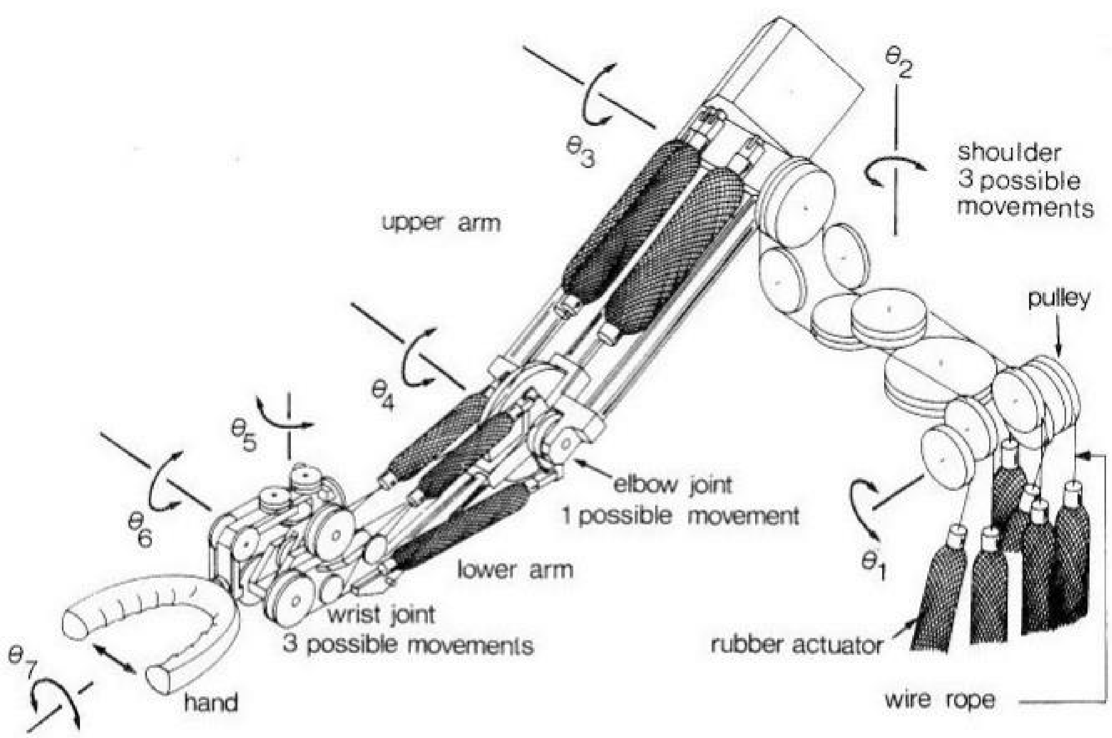

Figure 11. *Bridgestone's and Hitachi's robot arm [31].*

Despite the early commercialisation, comprehensive models that describe the movement of PAMs in dynamic and quasi-static scenarios are still under research. In addition, hydraulic artificial muscles and their use does not have as long history as the PAMs. The use of HAM has been reported in the literature for the first time by Yoshinada et al. in 1991 [33]. In addition, the research of HAMs in some categories like modelling and control is scarce [28]. However, the research in the HAM area has been growing since the late 2000s.

4.1.2 Definition of artificial muscles

Every AM has the same working principle of movement achieved by contracting or loosening [28]. This function can provide a bending, twisting, pushing or pulling motion. Force of the AMs is usually one-directional, which means that if an AM is designed for pulling, it cannot be used for pushing.

The contraction in AMs is achieved by increasing pressure inside the AMs membrane [34]. When the membrane tries to increase its volume against the non-extensible shell due to the increased pressure, the AM will be shortened. This shortening will generate a pulling force, if a load is connected at the end of the muscle.

The AMs are divided into PAMs and HAMs depending on the medium that is used inside the membrane. PAMs use air as the medium, whereas the HAMs use water or other fluid as the medium.

However, it is good to be aware, that the AMs are not limited to these two types. For example, a strain-programmable fibre-based artificial muscle have been developed [35]. This thermally controlled fibre-based AM operates either by twisting or contracting just like the PAMs and HAMs [36]. There are also AMs, which operation is achieved by changing voltage or current flowing through the AM's material [37][38]. These are mostly disregarded due to their infeasible pairing with the water hydraulic system. In addition, their robustness and resistance to wear and tear are not at the needed level. Furthermore, these kinds of AMs are hard to find as commercial off-the-shelf (COTS) products.

4.2 Hydraulic artificial muscles

This chapter is an overview of HAMs and their operation. Their performance and comparison to conventional hydraulic cylinders is also examined.

Surprisingly many studies about HAMs and their performance were found. In addition, big part of these studies has been made in the 2010s, which means that most of the results are new or up-to-date at least.

4.2.1 The structure of a hydraulic artificial muscle

The structure of a HAM is basically the same as a PAM's structure. The muscle-like tube consists of a flexible inner material, for example rubber, which is encased with a wrap of a braided fibre. Typical wrap material is a polymer fibre. The flexible inner tube and its wrap are closed with end caps, which usually contain a bracket for mounting. In addition, a port for the fluid flow is made for one end of the HAM. A typical structure of a HAM is shown in Figure 12. [28][33][39][40][43]

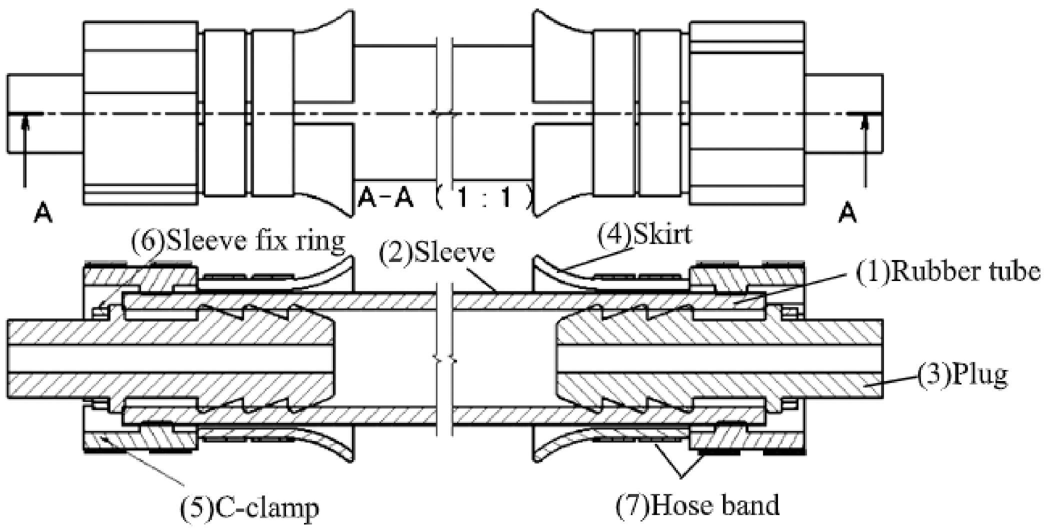

Figure 12. *A typical structure of a HAM [39].*

In this example, a rubber tube is enclosed with a sleeve and both ends of these are pinched between a plug and C-clamps. Additional “skirts” are attached to further fix the tube and the sleeve and to lead their movement. The sleeve is also secured with an additional fix ring behind the shoulder of the plug. Hose bands are used to keep the C-clamps and “skirts” attached. [39]

HAMs can be divided into different categories in many ways [41]. One is the operating fluid division introduced earlier, other one is the pressure operation, which divides HAMs into underpressure and overpressure types. Another way of distinguishing the AMs from each other is the membrane movement, dividing to stretching and rearranging of the membrane. The division can be also made according to the design of the sleeve. Three main types of designs of the HAMs can be distinguished:

- Braided muscles
- Netted muscles
- Embedded muscles.

The braided and the netted muscles are basically the same, but the braided muscles have higher density of the threads in the braided mesh shell. In the embedded muscles, the mesh is embedded inside the elastic tube. [33]

For this study, division according to the design is the best way to categorize the HAMs. This is since only overpressure and stretching types of HAMs are studied. Furthermore, only fibre-reinforced elastomeric enclosure (FREE) HAMs are studied [40].

In addition to the design of the mesh, the thread material is very important for the operation of the HAM. The maximum pressure that can be applied depends on the strength of the sleeve rather than the rubber tube. This is the reason why the selection of right mesh design and fibre material is important. In Figure 13, a stress-strain plot of 4 different sleeve materials is shown. [39]

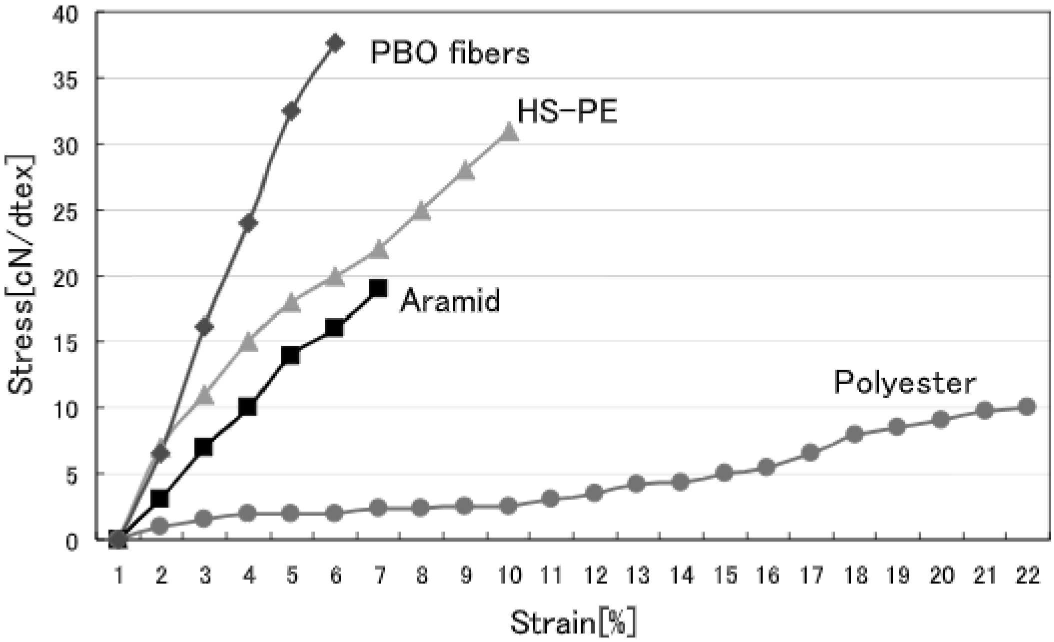

Figure 13. *Stress-strain plot of different sleeve materials [39].*

There are also other variables to consider when selecting the sleeve material. Figure 14 shows elasticity, fire resistance and heat resistance of these materials compared to Polyester.

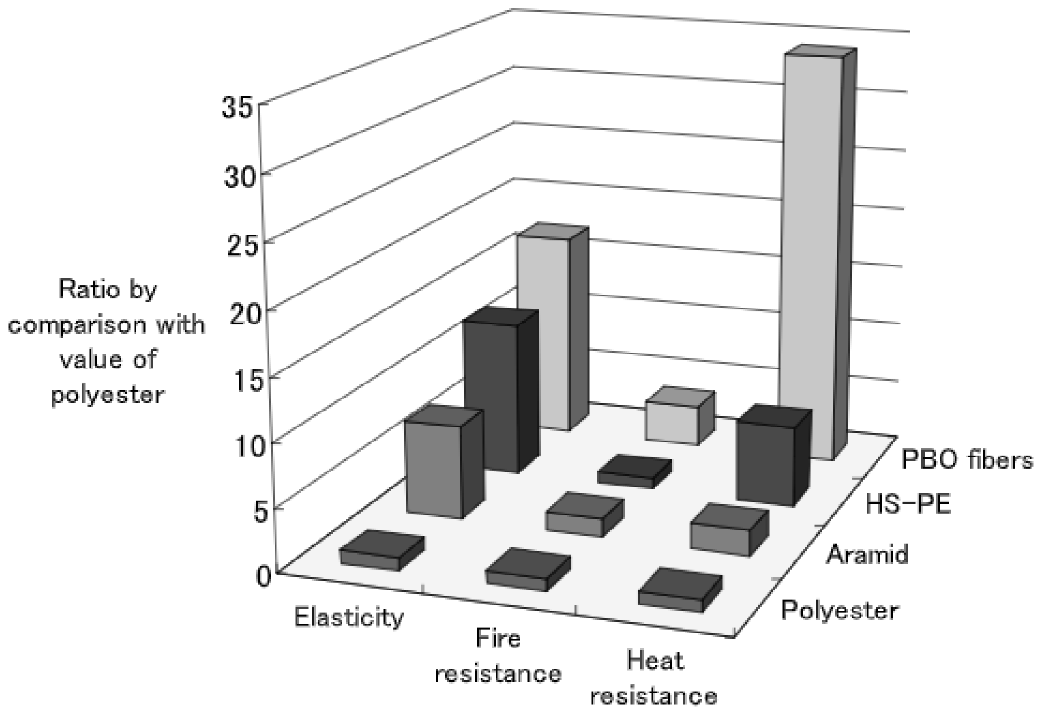

Figure 14. *Elasticity, fire resistance and heat resistance compared to polyester [39].*

The PBO fibres seems to be exceptional in resistance to fire, heat and stress. It is also the most elastic of these 4 materials. Furthermore, the PBO fibre is achieving 5,8 GPa tensile strength and 270 GPa tensile modulus [42].

