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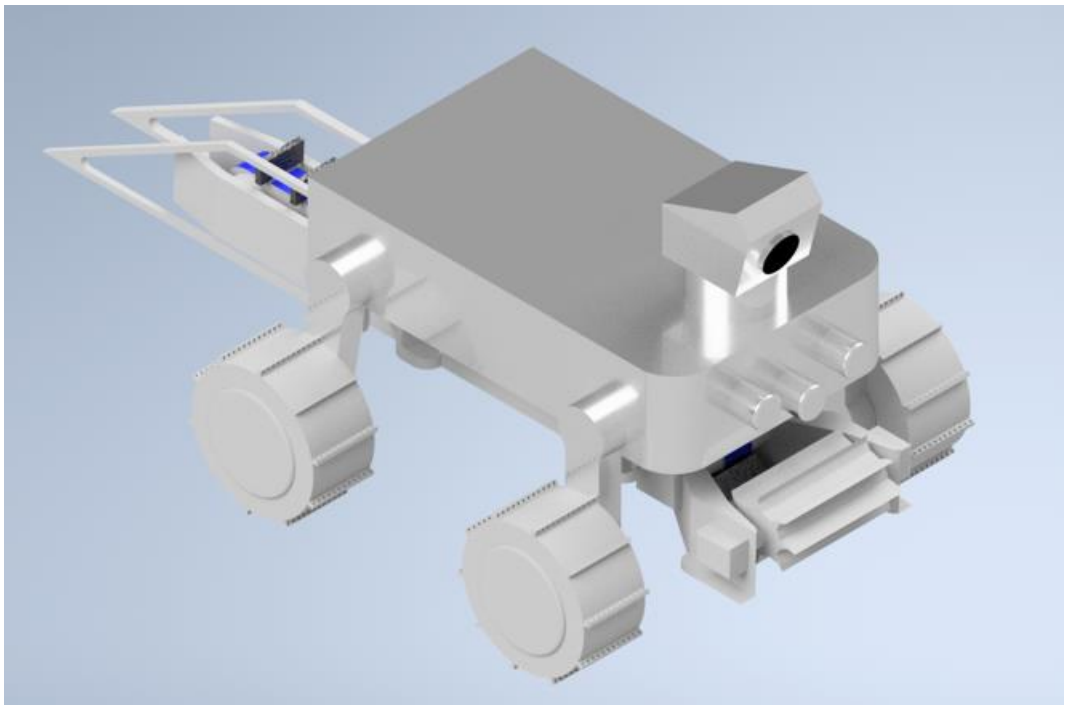
A Concept Design to Enable Lunar Mining



Kian Persson
Filip Svensson

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The authors declare that they are the sole authors of this thesis and that they have not used any sources other than those listed in the bibliography and identified as references. They further declare that they have not submitted this thesis at any other institution to obtain a degree.

Internet: www.bth.se

Phone: +46 455 38 50 00

Fax: +46 455 38 50 57

Contact Information:

Authors:

Kian Persson

E-mail: Kifa17@student.bth.se

Filip Svensson

E-mail: fise17@student.bth.se

Faculty of Engineering

Blekinge Institute of Technology

SE-371 79 Karlskrona, Sweden

University advisor:

Dr. Christian Johansson Askling

Department of Mechanical Engineering

Abstract

The space industry has been accelerating technological evolution since its inception. It has resulted in countless innovations being adapted and eventually finding their way into people's everyday life. It has also played a significant role in understanding life itself and the circumstances that are necessary to support it. A crucial step in obtaining an even further understanding of humanity's place in the universe is truly comprehending the Moon and its mysteries. In order to do the previously mentioned a manned research operation to the Moon is necessary. However, doing this requires an in-situ resources utilization (ISRU) approach due to the complexity as well as cost of launching material and equipment to space. The Moon holds a lot of valuable resources from which several critical substances and materials can be extracted, e.g., oxygen and hydrogen. In order to make use of the locally available resources, such as the regolith, a standardized approach is necessary.

There are several ways of designing something tasked with mining the Moon as well as enabling supporting activities, e.g., infrastructure development. A Design Thinking approach was used in order to get clarity regarding on how a concept doing this might look like. This thesis deals with the topic on a high, conceptual level due to the complexity of the subject.