As shown, different mesh materials will greatly affect the features of the HAM. In addition, the different mesh geometries will affect the behaviour of the HAM. This will be better explained in the next chapter, where the operation of the HAM is introduced.

4.2.2 The operation of a FREE actuator

As with many AMs, the operation of a fibre-reinforced elastomeric enclosure (FREE) actuator is achieved by alternating the amount of fluid inside it [28][33][39][40][43]. This type of HAM constructs from the elastomeric enclosure which is reinforced with a wrap. In this type of HAM, shown in Figure 15, forward and backward fibre wrap angles are equal and opposite [40]. It can be said, that FREE actuator is the most common type of HAM used [33][39][40][41][43].

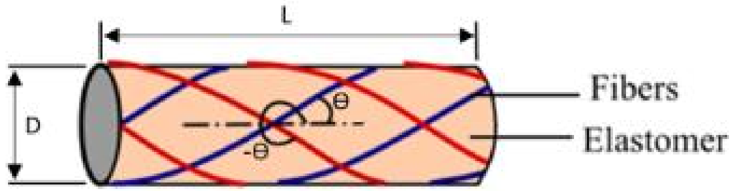

Figure 15. *The fibres and elastomer of a FREE actuator [40].*

When axial force is needed, fluid is pumped into the actuator, which makes the actuators diameter *D* increase and the actuators length L decrease [40]. Changing rate of these dimensions are dependent on the fibre wrap angle *θ*. In addition, the axial force is proportional to the input pressure. When the pressure inside the actuator drops, the axial force will also decrease. It is good to be aware, that a single actuator of this type can only produce one-directional axial force.

As examined carefully in Thomallas and Van de Vens article [40], there are couple of different methods for calculating the axial force of the muscle. However, in many models the elastic force originating from the elastomer have been disregarded. This is not significant for PAMs, as the wall thicknesses are smaller compared to HAMs. To prevent buckling and burst failure, hydraulically used actuators are usually thicker walled, which means that the elastic force will grow to the level that it should be considered in the calculations. This is even more true for applications, where precise force and position control are required.

The axial force can be calculated from the fibre angle, from the contraction ratio and from the fibre angle with the accounting for the wall thickness of the elastomer [40]. However, the most accurate results of the force have been achieved with a model, that is based on a function of contraction ratio and changing wall thickness, $F\ (\varepsilon, t)$.

The contraction ratio of the actuator is defined as

$$\varepsilon = \frac{L_0 - L}{L_0} \tag{1}$$

where ε is the contraction ratio, L_0 initial actuator length and L current actuator length. This can be rearranged to

$$L = (1 - \varepsilon)L_0 \tag{2}$$

which will give actuator length at a given contraction.

For the contraction force originating from the fibres, two different approaches are needed. Firstly, the following expression is defined from the geometry of the mesh:

$$\frac{L}{L_0} = \frac{\cos(\theta)}{\cos(\theta_0)} \tag{3}$$

where θ is the current fibre angle and θ_0 the initial fibre angle [44]. Secondly, the conservation of work relationship of fluid pressure and output force, originating from the axial displacement due to the change of volume, can be defined as follows:

$$-pdV = FdL \tag{4}$$

where p is the fluid pressure pushing towards the inner surface of the elastomer, V volume of the actuator and F the contraction force. Before further derivation of the force, the volume must be extracted.

Firstly, expression for the current elastomer wall thickness t is developed by assuming that the elastomeric material is incompressible and the volume of the elastomeric material stays constant. This way, following expression is obtained:

$$t = \frac{D}{2} = -\sqrt{\frac{D^2}{4} - \frac{t_0(D_0 - t_0)}{1-\varepsilon}} \tag{5}$$

where D is the current outside diameter, D_0 initial outside diameter and t_0 the initial wall thickness [40]. After the wall thickness is known, the volume of the actuator can be expressed as follows:

$$V = \frac{\pi(D-2t)^2 L}{4} \; . \tag{6}$$

Finally, the contraction force F from (4) can be rearranged and solved with the help of (2) and (6) to this form:

$$F = -p\frac{dV}{dL} = -p\frac{dV/d\varepsilon}{dL/d\varepsilon} \; . \tag{7}$$

This fibre force equation as a function of contraction ratio and changing wall thickness can be further solved and expressed as

$$F_{fibres} = -p\left(\pi C_1^2 + \pi C_1\left(\frac{t_0(t_0 - D_0)}{C_1(\varepsilon - 1)} + D_0(1 - C_2)\left(\frac{t_0}{C_1 C_2(\varepsilon - 1)} - \frac{1}{\sin(\theta_0)\sqrt{C_2}}\right)\right)\right) \tag{8}$$

where C_1 and C_2 are following constants constructed for viewing purposes:

$$C_1 = \sqrt{\frac{D_0^2 C_2}{4\sin^2(\theta_0)} - \frac{t_0(t_0 - D_0)}{\varepsilon - 1}} \tag{9}$$

$$C_2 = 1 - \cos^2(\theta_0)(\varepsilon - 1)^2 \; . \tag{10}$$

As can be seen from the equations (8), (9) and (10), the force originating from the fibres have been developed to the form, where there are only initial values of the actuator dimensions, such as fibre angle, length, diameter and thickness. Furthermore, variables that need to be solved during operation, like pressure and contraction ratio are easy to measure. These reasons and good accuracy compared to other equations are the main benefits of this fibre force equation [40].

The elastic force term of the actuator is developed as a function of the contraction ratio, changing wall thickness and initial actuator dimensions, and can be expressed as follows:

$$F_{elastic} = -\pi E\left((R_0^2 - (R_0 - t_0)^2 \frac{\varepsilon}{\varepsilon - 1} + \frac{2R_0^2(1-\varepsilon)^2}{R\tan^2(\theta_0)}\left(t - \frac{t_0}{1-\varepsilon}\right)\right) \quad (11)$$

where E is Young's modulus of the elastomer, R_0 initial outside radius of the elastomer and R the current outside radius of the elastomer [40]. As can be seen, the values of the elastic force might be harder to obtain during the operation. For example, the change of the elastomer thickness might be hard to measure during operation. In addition, the Young's modulus might be hard to measure accurately [40]. However, different methods like Gent's model can be used to approximate the Young's modulus.

Finally, by combining the forces originating from the fibre and the elastomer, total axial force can be solved:

$$F_{total} = F_{fibres} + F_{elastic}\,. \quad (12)$$

This force calculation method might be difficult for performance testing, as the equation (11) requires constant knowledge of variables that are changing. For this reason, alternative force calculation is shown [40]:

$$F = \frac{\pi D^2 p}{4}\left(\frac{1}{\sin(\theta_0)}\right)^2 (3(1-\varepsilon)^2\cos^2(\theta_0) - 1)\,. \quad (13)$$

With this equation, the force is predicted as a function of the contraction ratio and assuming there is no elastomer wall thickness and extensible fibres [40]. In addition, it is assumed that the actuator remains cylindrical and the measurements are taken far from the system boundaries. However, this equation is useful when the actuator can displace because knowledge of changing variables is not needed. In addition, this is the most used force calculation method in HAM researches to date [40]. Even though the predictions might not be as accurate as with the equation (12), sufficient accuracy can be achieved.

4.2.3 Performance of hydraulic artificial muscles

Now that the usual HAM's structure and operation are introduced, the focus can be moved towards performance. In addition, it is good to be aware what are the benefits and what are the downsides of HAMs.

In many studies it comes clear that HAMs achieve significantly high power to weight ratio [33][39][40][43]. Easily over 10 times higher power to weight ratios can be achieved compared to conventional hydraulic cylinders [28][43]. In addition, with right materials and 40 bar pressures even 28 kN contraction forces have been achieved with 40 mm diameter actuator [39].

In Figure 16 a good baseline of performance comparison is shown. HAMs are compared to human muscles, electromagnetic actuators and hydraulic actuators.

Actuator	Strain %	Stress [MPa]	Specific Power [W/kg]	Bandwidth [Hz]	Stiffness [MPa]
Muscle	20	0.35	50	30	20
Electromagnetic	50	0.035	200	30	0.1
Hydraulic	70	20	2000	50	1380
HAM	25	3.5	29560	50	2.75

Figure 16. *Performance of HAMs [28].*

A major drawback of significantly smaller strain compared to conventional actuators like hydraulic cylinders can be seen. This drawback can be countered with transmission and joints, but the capability of 25% displacement from the normal length is a major disadvantage to consider. In addition, the stress resistance of HAMs is quite poor compared to conventional hydraulic actuators. However, again the substantially higher power to weight ratio can be seen. This is the main reason why HAMs are better alternative compared to other actuators. Furthermore, the stiffness of a HAM is much lower compared to other actuators. The stiffness of a HAM is still over 5 times higher compared to same type of PAMs. In addition, this problem can be countered by increasing the amount of HAMs or by adding a mechanical support structure. Furthermore, the flexing and bending capabilities of HAMs can be utilised in soft robotics. [1][28][33]

Along with the performance benefits, HAMs have many great traits coming from the compact structure [33]. The actuating is achieved with minimal amount of moving parts, which makes the HAMs very simple. This simplicity makes the HAMs also reliable and cost effective. In addition, the closed and singular structure makes HAMs usable in dirty or underwater applications [1][33][43]. This is a big benefit compared to hydraulic cylinders, since if the cylinder rod is exposed to dirt it can lead to oil leakage and faults in case the rod seals get damaged.

Another benefit compared to hydraulic cylinders is the fact that there is no stick-slip phenomenon in HAMs [45]. This phenomenon appears in sliding structures due to the difference of static and sliding friction and causes vibrations and uneven movement at the start of the displacement. Stick-slip is problematic to hydraulic cylinders when they are moved at low rate [46].

One major challenge in the use of HAMs is controllability [33]. As the output force is a function of the contraction rate and pressure, HAMs are more complicated to control and model compared to hydraulic cylinders, as the force of cylinder is only a function of pressure [33][40].

5. WATER HYDRAULIC SYSTEM OF THE MINING ROBOT

Now that the differences of conventional hydraulic fluids and components compared to water and water hydraulic components have been explained, focus can be moved towards the mining robot prototype. The aim is to outline the most important factors to consider with the water hydraulic system of the prototype. This will ease the design of the system and hopefully lead to better execution of the future mining robot.

In addition, suppliers for water hydraulic pumps, valves and motors are surveyed. The important values of these components are also examined. Furthermore, the plausible production tools are studied. Finally, use of HAMs in the prototype is examined.

5.1 Selection of hydraulic system features

The mining robot prototype will have capabilities of a modern 1-ton excavator. This means, that the power input is between 20 and 30 kW. To improve the power density and reduce the system volume, high hydraulic system pressure will be used. The pressure goal is between 500 and 800 bar, which might be required for the underwater operation as well as in some production methods. The water hydraulic system should also be able to circulate the water from the cave or function as a closed system, if there is no water available from the mine. [1]

These requirements push many boundaries of the hydraulics. The change of medium from oil to water itself might lead to many challenges. Additionally, the desirable system pressures are quite high even for oil hydraulic systems. In addition, the filtration needed for the use of cave water inside the hydraulic system will require overcoming many challenges. However, if these challenges can be solved, the benefits of this system will be significant compared to the conventional ones.

As the structure of the prototype is not yet known, a precise design of the water hydraulic system is disregarded. However, due to the similarities of hydraulic systems, a rough estimate what the hydraulic system will include can be done. Therefore, the main components of a hydraulic system, including pumps, valves and actuators are examined.

Before diving into component selection, a fast look towards hydraulic system design options in general is advisable. Selecting the options is not an easy task because a compromise among many variables must be made [23, p. 133]. These variables include but are not limited to:

- space requirements
- accuracy requirements
- cost-effectiveness
- reliability
- energy consumption
- maintenance requirements
- maintainability
- use of standard components
- low environmental impact
- low fire hazard
- integration of the hydraulics with other systems.

In the mining robot's hydraulics, the low environmental impact, reliability, good power density and small size seems to be the top priorities. In turn, use of standard components and cost-effectiveness seem to be less important.

Furthermore, after the water hydraulic system is designed and built, the different maintenance needs compared to oil system must be considered. Some maintenance and cleanliness aspects are same as in the oil systems, but the stability of water is not as easily achieved as with the oil. For example, microbiological hygiene, purification of added water and frequent monitoring of water quality are additional maintenance tasks compared to oil systems [23, p. 151].

The growth of bacteria, fungi, molds and other microorganisms inside a water hydraulic system can also be prevented, thus making the maintenance easier. If the tap water is filtered and the system is closed from external particles, the good quality of water will remain longer. This means, that the air breather of the reservoir should have absolute filtration rating of 3 µm or better, tank lid must be air-tight, refilling water should be purified, quick coupling connections must be kept clean and the hydraulic components must be sealed from outside particles [23, pp. 53-54]. For comparison, the diameter of human hair is 70-80 µm and the diameter of bacteria is 2-3 µm [23, pp. 120-122].

5.2 Control system of the hydraulics

The mining robot's structure will be modular, and it is thus able to scale its size or increase its functions by adding more sections together [1]. This means that the sections must communicate with each other and the control system will consider how many sections are connected and what is the condition of each section.

This is the reason, why multiple hierarchy levels of the control system will be used [1]. Higher level of the control system will gather data from the lower levels, and then make decisions, which will influence the lower hierarchy levels. The lower hierarchy levels will then operate by computing the data from the sensors and from the higher hierarchy levels. For example, the lowest hierarchy level could be a processor sensing an actuators position and trajectory. The highest hierarchy level could be a master computer that would connect to the robots control system wirelessly.

The control system will also use closed-loop autonomy engineering [1]. The "autonomy-loop" in Figure 17 shows how this kind of system works. The requirements are sent to meta-controller, which also considers the data coming from the feedback loop. After that the meta-controller will send system configuration for the execution part of the system, which outputs the wanted behavior of the system. When the meta-controller notices external or internal disturbance, it will perform a re-design to produce a new system configuration, which is the corrective control action executed at runtime.

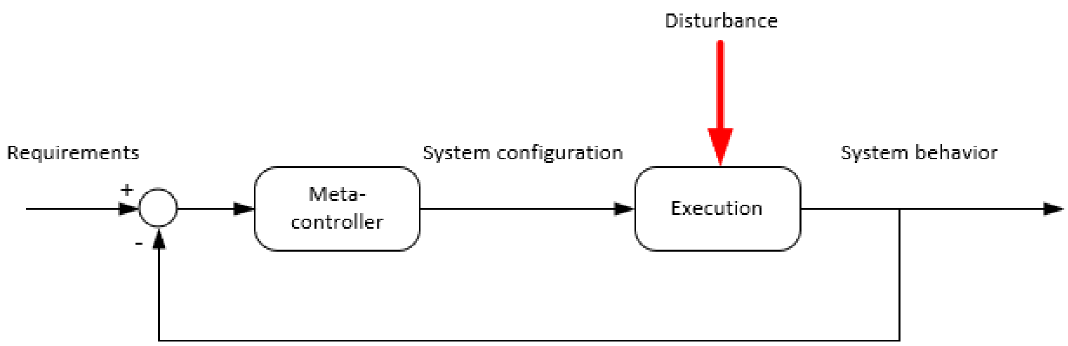

Figure 17. *Resilient control architecture.*

This kind of reconfigurable system is required for the resilient operation and redundancy [1]. The capability to recover original functions under failure and fault-tolerant design are the strategies that the mining robot will use to minimize downtime.

To get the water hydraulic system also as a part of the main control system, most of the valves need to be digitally controllable. The digital valves also could acquire data for the control system, thus minimizing the need of sensors.

In the future, the control system could be upgraded to observe multiple mining robots at the same time. This would enable the swarming possibility of mining robots, which could be beneficial in some mining scenarios.

5.3 Components of the water hydraulic system

Water hydraulic systems require components distinct from the conventional hydraulic systems that usually use mineral oils as fluid. As the usage of water hydraulic systems is scarce, supply of water hydraulic components might be narrow. For this reason, water hydraulic component suppliers are searched, and the component supply outlined.

5.3.1 Water hydraulic pumps

As the flow rate and maximum pressure of the mining robot prototype is not solved yet, it cannot be defined what type of pump is or is not suitable. However, good estimation of maximum values that can be achieved can be examined by looking water hydraulic supplier's data. In addition, this way new constrains or possibilities can be found concerning the design of the prototype's hydraulic system.

It might come as a surprise, but there are not many water hydraulic pump suppliers. There are many centrifugal water transfer pumps, but hydrostatic ones are rare. However, the three suppliers shown in the Table 2, are manufacturing water hydraulic pumps with a large variety of qualities. As it can be seen, there are pumps with suitable power and weight values for the mining robot. In addition, the speed ratings and volume flow rates of the pumps seem suitable. Only property that might seem too low, is the maximum pressure. In today's water hydraulics, the ultra-high pressure seems to be unachievable with small sized pumps.

Table 2. *Water hydraulic pump suppliers and pump specifications [47][48][49].*

Supplier	Power [kW]	Pressure [bar]	Volume flow rate [l/min]	Weight [kg]	Maximum Speed [rpm]
Danfoss	1 - 55	30 - 160	1 – 187	4.4 - 31	1800
Water Hydraulic Company	0.55 - 114	20 - 160	1 - 430	1.5 - 82	2000
Hauhinco	1 - 400	130 - 575	42 - 738	590 - 2164	1800

For this reason, the high pressures needed in hydrodemolition or other actuation methods require hydraulic pressure intensifiers. This also means, that the benefit of small components due to high pressures might be hard to achieve. On the other hand, the use of hydraulic pressure intensifiers is not problematic, as they are quite small and achieve high pressure increase ratios [50]. As high as 800 bar outlet pressure can be achieved with only 15 bar inlet pressure [51]. There are also hydraulic pressure intensifiers suitable for tap water, which will ease the production of the water hydraulic system of the mining robot prototype [52].

To ensure the environmental-friendliness of the pump, it should be noticed if oil is used for lubrication of the pump or the gearbox of the pump. In the Hauhinco pumps for example, oil is used to ensure lubrication of the crankshaft and gearbox of the pump [49]. Danfoss' and Water Hydraulic Company's pumps use only water for the lubrication, and different displacement may be achieved without gearboxes, which usually require oil lubrication [23, pp. 71-77] [47] [48].

After the supplier selection, a closer inspection for requirements of the pump is needed. For example, inlet pressures as high as 30 bar is required in Danfoss' pumps [47]. In addition, pump materials might differ between stainless and acid-resisting steel, which might be important when using additives with water [47][48].

Water filtering must be considered too. The Water Hydraulic Company recommends, that all their pumps receive only pre-filtered water with absolute filtration level of 25 μm or better [48]. Quality of the water should also conform to the EEC-directive 98/83/EC. It is the European Commission's Drinking Water Directive, which regulates for example the quality of tap water [53].

The hydraulic pump of the mining robot will be rotated with an electric motor [1]. The electric pump is connected to a cable, which is run up to the surface.

5.3.2 Water hydraulic valves

The same three suppliers as in the Table 2 manufacture also water hydraulic valves [54][55][56]. The Danfoss' valve selection seems a bit narrow, but the other two suppliers have a large variety of valves available for water hydraulic applications. There is pressure, shut-off, flow control, proportional and directional valves available from the two suppliers. The Water Hydraulics Company mostly manufactures smaller valves, which handle maximum of 160 bar pressure and volume flow of 30 l/min [55]. The Hauhinco on the other hand, can achieve maximum pressures between 300 and 500 bar with volume flow from 10 l/min all to way up to 500 l/min [56]. However, the high pressures and volume flows require big and heavy valves, the weight reaching 578 kg at the maximum and 10 kg at minimum. Manually, hydraulically of electrically controlled valves can be found from all these suppliers.

It seems that there is a large selection of valves for the mining robot prototype. Yet the size and weight requirements of the valves might be a challenge. In addition, the high pressures for achieving the small hydraulic component sizes can make it difficult to find COTS valves [25].

Like the water hydraulic pumps, pilot lines of the valves require 25 µm absolute filtration rating. The pressure and actuation lines of the valves require looser absolute filtration rating of 100 µm [56].

5.3.3 Water hydraulic motors

The mining robot might need motors for moving, production tools or other actuation methods. Unfortunately, the COTS water hydraulic motors are even more rare than the water hydraulic pumps [23, p. 85]. Only Danfoss and Water Hydraulic Company seems to be viable suppliers for water hydraulic motors [57][58]. However, both suppliers have a few different displacement options for the motors. The specifications of the motors, shown in Table 3, should reach the requirements of the prototype's water hydraulic system.

Table 3. *Water hydraulic motor specifications [57][58].*

Supplier	Maximum torque [Nm]	Maximum pressure [bar]	Displacement [cc/rev]	Weight [kg]	Speed range [rpm]
Danfoss	8 - 25	140	4 - 12.5	4.1 - 6.3	300 - 3000
Water Hydraulic Company	7 - 550	160	3 - 225	1.5 - 82	300 - 4000

The drawback of Danfoss' motors are the level of the maximum torque. These values mean, that in many applications a gear would be needed in between the motor and the actuated unit. The Water Hydraulic Company's motors on the other hand reach high level of torque with the other specifications staying in suitable limits. All the motors are fixed displacement type, but some adjustability can be achieved by replacing the inner parts of the motor [23, p. 86] [57].

Another drawback of Danfoss' motors are the filtration rating needed. The motors require 10 μm absolute filtration rating. The Water Hydraulic Company's motors require only 25 μm absolute filtration rating like the pumps and valves. [57][58]

In the selection of the motor, its efficiency should be considered. When using over 140 bar pressure, the smaller motors start to lose their efficiency rapidly. On the other hand, the bigger motors increase their efficiency greatly when reaching pressure of 80 bar. [58]

5.3.4 Production tools

The mining robot will need cost-effective production tool or tools for mining [1]. Conventional mining methods, like blasting and hauling, seem unprofitable for the size of the mining robot. In addition, conventional mining tools may not be suitable for the operation inside a slurry or underwater. These are some of the main reasons, why innovative production tools might be needed for the mining robot.

As explained earlier, inside a water hydraulic system the medium must be clean from particles and microorganisms. This is a challenge also for the production tools such as drills since they have moving parts with sealed surfaces.

There is also an innovative idea of adding more sections to achieve adaptation of robot size, production power and reach of the tool [1]. This could be beneficial for example hydrodemolition, where high pressures might need additional hydraulic pumps and pressure intensifiers. However, the connection of these sections under dirty conditions is challenging. Even small particles passing the filters and dirt protection of the connectors might be destructive to the water hydraulic system components. Self-alignment and self-locking mechanisms will help the connection, but water and dirt protection of the couplings must be engineered precisely to prevent water contamination.

On the other hand, some of the production tools might be functional without additional pumps and power intensifiers. For example, the water hydraulic components shown in Table 2 and Table 3 are capable of same volume flow, torque and pressure ratings as Sandvik's smaller rock drills [59]. However, the percussion of top hammer rock drill might not be easy to achieve with water hydraulics. A top hammer rock drill hammer and rotate the drill rod simultaneously. One option is to use Sandvik's drills but combining water hydraulic system with the oil lubricated rock drills might be challenging. Biodegradable oils are an option for the hydraulic and shank lubrication of the drills. This could be a suitable option for the lubrication of the drills and water could be only used for power transmission.

A top hammer rock drill could form a section of the mining robot. However, the smallest rock drill weighs only 54 kg, which means that the drill could probably fit with the hydraulic system inside a single section [59].