The needfinding and literature study provided background and context to design a solution enabling the earlier mentioned goal. The solution is a swarm system of Lunar rovers that are capable of operating together, as a unit, as well as on their own depending on the nature of the task that is performed. The activities are performed by interchangeable tool modules operated by the robots rather than the robots themselves. This provides prerequisites for a more flexible as well as resilient mission operation compared to many other scenarios. The interchangeable modules mechanism is the most important aspect of the proposed concept. Another important aspect concerning the platform of the concept is that it enables an infrastructure for new activities post-launch as long as the module fulfills some constraints. The thesis provides concepts for the robot, a regolith collector module as well as the container module.

As a means of verifying the concept, a subsystem was selected and tested. The subsystem that was chosen was the module exchanging mechanism. Thus, a conceptual version of this was built and tested. The test was delimited and intended to determine whether an approach using screws and movable arms was appropriate to pick up a simplified container module. The test performed concluded that the subsystem has potential, even though a more similar mechanism to the one actually envisioned would be necessary to test. However, there are certain iterations that beneficially may be performed prior to a complete representation of the module equipping mechanism is built.

Keywords: Lunar Mining, Swarm Robotics, Lunar rover

Sammanfattning

Rymdindustrin har påskyndat den tekniska utvecklingen ända sedan dess uppkomst. Den har resulterat i att många innovationer anpassats och så småningom blivit en del av människors vardag. Det har också spelat en betydande roll för att förstå livet självt och de omständigheter som är nödvändiga för att stödja det. Ett avgörande steg för att öka denna förståelse för mänsklighetens plats i universum är att utveckla förståelsen om månen och dess mysterier. För att göra det tidigare nämnda krävs en bemannad forskningsbas till månen. Att göra detta krävs ett in situ resursanvändning (ISRU) tillvägagångssätt på grund av komplexiteten samt höga kostnader för att skicka upp material och utrustning till rymden. På Månen finns flera värdefulla resurser från vilka flera nödvändiga ämnen och material kan utvinnas, t.ex. syre och väte. För att kunna använda de tillgängliga resurserna, t.ex. regoliten, krävs ett systematiskt tillvägagångssätt.

Det finns flera sätt att designa något i syfte att ta tillvara på månens resurser. Ett Design thinking-tillvägagångssätt användes för att få förståelse och insikter för hur ett koncept som gör detta kan se ut. Detta examensarbete behandlar ämnet på översiktlig konceptuell nivå med anledning av de utmaningar som finns.

Needfinding och litteraturstudier gav en bakgrund och sammanhang för att utforma en lösning som möjliggör det tidigare nämnda syftet. Lösningen är ett svärmsystem av Lunar rovers som kan fungera tillsammans, som en enhet, såväl som på egen hand beroende på vilken typ av uppgift som utförs. Aktiviteterna utförs av utbytbara verktygsmoduler som drivs av robotarna snarare än robotarna själva. Detta ger förutsättningar för en mer flexibel och motståndskraftig uppdragsverksamhet jämfört med många andra scenarier. Mekanismen för utbytbara moduler är den viktigaste aspekten av det föreslagna konceptet. En annan viktig aspekt av konceptets plattform är att det möjliggör en infrastruktur för nya aktiviteter efter lansering så länge modulen uppfyller vissa begränsningar. Examensarbetet tillhandahåller ett koncept för roboten, en regolituppsamlarmodul samt containermodulen.

För att verifiera konceptet valdes ett delsystem ut och sedan testades. Detta delsystem var modulbytesmekanismen. Det vill säga det byggdes och testades en konceptuell version av denna. Testet var avgränsat och avsett att avgöra om ett tillvägagångssätt med skruvar och rörliga armar var lämpligt för att plocka upp en förenklad containermodul. Slutsatsen av testet var att delsystem har potential, även om en mer liknande mekanism som den som faktiskt föreställts skulle vara nödvändig för att testa. Det finns dock vissa iterationer som med fördel kan utföras innan en fullständig representation av modulhållarsystem byggs.