Another option of current rock drilling technology would be down-to-hole (DTH) drilling [60]. In this type of method, the percussion is achieved by air pressure and a special DTH hammer. Compared to the top hammer rock drill, only rotation for the drill pipe is needed because the DTH hammer will operate by means of compressed air. However, the air consumption of even the smallest DTH hammers is 4,87 m^3/min with 10 bar pressure. And for higher pressure of 24 bar, the air consumption increases to 12.34 m^3/min. To keep up with the air consumption, a large compressor is needed. To comparison, a smallest DTH surface drill rig from Sandvik, requires a 261kW diesel engine to run the drill rig and its compressor [61]. The air delivery of this unit is 18 m^3/min at 24 bars. However, it might be possible to deliver the air from a compressor lying on the surface to the mining robot, which would decrease the weight and size of the mining robot.

There is also option for a DTH hammer which uses water instead of the air to achieve the percussion [62]. Wassara promises a wide range of advantages of their water-powered DTH hammers, including low energy consumption, a cleaner environment, minimal hole deviation, deeper drilling capabilities, a high power-output ratio and minimal impact on the surrounding ground. However, the water consumption needs to be taken into consideration, as it fluctuates between 55 and 670 l/min depending on the hole size.

Third drilling method would be rotary drilling, where the drilling rod is only rotated and pushed towards the rock without percussion [63]. The rotating drill bit will cut or crush the surface.

These three methods are shown in Figure 18 in more detail. The different components needed for the methods are indicated.

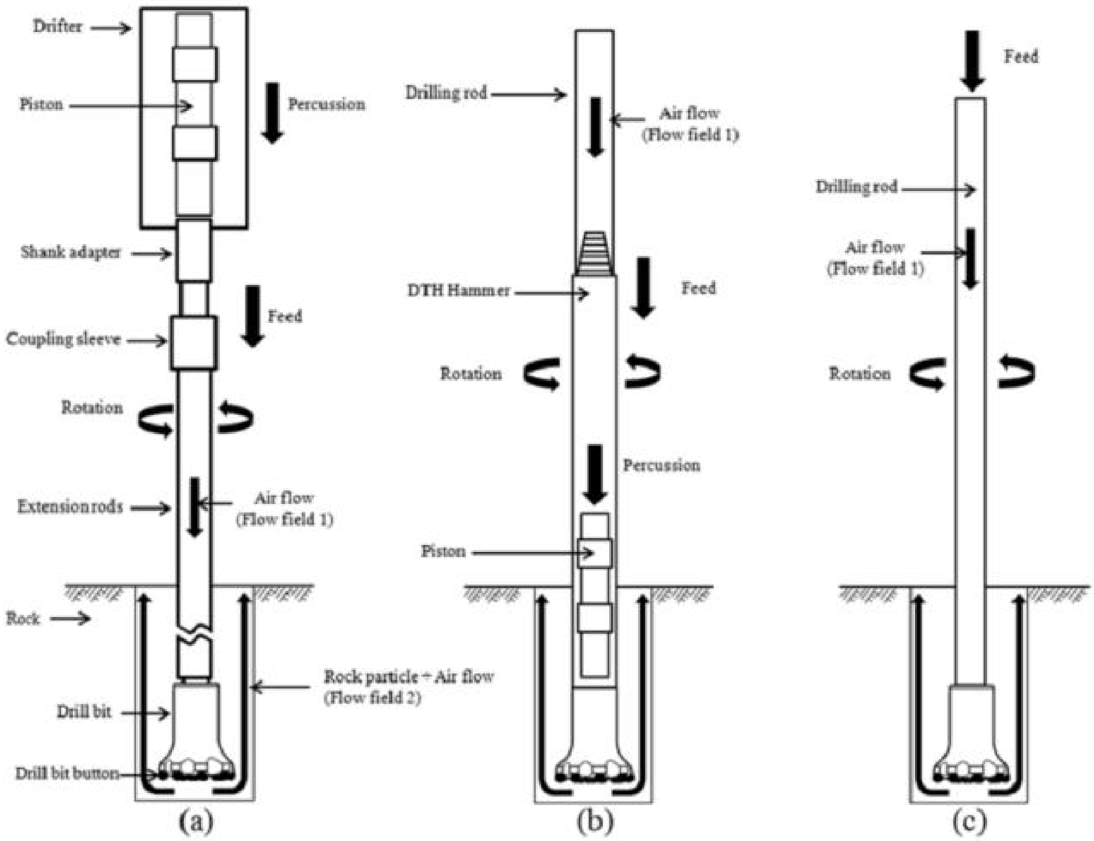

Figure 18. *Three methods of rock drilling. (a) Top hammer drilling. (b) Down-the-hole drilling. (c) Rotary drilling. [64]*

These drilling methods, especially the two percussion methods, are usually used for drilling blastholes for explosives [11, p. 209]. The rock type determines which drilling method is the best. Percussion drilling is required for hard rock, for example volcanic rock [11, p. 211]. In addition, top hammer drills are capable of drilling trough harder rock than DTH drills. Furthermore, rotary drilling can only be used for sedimentary rock, which is much softer than volcanic rock.

The drills designed for fast and cost-effective blasthole drilling might not be the suitable ones for the mining robot. However, the blastholes might be beneficial for the hydrodemolition. In the conventional mining, detonation of explosives will increase the pressure inside the blasthole and develop a detonation wave [11, p. 209]. The combination of these two effects will then break the rock around the blasthole. The hydrodemolition could use the blastholes in similar fashion. First, the borehole could be drilled with a suitable method. After that, the hydrodemolition equipment could close the opening of the borehole. Finally, the borehole could be filled with high pressured water, that would fracture and break the rock. In this method, the “cap” of the hole must be tight and the water pressure high enough to break the rock.

The more conventional method of hydrodemolition, technically hydro-erosion, is a process where high-pressure water is used to cut and remove material [65]. In this method, the water jet removes material by crushing the microstructures, shearing and by the explosive action of water pressure.

This type of hydrodemolition is not a new technology and is widely used in controlled demolition and removal of concrete [66][67][68][69][70][71]. However, its usage in the mining industry and rock breaking still needs researching and testing.

Alternative for the drilling and blasting, or hydrodemolition, would be tunnel boring. The small disturbance to the surroundings would make this production method suitable to use in heavily urbanized areas [72]. There is a research of micro tunnel boring machines, which could help the research and testing of this kind of drilling method in the mining robot [73]. A rotary drilling method based on a tunnel boring machine could be a second possible production method for the mining robot. However, the rotary drilling might be challenging and uneconomical in hard rock conditions [11].

The production tool options do not limit to these two methods. However, these seem to be the most promising methods for the mining robot. The water hydraulic system in mind, it should be possible to change the production tools easily so that the adaption for the soil can be done.

5.4 The use of hydraulic artificial muscles in the mining robot

As there will be water hydraulic system in the mining robot, HAMs will be a great option compared to the sliding and heavy hydraulic cylinders. An additional benefit of using HAMs in the mining robot is to learn more about these actuators and make them suitable for other biomechanical machinery.

This chapter is divided into two parts. First, actuation system of the robot is examined. Secondly, the HAMs that will be tested are selected.

5.4.1 Actuation system of the robot

The actuation system of the robot is not yet outlined. In the matter of fact, even movement type of the mining robot is not decided at this early state of the development [1]. However, it is known that water hydraulic system will be the drivetrain of the robot. In addition, HAMs will be used as actuators of the robot.

As the actuation system development is still at an early state, it is not possible to sketch a system or decide components. However, some rough estimation can be done, and certain things decided.

Estimation of the forces needed from the actuators can be achieved by looking at the Table 1. The actuators should be achieving forces that can move 1-ton machine. Some smaller actuators might also be needed to move limbs or arms that are connected to the production tools.

Displacement and size limitations can be estimated from the fact, that the mining robot should fit in a borehole which will be drilled for it [1]. The borehole diameter is not yet expressed, but no larger borehole diameter than 1 m should be estimated.

From these factors it can be said, that the actuators should be achieving forces between 1 and 10 kN. In addition, the amount of displacement needed should not go much over 1 m. This is a good baseline of how large forces and movement is needed from the actuators.

The actuators should also be suitable for the water hydraulic system that will be used in the mining robot. This should not be a challenge, but suitable valves and controlling devices for the actuators might be harder to find. The actuators and their accessories should be embedded for wear and tear resistance [1]. In addition, protection for dust, dirt and water should be considered. Temperatures that the actuators will be operating will differ depending on the mining operation. However, this should not be a problem, as the water hydraulic system of the mining robot will be the first limiting factor of operating temperatures.

It is good to be aware, that the HAMs are not the only option for the actuators. For example, some hydraulic motors could be used as their efficiency usually overcomes linear actuators [21]. The selection of correct type of actuator should be done in every part where movement is needed.

It is unfortunate that extensive information of the actuation system cannot be combined, but this information should give some baseline for the test actuator selection. Furthermore, the HAMs selected for the testing does not need to be the ones used in the prototype.

5.4.2 Selection of the test hydraulic artificial muscle

It was seen necessary to test some HAMs to gather information for the mining robot's actuating system. The aim was to see what kind of behaviour and performance HAMs will deliver.

Different criteria of the test HAMs were made, but surprisingly only one manufacturer did sell COTS actuators. It was important that the HAMs would be easy to obtain, as several HAMs will be needed in the development. The properties of the test HAM were not that strict as there is possibility to develop and build a suitable actuator for the prototype.

Festo's single-acting DMSP Fluidic Muscles was selected for the testing. These Fluidic Muscles consist from pressure-tight rubber hose and from sheathed high-strength fibres that create a rhomboidal pattern with a three-dimensional grid structure [45]. The selected test HAM is shown in Figure 19.

Figure 19. *Festo's DMSP Fluidic Muscle [45].*

The Fluidic Muscle is rated to 6 bars and can achieve 6 kN force in the most straightened position. Contrary to Figure 16, Fluidic Muscle can achieve frequencies of 100 Hz. Acceleration values go up to 100 m/s^2 and speed up to 3 m/s. Operating temperature is between -5 and 60°C. [45]

Because the forces needed in the actuation of the prototype mining robot are over 1 kN, the 40 mm inner diameter Fluidic Muscle was selected. The length of the test Fluidic Muscles was decided to be between 250 and 750 mm, as shorter actuator would be harder to test and longer would not fit in the test bench. Finally, 500 mm long DMSP-40-500N-RM-CM and 250 mm long DMSP-40-250N-RM-CM were selected. Table 4 shows the properties and designated names of the test HAMs.

Table 4. *Properties and designated names of the test HAMs [45].*

Test name	FMA	FMB
Supplier	Festo	Festo
Commercial name	DMSP-40-500N-RM-CM	DMSP-40-250N-RM-CM
Function	Single-acting, pulling	Single-acting, pulling
Max. contraction (%)	25	25
Inner diameter [mm]	40	40
Nominal length [mm]	500	250

Both test HAMs are structured in the same manner. Only difference of the two are the length. Longer test Fluidic Muscle was named to FMA and the shorter to FMB.

In figure 20 a graph of force as a function of displacement is shown. The displacement, also known as contraction rate, shows the percentual amount of contraction from the nominal length.

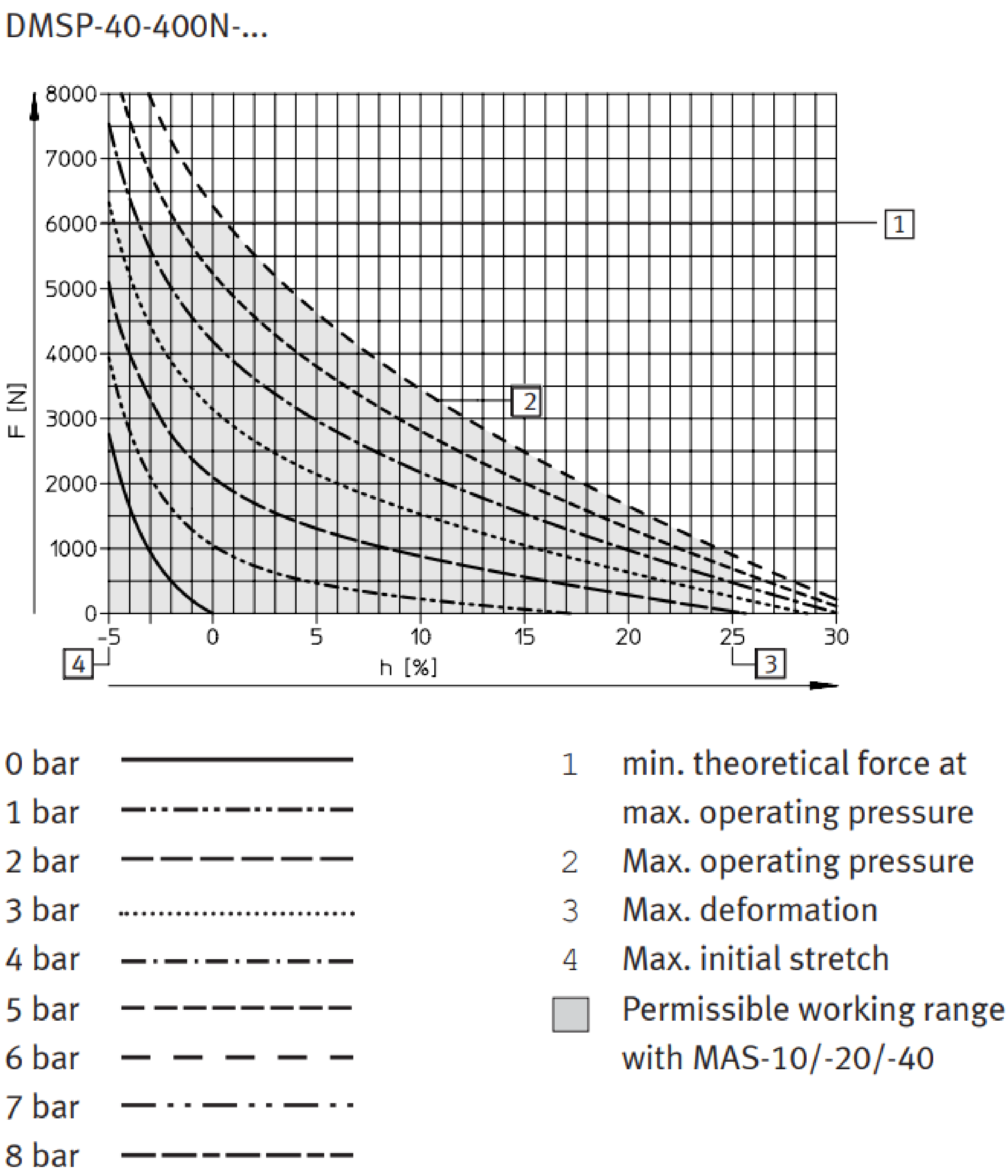

Figure 20. *Force and displacement graph of the Fluidic Muscle [45].*

As it can be seen, the force will decrease substantially as the Fluidic Muscle constricts. The working range is limited to 6 bar, but higher pressures will be tested to see how high forces can be achieved.

There are also second type of Fluidic Muscle available from Festo. The operation is the same as in the DMSP, but the connection is different as the ends have inside threads. The DMSP type was selected as it will be easier to connect to the test bench introduced in the next chapter.

6. TESTING OF THE HYDRAULIC ARTIFICIAL MUSCLES

For achieving better understanding of the HAM and its opportunities in actuation system, some tests were performed. The tests will also second or question the findings of the earlier chapter.

This chapter is divided into two sections. First section will cover the testing arrangements and execution. The second section will introduce results and examine reliability of the results.

6.1 Test setup and execution

As shown in the equation (7), movement and force can be achieved by changing the volume and pressure of the HAM. However, the contraction rate will also affect the output force unlike in the hydraulic cylinder, where the force is the same at every stroke length.

Two different length HAMs were tested. The main aspects that were measured was inlet pressure, output force and contraction ratio of the HAM. In addition, behaviour of the HAM and the water hydraulic system were observed during operation.

The tests were performed at Tampere University's Mechatronics Research Group's laboratory. Big part of the test system was already available, but considerable amount of work was made to achieve the right operating and measuring setup.

The first aim was to drive the test HAMs with water, as they had only pneumatic operation data available [45]. At the same time, the force at given contraction ratio was measured. In addition, different pressure levels were tested to see the maximum force and the pressure limit before failure. Furthermore, influences of fluctuating external forces were put to test.

6.1.1 The test system of linear actuators

Tests of the HAMs were executed with an earlier constructed test bench, which included a hydraulic system and measuring devices. Even though the test bench was ready-made, some fittings for the test HAMs was made. In addition, a water hydraulic system was added to operate the HAM. In Figure 21, a sketch of the test bench and its hydraulic systems is shown.

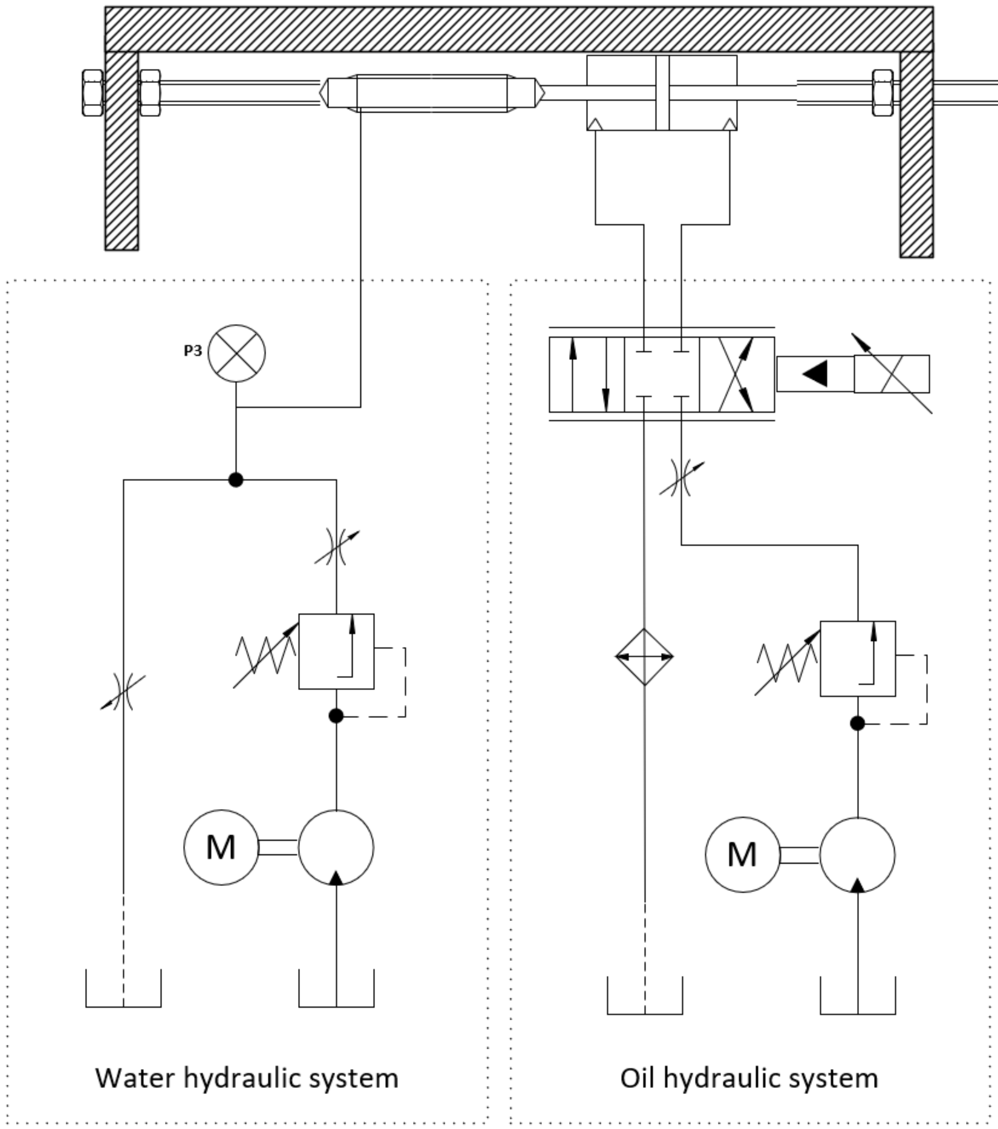

Figure 21. *Test bench and its hydraulic system.*

On the contrary to the sketch, the test bench constructs from a rectangular frame. A double acting hydraulic cylinder is mounted in the frame and a long axle is fixed to one side of its rod. This axle runs through one end of the test bench's frame. Nuts are added to the axle on both sides of the frame to limit the displacement of the hydraulic cylinder. One end of the HAM is fixed in the other side of the hydraulic cylinder's rod. The other end of the HAM is fixed firmly to the test bench frame.

The water hydraulic system is solely used to operate the HAM and the oil hydraulic system is used to operate the double acting cylinder. The water hydraulic system is controlled with two manual flow control valves and the pressure readings are measured with a pressure gauge. The hydraulic cylinder on the other hand is controlled with a servo valve. The servo valve control and the measuring setup is shown in Figure 22.

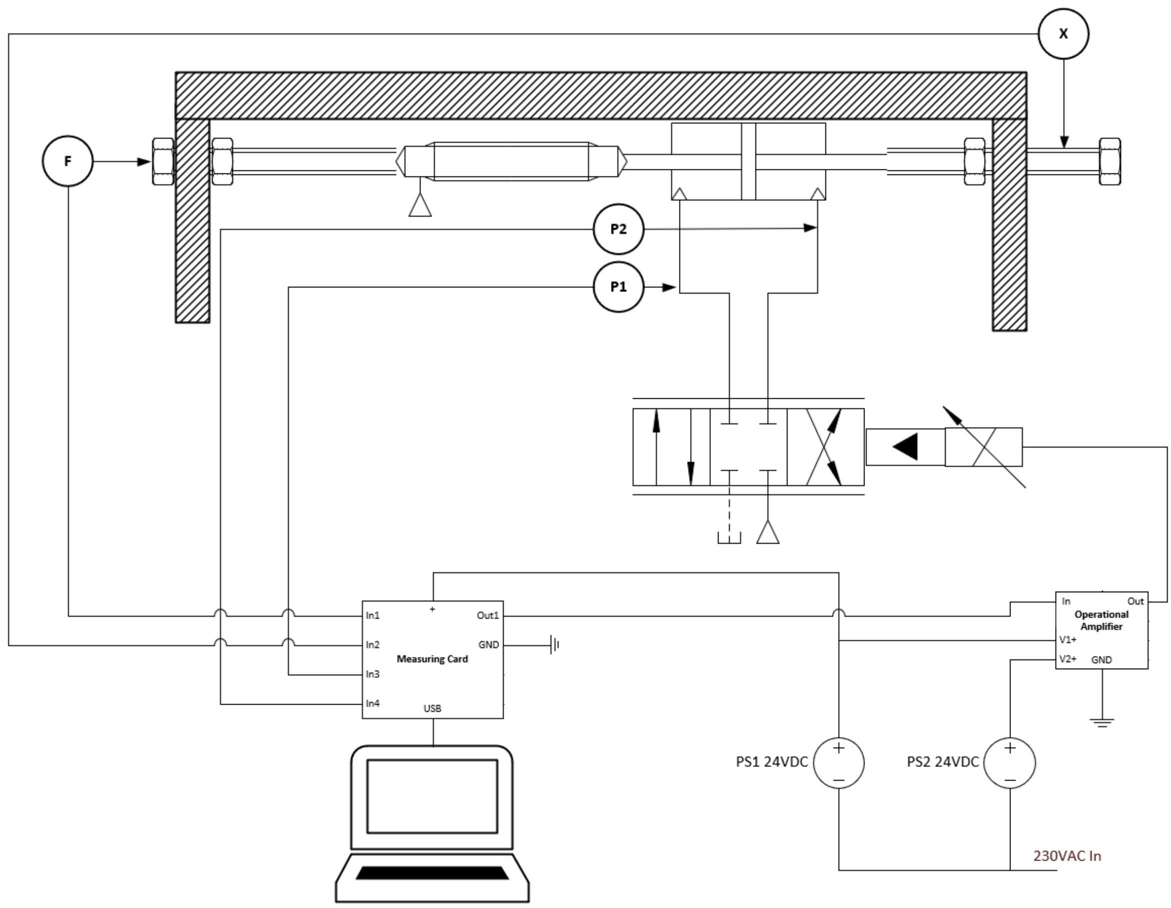

Figure 22. *Measuring setup and servo valve control.*

The measuring setup constructs from 4 sensors and 2 power supplies, from a measuring card, control PC and from an operational amplifier of the servo valve. The sensors F and X are measuring output force and displacement of the HAM, respectively. The sensors P1 and P2 are measuring the pressures of the hydraulic cylinder. On the contrary to the Figure 22, the displacement of the HAM was measured between it and the hydraulic cylinder.