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List of Abbreviations

CNSA……. The Chinese Space Agency

CPU..... .....Central Processing Unit

CSMC……. Canadian Space Mining Corporation

ESA……. European Space Agency

FAST……. …… Functional Analysis System Technique

FMEA……. Failure modes and effects analysis

ISRU……. …… In situ resource utilization

LRO…… Lunar Reconnaissance Orbiter

LRV……. Lunar Rover Vehicle

NASA……. National Aeronautics and Space Administration

SMART……. Specific, Measurable, Achievable, Relevant, Timebound

1 Introduction

Ever since humanity left the Moon in 1972 many have long awaited to return [1]. This is in order to learn more about it. However, since the Moon does not have the necessary prerequisites to sustain human life any extended stay is impossible since it would require too much to constantly supply the operation with resources and the weight and the cost for that would be very high [2]. Therefore, another approach is needed; an approach that utilizes the resources that the Moon has to offer. The Moon has a lot of potential resources that humanity could benefit from, especially resources that could help to sustain human exploration of the Moon such as oxygen and water. Furthermore, are other resources, such as hydrogen, available which could be used in making rocket fuel. Therefore, the Moon could be an appropriate stop for a rocket intended for Mars in order to refuel [3] and then launch from more beneficial conditions i.e., vacuum and a weaker gravity.

In order to do the above mentioned, the resources of interest need to be produced from the Lunar dust, the so-called regolith [4]. Making use of the resources where they are found and using them for appropriate purposes is an approach called in situ resource utilization (ISRU) [5]. Such an approach is key for enhancing the understanding of the Lunar environment. This provides resources that are crucial for continued exploration of space and everything this implies. This provides resources that are crucial for continued exploration of space and everything this implies.

However, mining on the Moon is extremely complex. The environment is very hostile and challenging for a number of reasons. For instance, the temperature is very unstable [6] which puts strain on electronic technology as well as rendering some materials useless [7]. Furthermore, the regolith itself is abrasive for the structures and wears them down at a high pace. Another aspect that needs to be considered is to make the operation as failproof as possible. One consequence of this is the fact that it is not advisable to send one or a few robots with one dedicated purpose as these make the operation very fragile [8]. The previous since if all units with a certain task are incapitated then the entire operation will be canceled even though the rest of the robots may work as planned. Therefore, all robots must be able to perform all activities with one or a few exceptions since this enables a greater resilience to withstand unforeseen events. The robots' design shall take the need for repairs into consideration. This is an aspect that is important since it is expensive and complex to send new units to the Moon.

The robots should be able to perform several activities which are necessary to set up a base for exploration. It is also possible that the Moon becomes a planned stop for refueling and resupplying rockets that are intended to travel to Mars. A good maneuverability and terrain capabilities are required. The robots must also be able to acquire the regolith and transport it to a location where it will be processed to the resources that are of interest. Since acquiring and transporting the regolith is one of the most central aspects for the initial phases this

aspect was given adequate attention for this project since it was impossible to design all the modules that will be needed.

1.1 Background

Space mining is one key aspect in enabling and sustaining a base on the Moon. This simplifies the further exploration of the Solar System [9]. One way to provide necessary resources for the base is to use an in-situ resource utilization (ISRU) approach [10]. This will allow the knowledge-gaining efforts to continue and provide possibilities that previously were not feasible due to technical restraints. This will be useful as space mining will aid in achieving new innovations and understandings that will result in a positive impact on humanity at large [11].

Space mining is one key aspect in enabling and sustaining a base on the Moon. This as it simplifies the further exploration of the Solar System [9]. One way to provide necessary resources for the base is to use an in-situ resource utilization (ISRU) approach [10]. This will allow the knowledge-gaining efforts to continue and provide possibilities that previously was not feasible due to technical restraints. This will be useful as space mining will aid in achieving new innovations and understandings that will result in a positive impact on humanity at large [11].

In order to gather the regolith resource, several concepts have been suggested by academics and enthusiasts alike. One concept developed by NASA, called RASSOR, is a solution that utilizes rotating drums to gather and store regolith to transport it to a processing station. The concept operates independently and is saleable as several robots may be used simultaneously but with no interaction [12]. The robot is shown in *Figure 1.* Another envisioned concept utilizes a swarm approach where several differently designed robots are tasked with one or a few things thus collaborating to complete the operation [13]. As such, there is a certain variety of concepts that currently are being developed and investigated depending on the preferred strategy.

Figure 1. The RASSOR robot developed by NASA (License class: Public domain). [14]

1.1.2 Scope of the thesis

This thesis concerns the high-level concept generation of a robot design that shall provide prerequisites in establishing a human presence on the Moon. The main purpose of the robots is to enable the use of the resources that are available on the Moon, i.e., the Lunar regolith. An approach as previously mentioned is ISRU and is a key feature that the design will relate to. As such, the concept will collect regolith and transport it to a processing station.