One power supply is needed for the measuring card, but for the operational amplifier total of two power supplies are needed. This is due to the fact, that the operational amplifier needs electric potential in two directions. This way the amplifier can adjust the servo valve to right or to left. The measuring card will send the signals from the control PC to the amplifier and gather information from the four sensors.

The control PC uses DASYLab software to gather the real-time data and to control the servo valve. The DASYLab software is also used to export the measurement data to ASCII format for data management. The DASYLab had ready interface for the operation, but a program for the measuring and valve control had to be constructed. In addition, sensor calibration had to be done before measurements. The DASYLab interface and program constructed is shown in Appendix B.

6.1.2 Measuring the output force at given pressure

The first tests were done to FMA. Before the tests, the FMA was fixed into the test bench with the fabricated adapters.

At the start of the test, both power supplies were switched on and the sensor readings were checked. After that, both hydraulic systems were turned on which meant that the test setup was ready for the measurements. Before the start, the pressure of the FMA was set to the wanted level with the two flow control valves of the water hydraulic system. After the pressure was set to the wanted level, the test cycle was ready to be started.

At the start, the slider of the DASYLab control program was carefully moved to get the cylinder moving. Moving the slider in the program sent a signal from the computer through the measuring card to the operational amplifier, which moved the servo valve to the wanted position. After the servo valve generated needed pressure difference inside the hydraulic cylinder, the cylinder and the axle started to move. The slider was moved slowly and continuously to allow constant and stable movement. After the FMA was at the end of its travel, the measurement program was stopped, and the data was saved. This kind of cycles were ran from lower pressure levels towards higher pressure levels. For the FMA, pressures between 1 and 10 bar was measured.

The tests were started in a position where the HAM was at its shortest stage. For the FMA, 20% contraction rate was the start point. From here, the hydraulic cylinder was driven outwards to stretch the FMA to its longest stage. The FMA resisted the movement of the hydraulic cylinder and generated a force, which was measured with the sensor at the end of the axle as shown in the Figure 22.

The same test was also done to the shorter FMB. Start point was set to 25% contraction rate, as this is the maximum allowed. With the FMB, it was tested how high pressures the Festo's Fluidic Muscles could withstand. The pressures between 1 and 20 bar was measured. Compared to the longer FMA, no behaviour differences were noticed with the FMB.

The testing cycles of both HAMs went well overall. The first challenge with both HAMs was that with higher operating pressures the force increased so high, that the pressure relief valve of the hydraulic system needed to be adjusted to get higher pressure differences inside the cylinder. However, this did not affect the measuring results and even gave additional way of calculating and ensuring the force values. This is expressed in the next chapter. The second more major challenge with both HAMs was the fluctuating pressure when moving the hydraulic cylinder. At water pressure levels between 1 and 4 bar, the pressure fluctuated between 0,2 and 0,5 bar. However, when increasing the pressure towards 10 bar, the fluctuating of the pressure increased to 1 and even 2 bar. This fluctuating could be dampened by keeping the movement stable, but in every measurement it was present. This pressure fluctuating could also be dampened with a better water hydraulic system control, as the flow restriction valves were not the most functional solution for pressure control.

6.2 Results of the performance tests

This chapter shows the results generated from the measurement data. The main results are covering pressure and force levels of the test HAMs. The reliability of the results is also examined.

The results are mainly shown in figures, as the data point amount for tables was too large. The measurement data was exported from the DASYLab software and the data processing was made with Excel. The data point amount of each curve was between 10 000 and 15 000. Excel's memory started to run out with that amount of data, which is the reason why only every 5th data point was considered when plotting the curves. However, this did not differ the curves at all because the trendline resolution is much larger compared to the data point's resolution.

6.2.1 Fluidic Muscle performance

By testing the force at given pressure, a good baseline of the Fluidic Muscle performance can be achieved. The first performance test was done to the FMA. The results of this test are shown in Figure 23.

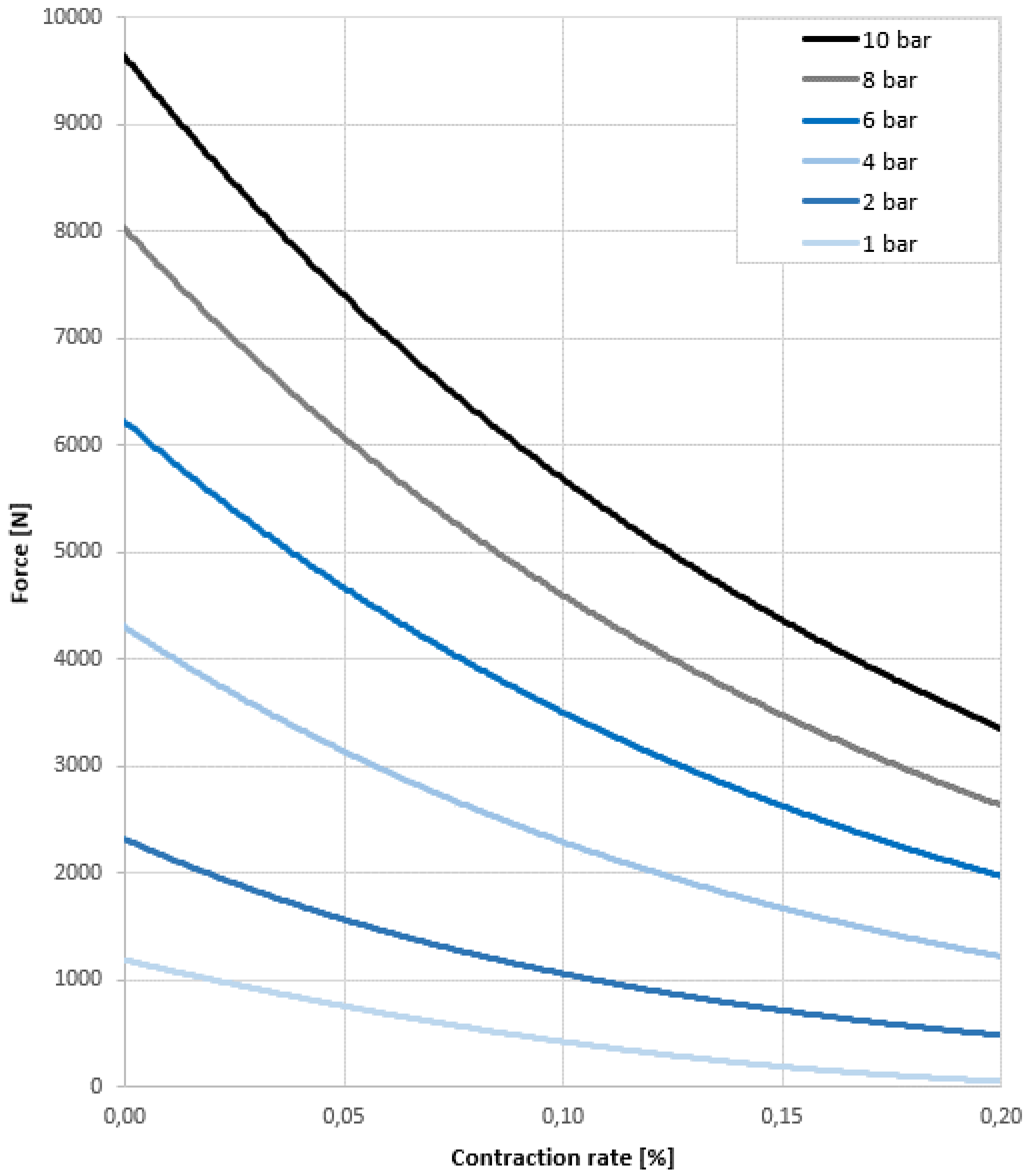

Figure 23. *Performance results of the FMA.*

As explained earlier, the maximum measured contraction rate of the FMA was 20%, meaning that the total travel of the Fluidic Muscle was 100 mm in each test. The first test was done with pressure level of 1bar, after which it was risen to 2 bar. Finally, the pressure was risen to 10 bar in 2bar steps. As can be seen, the force will increase when the muscle is straightened and decrease when the muscle is contracted. With the 10-bar pressure, almost 10 kN of force was measured. In addition, over 1 kN of force was achieved with the low pressure of 1 bar. However, it is important to knowledge that these maximum forces can only be achieved when the Fluidic Muscle is straightened. Furthermore, the force will rapidly decrease if the Fluidic Muscle is contracted.

The same plot was drawn from the test of FMB. However, in this graph there are additional curves for 15 bar and 20 bar pressures. Furthermore, the contraction rate at the start is 25% compared to the 20% of the earlier tests. The results of this test are shown in Figure 24.

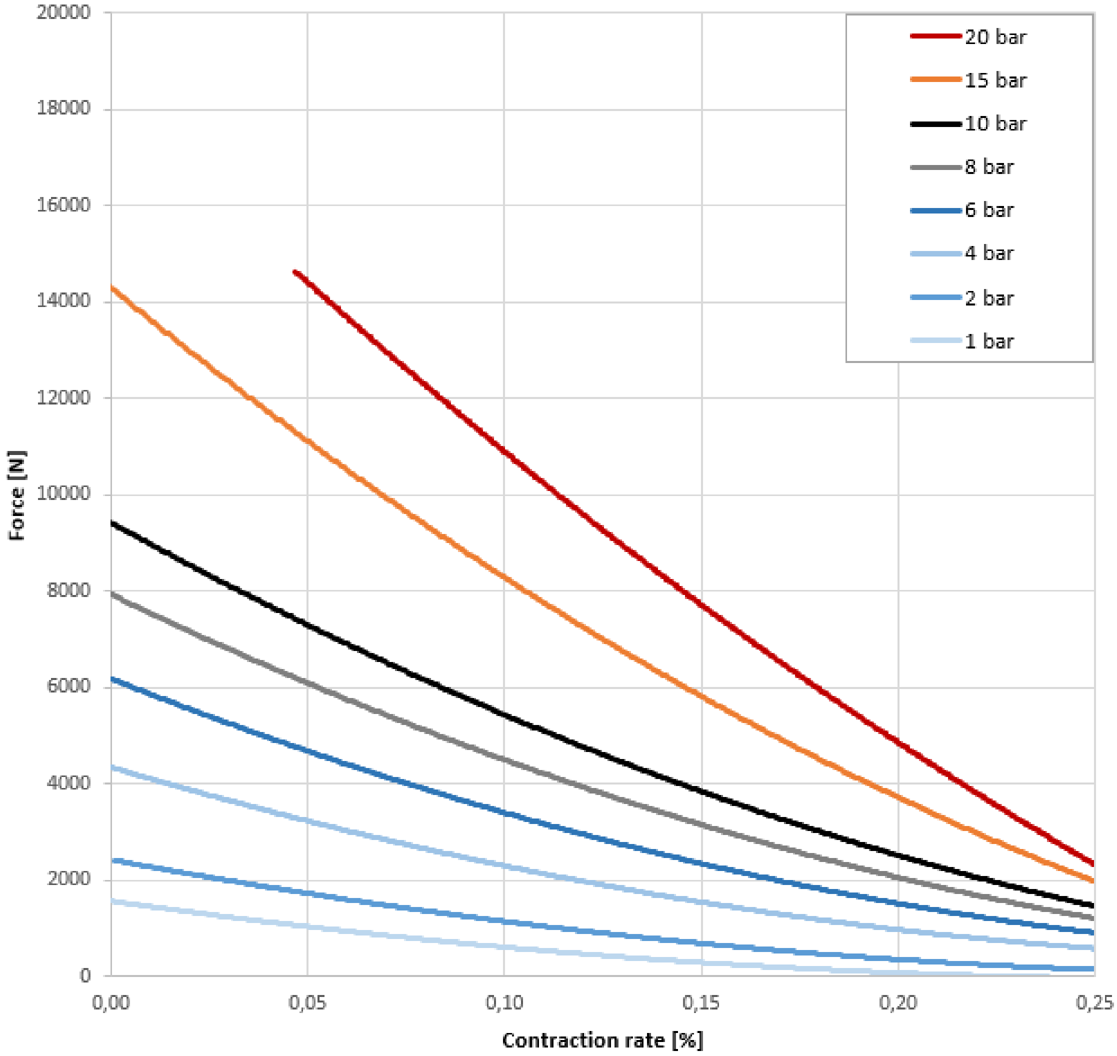

Figure 24. *Performance results of the FMB.*

The Fluidic Muscle performed well with the 15 bar and even with the 20 bar pressure levels. However, the hydraulic system's pressure relief valve opened at the 15 kN force, which is why the 20-bar curve does not continue to contraction rate of 0%. The pressure relief valve threshold was risen from 100 bar to 150 bar and the 20-bar test was started again. Unfortunately, at the second start of the test, the Fluidic Muscle did not withstand the pressures anymore. At around 21 bars a loud cracking sound was heard. The test was stopped, and the Fluidic Muscle was inspected. It seemed to be intact, but some transformations of the structure could be felt. After the inspection the test was started again and when the pressure reached again the 21 bar mark the Fluidic Muscle finally ruptured from the middle. A 5 cm fine split was spawned at the middle of the muscle, which went in the same direction as one layer of the fibres.

Even though the 20-bar test was failed, it can be said that the Fluidic Muscle can withstand around 14 bar overpressures, as the Fluidic Muscle is rated to 6 bar [45]. In addition, maximum forces of 14 kN is proved and even higher forces could be achieved with 18-20 bar tests.

6.2.2 Reliability of the results

As the measurement system was not precisely inspected and some of the sensor calibrations were updated before the tests, reliability of the results needed to be evaluated. First way to confirm the results was to compare the measured results to the data given from the manufacturer. In Figure 25, FMA test results are on top of the graph given from Festo [42].

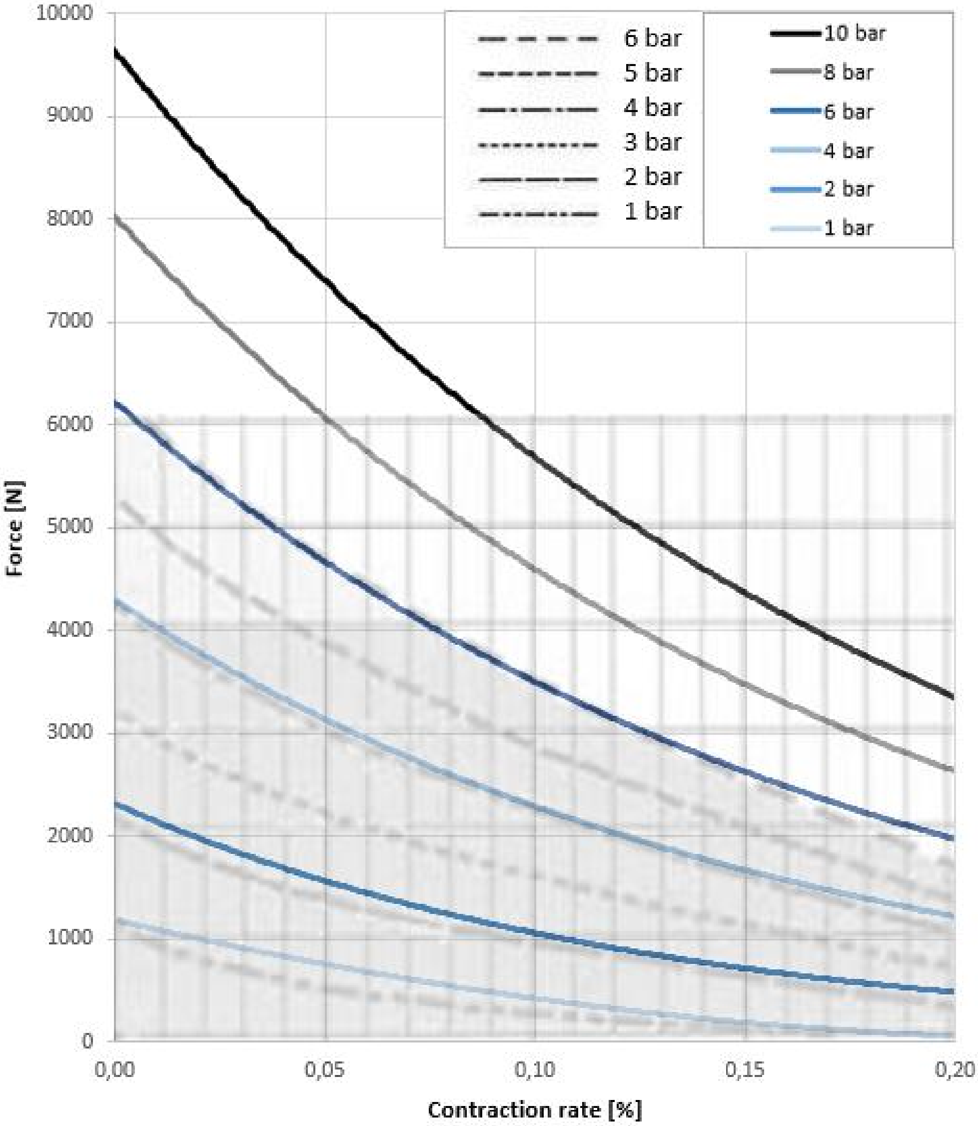

Figure 25. *Comparison of FMA's test results and given graph.*

As can be seen, the measurements follow closely the given graph. Slight difference can be seen at the low-pressure levels, but overall the results seem to be relevant. As the Fluidic Muscles are rated to 6 bars, this method cannot be used to confirm the highest-pressure curves. However, as the behaviour and results seem to be similar with the lower pressures, it can be said that the higher-pressure results are also relevant.

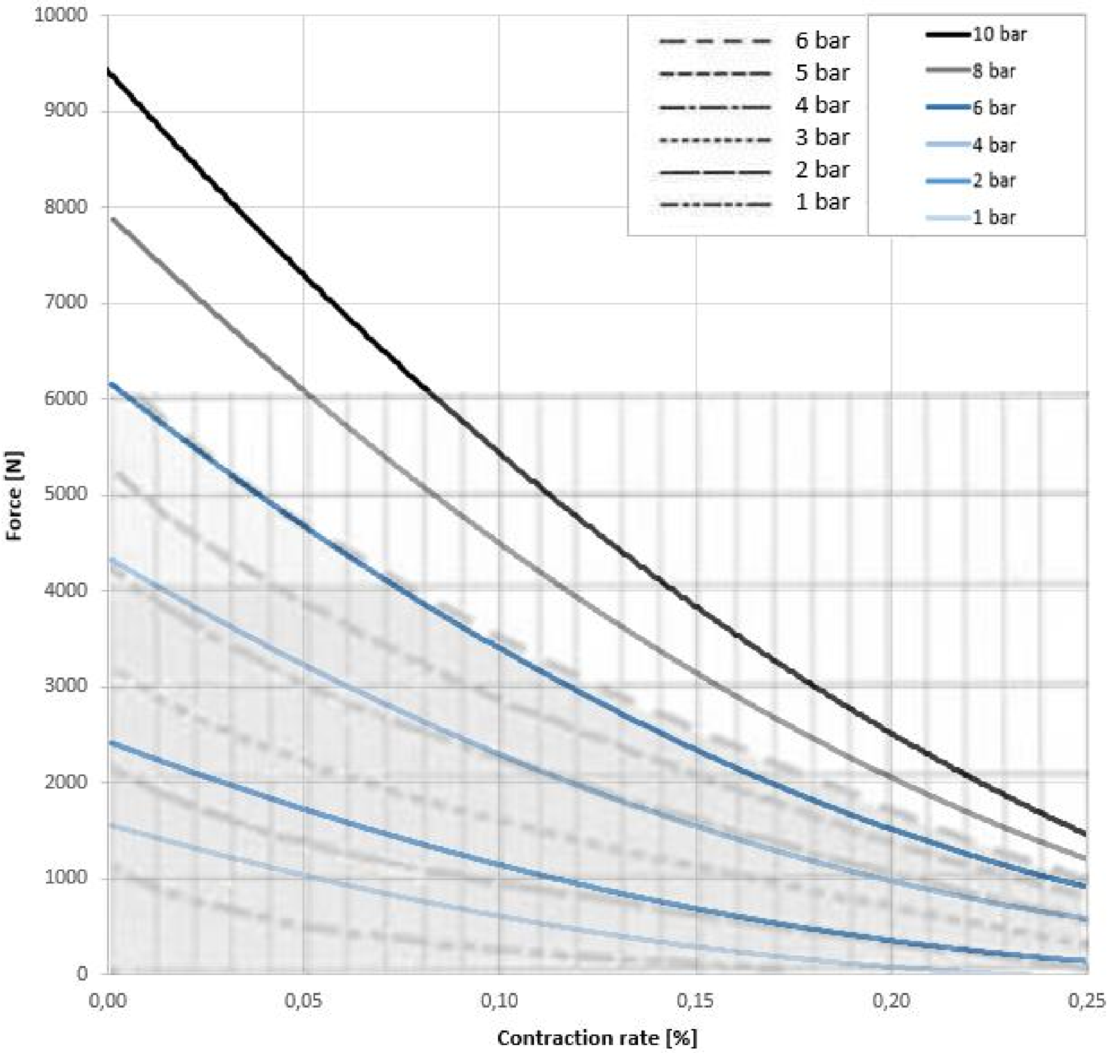

Figure 26. *Comparison of FMB's test results and given graph.*

In Figure 26 the same comparison of FMB is shown. The 15 bar and 20 bar curves were disregarded at this graph, as the Festo's graph does not show that high pressures. Again, some slight differences can be seen, but overall the results seem to follow the given graph. However, the 1 bar and 2 bar curves seem to differ substantially from the given graph at the low contraction rates. The data points of these curves were inspected, but nothing unusual was discovered. In conclusion, it seems that the results are relevant with this confirmation method.

As expressed earlier, the test with FMB with pressure of 20 bar was stopped due to the opening of the pressure relief valve of the hydraulic system. This means, that the hydraulic cylinder was not able to move as the Fluidic Muscle resisted the movement too much. This gives a new possibility to confirm the measured forces. As the hydraulic cylinder is stopped by the Fluidic Muscle, it means that the Fluidic Muscle force must be the same as the hydraulic cylinder generates.

The hydraulic cylinder dimensions are known (63/40-200), which means that the output force can be calculated from the pressure difference of the cylinder. The pressure reading of P1 shown in Figure 22 was gathered from the measured data. It was then converted to force by multiplying it with the area pushing the oil. The readings of the P2 was confirmed to be 0 bar. The calculated force is shown next to measured force in Figure 27. Note that the x-axis shows timeline of the test.

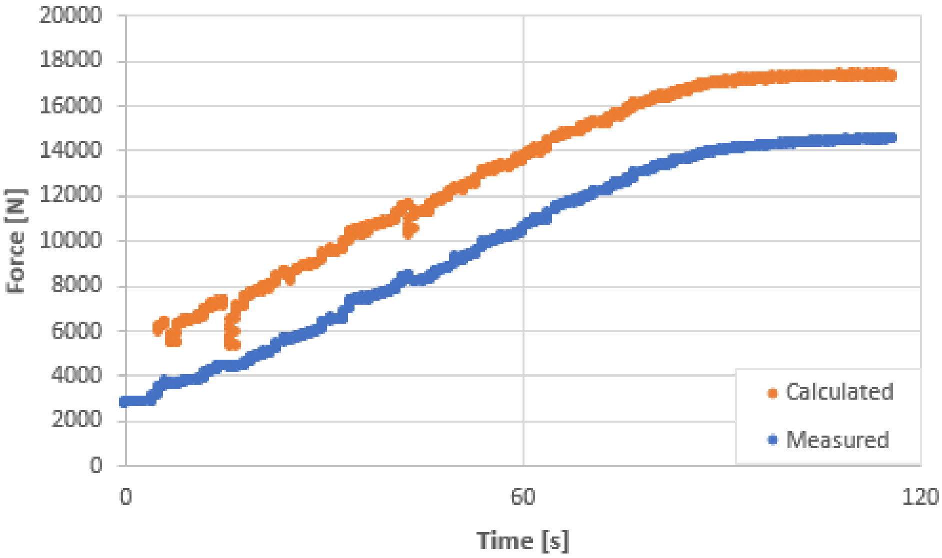

Figure 27. *Measured and calculated force of the 20-bar performance test.*

As it can be seen, there is a significant difference of the force values. One probably reason for the difference is the friction which the hydraulic cylinder must overcome in addition to the resisting force of the Fluidic Muscle.