Designing robots and equipment intended for operation in an extraterrestrial environment is an extremely complicated and resource-intensive process. This is since the level of complexity needed to fulfil the purpose is high. Moreover, the environment is harsh and hostile as such several challenges emerge as a result. The knowledge level to deal with these types of issues is high and often requires a lot of different sciences. As such, this work does not intend to result in a finished product complete with all details that are necessary to be elaborated in order to call the product "space worthy." This is simply not realistic given the circumstances such as time, experience and involved individuals. What this work strives to achieve, however, is a concept containing the most vital information regarding the key features and aspects of questions regarding "how" something shall be done and "why." Consequently, this will result in some specific respects being left relatively undefined due to the level of insight they require to be completed in an adequate way.

It is important to keep in mind that a lot of the robots/rovers, satellites and other equipment that is sent to space, historically, have been backed by major financiers such as governments [15]. Moreover, usually only one end result in some form is ultimately produced. A predetermined goal of the project was to come up with a concept that has a scalable design. This means that the solution will consist of several robots: either working together or in parallel. This has several implications for the outcome of the design. It also means that instead of only launching one of something into space, several entities must have to be launched. Since the cost of launch is extremely high (1-1.4 million dollars per kg) [15] this means that the robots of the design need to be kept at a minimum weight. At the same time, it is not only weight that is expensive; complex and advanced technology is also greatly costly. This means that equipping the design with more advanced technology or functionality that is not necessary significantly reduces the viability of the concept due to the "waste" being multiplied for every design that is created. However, the previous must be done in a way that does not hinder or limit the operation itself. The earlier mentioned facts create a framework of constraints that needs to be considered when the concept is conceived. As such, the goal of the project may be summarized as to answer the question directly below with the constraints being acknowledged:

- How might a concept that is enabling Lunar resources to be gathered and transported look like?

Moreover, in respect to design additional demands were specified by the collaborating company CSMC. It was specified that the robots need to be multifunctional, have a saleable

design as well as being robust. These criteria were considered when the following design activities were carried out. The interpretation of the demands was that all robots should be able to carry out a variety of activities and not be specifically designed for one or a few purposes. Also, the robot fleet shall be upscaled seemingly without any issues taking place. The robustness criterion was interrelated as that the robots need to be resilient to a lot of potential problems that might occur on the Moon. Other criteria that were specified was the fact that the preferred method of gathering regolith was scraping rather than other alternatives such as digging or drilling. This is due to efficiency reasons as well as the fact that the top layer of the regolith contains the desired chemical compositions. [15]

Furthermore, in order to keep the work manageable some assumptions for the design were made. The first of this is that it is assumed that power will be provided by a nuclear power plant that is available on the Moon. There is a developed plan of putting such a power plant on the Moon by NASA within ten years [16]. As such, this seems like a reasonable assumption and will provide enough and stable energy to have a substantial improvement of the design when it comes to operating velocities and allowed energy consumption per time unit. The second assumption that was made relates to the communication aspect of the robots. There are at the time of writing plans of putting several satellites into orbit of the Moon and these will allow the robots to communicate more efficiently and stable [15]. This is beneficial since it will allow the ground control to take part in the imaging of the robot fleet with a small delay to get a proper understanding of what is going on the Moon. The autonomous robots may end up in a situation where they "do not know" what they will do and will as such require assistance from the ground control unit. This is significantly simplified by the improved communication abilities and will allow manual take-over with a negligible delay of imaging sent over to the unit, which will not cause any substantial delays in the operation. Also, the temperature prerequisites are simplified since it is assumed that the proposed design will be able to be equipped with heating coils which is a way of making sure that all electronics survive the cold temperatures [15]. The material that is provided will however be suitable for the full range of the temperature variation. The radiation and its effects are being neglected in order to keep the thesis work manageable. Another assumption that was made was that the enviable build–up of the so-called Lunar dust will be able to be cleaned by appropriate equipment at the processing facility (see below).

Moreover, the processing aspect of the project was left out due to the complexity of this topic. It also requires a deep knowledge of materials sciences and physical chemistry. Therefore, this aspect is not developed apart from the fact that it is assumed that some sort of processing facility will be used. It is to this facility that all regolith that is collected is delivered. The regolith will be processed and desired materials such aluminum, hydrogen, hydrogen will be extracted in order to allow the exploring effort to continue with the goal of minimizing any transport from the Earth [15]. This is since such means of transport are very expensive to send as well as minimizing any waiting times that might occur due to lack of resources.

1.1.3 Outline

The first chapter contains background of why space endeavor is worth pursuing. Chapter two presents information that is good to have an insight into. The third chapter deals with related work. Chapter four presents the methods used for this work. The fifth chapter presents relevant information of Lunar design criteria and makes a bridge between the methodology and the result. Chapter six presents the result and analysis of the thesis. The seventh chapter contains the discussion where it is explained why the proposed solution is suitable. Chapter eight sums up the thesis providing a conclusion and suggest future work.

2 Knowledge domain

2.1 The Moon

The Moon is the fifth largest Moon in the solar system and the only Earth's natural satellite. Moreover, the Moon is the second brightest object in the starry sky after the sun. The Moon is in a bound rotation, which means that it always turns the same side towards the Earth and rotates exactly once around its own axis for each revolution it rotates around the Earth. The surface of the Moon consists approximately of two different types of landscapes, the dark part so-called oceans and the bright highlands [17]. It takes 29.5 days for the Moon to pass one revolution around the Earth and this is called synodic orbital time. At the equator, the Moon has a diameter of 3476 km, and it has a density of 3.34 kg/dm³. 384 392 km is the average distance between the Moon and the Earth. The Moon has an area of about 38 million square meters and has a circumference of 10921 km. The attraction force from the sun is twice as great on the Moon than on Earth, this makes the Moon's orbit around the Earth more complicated, and it takes about 18 years before the Moon returns to its starting position. The Moon has a very thin atmosphere and the exosphere weighs a total of about 25 tons. That is, the Moon's atmosphere is negligible, which makes it vacuum. The Moon atmosphere consists mostly of hydrogen, but among it are small amounts of neon and helium [17].

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estimated that every 24 hours, 5 tons of competing particles hit the Moon. It is said that the dust stays above the Moon for about 10 minutes, that is, it takes 5 minutes to rise and 5 minutes to fall [19].

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2.2 Characteristic of the Moon Environment

As mentioned earlier, the Moon provides unique design challenges. Dangerous radiation, almost total vacuum, extreme temperature differences, micrometeorite impact and very low gravity are among the most critical factors that can affect a Lunar mining concept design and make it more challenging [19].

2.2.1 Radiation

Since the Moon does not have a strong magnetic field and no thick atmosphere, the radiation on the Moon differs from the Earth. Radiation on the Moon includes electromagnetic wave radiation which is characterized by a wave and its frequency and includes visible light. Energized particle radiation is also a form of radiation on the Moon [20]. The energetic radiation present on the Moon affects the outer and inner surface of material on the Moon. The strong radiation can affect material properties by radiation ionizing material in its path. The material used for Lunar mining operations must be protected in order to survive the radiation environment [21].

2.2.2. Temperature

The primary source of heat for the Moon is the sun. The outside temperature of the Moon varies with latitude, longitude, and the time of day. There are very large temperature differences between shade and sunlight. The regular temperature rises sharply during the day, this is because the Moon absorbs most of the light that falls on it [22].

The Moon's temperature will be 120 ° Celsius during the Moon's daytime time at the Lunar equator. The Moon's daytime is about two Earth weeks long because a day on the Moon is about 27.3 days says [23]. During the night on the Moon the temperature can drop to -130 ° C. Moreover, the temperature can drop to -253 ° C in some places [22].

Therefore, it is important to choose the right material for the equipment. High temperatures lead to evaporation of materials and lubricants and the extremely low temperature leads to brittleness of certain materials. To prevent the lubricant from evaporating, all equipment that is dependent on lubrication must be sealed [22].

2.2.3 Vacuum

The fact that the atmosphere is negligible on the Moon leads to about $1.33 * 10^{-10}$ Pascals which is almost a total vacuum. The fact that there is almost a complete vacuum on the Moon's surface can lead to several problems for Lunar mining equipment. Low pressure leads to evaporation of lubricants and other materials. This is due to the dryness and the high temperature on Moon days. What happens is that moist components in the base oil become gaseous, which in turn leads to a thickening of the lubricant. This leads to a change in the viscosity of the oil and a change in lubrication behavior [24].

2.3 Oxygen on the Moon

Oxygen is found in many minerals on the Earth and the Moon is mostly made of the same rocks that are found on Earth. Minerals such as aluminum, silica, iron and magnesium oxides are the dominant minerals on the Moon. All these minerals contain oxygen but not in the same form as fins in the Earth's atmosphere. The Moon contains oxygen in the form of hard rock, gravel, and rocks that cover the surface [25]. One way to extract oxygen from regolith is electrolysis of molten salt source. In the chemical process, the regolith is heated, then the oxygen can move along the salt until it collects in an anode, the source explains. However, there is still no solution for how the oxygen created on the moon should be stored source [26].