To get an accurate reading of friction of this setup would need a long calculation and measurement process. For this reason, some estimates were looked from the literature. Friction of equivalent hydraulic cylinder is around 1 kN, which could explain some of the error [46]. In addition, the test bench will generate additional friction because at the one end the axle is contacting the bench frame.

Another possible reason for the difference would be a calibration error of the hydraulic pressure sensors or the force sensor. As the force seems to follow the manufacturers graph in Figure 25 and in Figure 26, the calibration of the pressure sensors should be inspected.

Third way to confirm the measured values is to compare the results to calculations created with the equations shown in earlier chapter. As the Fluidic Muscle was in motion during measurements equations (11) and (12) should be disregarded. This is due to need of knowledge about the current radius *R* and current wall thickness t of the Fluidic Muscle. Instead the equation (13) should be used. A graph created with the equation (13) is shown in Figure 28.

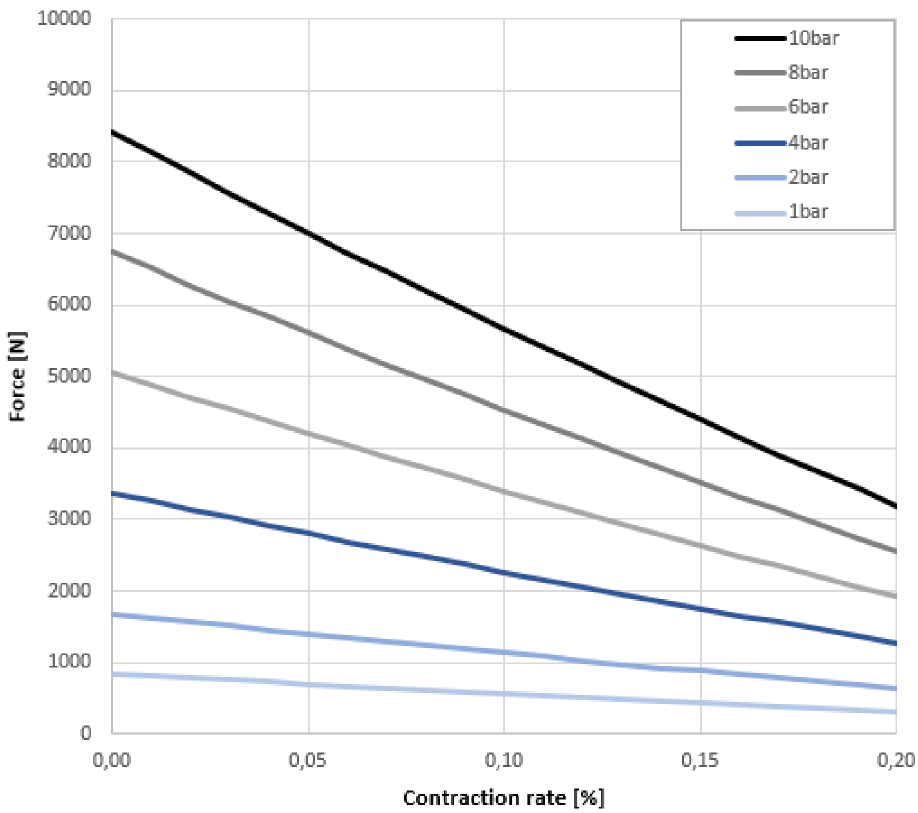

Figure 28. *HAM's predicted output force as a function of contraction rate.*

As can be seen from the graph, the calculations predict similar force behavior as measured and presented in Figure 23. However, the force calculated with the equation (13) shows more moderate values. The difference to the measured values is around 1kN. Reasons for this deviation is hard to state reliably as the calculations ignore multiple factors of the Fluidic Muscle. Nevertheless, same behavior and similarity of the calculation based graph and the results can be stated.

Even though the (11) and (12) equations was disregarded, force could be predicted also with the equation (8). These calculations predicted almost same forces as shown in the Figure 28 with 8426 N maximum and 2966 N minimum force.

To get more accurate results, a better calibration of the sensors should have been executed. In addition, extensive inspection of the measurement system could have been done before the measurements. However, 1 kN overall accuracy of the results can be stated. With this accuracy, it can be said that the results are showing baseline of the Fluidic Muscle performance. In addition, the behavior of the actuator can be learned from these results.

For future testing, a new calibration of the system should be done. After this, the measurement system and test bench setup should be quite accurate and similar tests can be executed without reliability issues of the results.

7. CONCLUSIONS

This thesis laid down the foundations of water hydraulic systems and water hydraulic actuators for the actuation system development of the mining robot prototype. This thesis also provides an introduction to water hydraulic systems and water hydraulic actuators for the ROBOMINERS project group.

Before the study, there was no concise source of information about water hydraulic systems and water hydraulic actuators in similar applications. This study aimed to find the basic information of these two to proceed to the actuation system development of the mining robot prototype.

This study started with a compact background of mining and the mining robot. The aim of this was to introduce the environment where the mining robot and thus the water hydraulic system and water hydraulic actuators will operate. This introduction provided the limits for the concept development and helped to focus on the right aspects.

After the mining environment and operations were introduced the aim was moved towards water hydraulic systems. Water hydraulic systems were examined from the water characteristics to the component supply. The aim of this was to gather all important information that would be needed in the development of the water hydraulic system of the prototype.

It was shown, that there are surprisingly many differences compared to conventional oil hydraulic systems. Differing characteristics of water mostly due to the lower viscosity make some component structures incompetent. To summarise, seat type valves are preferred over spool type valves, lubrication should be done mostly by surface materials of the components, corrosion resistance is necessary in every inner surface and intensive filtering should be considered. Another completely new challenge compared to oils are the bacteria and fungi growth that could damage the hydraulic system if the water gets contaminated even slightly. Operation temperature should also be considered since the freezing difficulties at 0°C and cavitation risks at over 50°C might lead to challenges. One plausible solution for this is the use of environmentally friendly fluid mixtures as introduced in the Appendix A. All these properties might also lead to more practical challenges. For example, quick couplings of the mining robot sections should be clean or isolated from the environment to prevent water contamination.

Another major finding of the water hydraulic systems was the fact that there are not many suppliers available. Only 3 European suppliers were found. However, each of these had satisfactory selection of components at least for the mining robot prototype. With this information it can be stated that at the concept development stage of the mining robot prototype COTS parts can be utilised. More suitable parts or parts with exceptional properties might need to be developed, but this will not be required until later stages of the development.

The last major finding of the water hydraulic systems was the production tool variety. There are many kinds of production tools that could be utilised in the mining robot, but there seems to be low amount of information about these kinds of applications. Especially the size and performance requirements should be determined before moving into selection of the correct production tool. With the hydrodemolition methods the pressure intensifiers should also be tested to see how they will comply with water hydraulics and production tools.

After examination of water hydraulic systems, the study moved to muscle-like actuators. Examination of the muscle-like actuators, also called artificial muscles, started from the history and moved towards definition. After the brief introduction, the examination was limited to hydraulic artificial muscles. The HAMs were covered thoroughly as the structure, operation and performance were examined.

Some benefits and challenges of the HAMs were perceived from this study. For example, the outstanding power to weight ratio was shown. Another great benefit of the HAMs is the closed structure that keeps the hydraulic fluid clean compared to conventional hydraulic cylinders. The biggest challenges will probably be the controllability and bad displacement performance of the HAMs. Another major thing to consider is the required motion mechanisms and the amount of HAMs in each actuation need.

For the testing, a suitable HAM was found. Unfortunately, this was the only COTS water hydraulic AM that was found. However, the manufacturer has a good selection of different size HAMs that could be used in the development of the actuation system of the prototype. It was also discovered, that surprisingly many studies concerning HAMs have been established in the last 10 years.

Before the testing, notable amount of work was done to get the test bench and measurement setup ready. After the setup was constructed and calibrated, the testing could be started. Major findings of the testing were the performance and behaviour of the Fluidic Muscle and HAMs in general. High forces were achieved with moderate pressures. As the manufacturer gave only performance readings of pneumatic operation, water hydraulic performance measurements provided a more reliable baseline for the actuation system development. The Fluidic Muscle's maximum force of 14 kN and pressure of 21 bar were also discovered, which gave information about the limits of the current COTS HAMs.

For the further testing with this setup an accurate calibration and inspection of the measurement devices are recommended. In addition, the water hydraulic system should be changed so that it could better keep the pressure stable despite the external force fluctuating. The influences of the external force fluctuating should be studied further as well, due to the controllability issues that it might generate. Furthermore, position accuracy due to flexing and pressure fluctuating could be studied more to understand better the dynamic behaviour of a HAM. Further performance testing could also be done with this setup. For example, sleeves constructed with different materials could be added on top of the Fluidic Muscle to see what kind of changes that would generate in the terms of performance and behaviour.

It is good to be aware that this study aimed only to lay down the foundations of the actuation system development. This means that detailed explanation of some applications and methods might have been disregarded. For this reason, there might be some aspects that have not been examined in the statements. However, the examinations should be accurate enough to provide information and direction to the development of the actuation system of the mining robot prototype.

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APPENDIX A: HYDRAULIC FLUIDS

ISO Code	Description
HH	Standard mineral oil without additives.
HL	Mineral oil with improved corrosion, anti-oxidation and temperature/viscosity properties. The selected viscosity classes range from 10 cSt to 100 cSt at 40°C.
HLP, HM	Mineral oil with improved corrosion, anti-oxidation, temperature/viscosity and anti-wear properties.
HV	Mineral oil with low temperature effect on viscosity, usable for hydraulic systems in Arctic climates (high-viscosity index, VI)
HLPD	Mineral oil with additives that decrease stick-slip effect and emulge entrained water

ISO Code	Description
HFA	Oil-in-water emulsions (>80% water).
HFAE	Oil-in-water emulsions with anti-wear additives. Can be discharged to the drain (sewer).
HFAS	Aqueous solutions. Less aggressive to waste water than HFAE. Applied, for example, in coal mines and steel plants.
HFB	Water-in-oil emulsions. Flammable ingredients max. 60%. In some applications considered to be fireproof.
HFC	Aqueous polymer solutions. Polyglycol-water solutions in 6 classes of viscosity. Used, for example, in machinery for coal mines and diecasting machines.
HFD	These fluids are all water free and are synthesized on the basis of phosphate esters (HFDR), chlorinated and fluorinated carbons (HFDT) and other organic components (HFDU).

ISO Code	Description
HPG	Polyglycol. Good lubrication and corrosive protection. Viscosity classification comparable to mineral oils.
HTG	Vegetable oil, such as rapeseed oil. Only few classes of viscosity.
HE	Synthetic ester. Viscosity classification comparable to mineral oils.

Liquid	Mineral oil HLP	HFA	HFC	HFD	Bio-oil (rapeseed) HTG	Water
Kinematic viscosity at 50˚C [mm^2/sec]	15 - 70	~ 1	20 - 70	15 - 70	32 - 46	0.55
Density at 15˚C [g/cm^3]	0.87 - 0,9	~ 1	~ 1.05	~ 1.05	0.93	1
Vapor pressure at 50˚C [bar]	$1.0 \cdot 10^{-8}$	0.1	0.1 - 0.15	$<10^{-5}$	?	0.12
Compression modulus β_s [N/m^2]	$1.0 - 1.6 \cdot 10^9$	$2.5 \cdot 10^9$	$3.5 \cdot 10^9$	$2.3 - 2.8 \cdot 10^9$	$1.85 \cdot 10^9$	$2.4 \cdot 10^9$
Speed of sound at 20˚C [m/sec]	1300	?	?	?	?	1480
Thermal conductivity at 20˚C [W/m·˚C]	0.11 - 0,14	0.598	~ 0.3	~ 0.13	0.15 - 0.18	0.598
Specific heat at 20˚C and constant pressure [kJ/kg·˚C]	1.89	-	-	-	-	4.18
Max. working temperature range [˚C]	-20 - 90	5 - 55	-30 - 65	0 - 150	-20 - 80	~ 3 - 50
Flash point [˚C]	210	-	-	245	250 - 330	-
Ignition point [˚C]	320 - 360	-	-	505	350 - 500	-
Corrosion protection	Good	Sufficient	Good	Good	Very Good	Poor
Environmental impact	High	High	High	High	Small	None
Relative costs for liquid [%]	100	10 -15	150 - 200	200 - 400	150 - 300	~ 0.02
Usage [%]	85	4	6	2	3	~ 0 (at present)

APPENDIX B: DASYLAB INTERFACE AND PROGRAM