The Moon's regolith consists of about 45% oxygen, but as mentioned, the oxygen is bound in various minerals. Extracting oxygen from regolith requires significant industrial equipment. First, solid metal oxide must be converted to liquid form by applying heat, heat combined with solvents or electrolytes [25].

One cubic meter of Lunar regolith contains an average of 1.4 tons of minerals, this includes about 630 kilos of oxygen. It is estimated that the top ten meters of the Moon's surface will provide enough oxygen to support all eight billion people on Earth for about 100,000 years. However, this depends on how efficiently humans manage to extract and use the oxygen [25].

2.4 Geology of the Moon and minerals

The Moon's geology is very different compared to Earth's. A significant difference is that the Moon lacks a significant atmosphere, which eliminates erosion. The Moon has a lower gravity than Earth and it has no known form of plate tectonics and due to its size, it cools down faster than Earth. The complex geomorphology of the Lunar surface has been created by a combination of processes such as impact craters and volcanism. It is a differentiated body that has a crust, mantle, and a core [27].

The known elements that are present on the Lunar surface are Oxygen, Silicon, Iron, Magnesium, Calcium, Aluminum, Manganese and Titanium. The elements that should be

present a lot on the Moon are Oxygen, Iron and Silicon. *Table 1* shows the Moon's surface chemical composition in percent [27].

Table 1. Moon's surface chemical composition [27]

Compound	Formula	Composition	
		Maria (Basaltic plains)	Highlands
Silica	SiO_2	45.4%	45.5%
Slumina	Al_2O_3	14.9%	24.0%
Lime	CaO	11.8%	15.9%
Iron(II) oxide	FeO	14.1%	5.9%
Magnesia	MgO	9.2%	7.5%
Titanium dioxide	TiO_2	3.9%	0.6%
Sodium oxide	Na_2O	0.6%	0.6%
		99.9%	**100.0%**

2.5 Regolith

The Moon is covered in a layer of unconsolidated debris so-called regolith. It is a parish name for Moon dust and Lunar soil. Regolith is a blanket unconsolidated and loose deposits which covers solid rocks, which may be several meters thick. Moreover, regolith is not unique to the Moon as it is present on a lot of extraterrestrial environments such as Mars; any airless celestial body will create regolith because of meteorite and solar wind bombardment. The regolith is the result of billions of years of asteroid and meteorite bombardment and superimposition of countless instances of bedrock shattering, pulverization, melting, mixing and debris dispersal [23].

2.6 Lunar soil

The fine part of the Lunar regolith, with a diameter of maximum 1cm, is called Lunar soil. It is worth noting, however, that Lunar regolith and Lunar soil are often used interchangeably and are thus not separated. The properties of Lunar soil can differ significantly from terrestrial dirt. Its physical properties are the result of mechanical decomposition of basaltic rock which is caused by continuous meteoric impacts and bombardment of solar and interstellar charged atomic particles for several billion years. The process takes place according to a mechanical weathering where the particles are ground to a finer size over time. Lunar dust refers to even finer material than Lunar soil that exists on

the Lunar surface. [28] Countless meteorite impacts cause the Moon's surface to be covered by a thin layer of dust. The Lunar dust is electrically charged, and it gets stuck everything it comes in contact with [23].

The Lunar regolith has a density of about $1.5 g/cm^3$. Under the top layer of regolith, namely the Lunar soil, dirt becomes very dense. Large temperature differences, the presence of a hard vacuum and the absence of a significant number of magnetic fields are examples of factors that can affect the properties of the Lunar soil [29].

The Lunar environment has a lot of resources that could be utilized to, at the very least, partly sustain a crew on the Moon. The regolith itself is the most accessible resource to obtain. Furthermore, the regolith itself has a lot of different potential when it comes to usage. For instance, it has the possibility to be used as construction material which is suitable since it protects from cosmic radiation. It is also possible to extract other necessary resources such as oxygen and hydrogen which would be necessary in a Lunar operation scenario. The oxygen may be used by astronauts as it is fundamental for life and the oxygen may be used as a component for rocket fuel [30].

However, the regolith itself is also a factor that has implications on the Lunar vehicle design as well as the wellbeing and safety of the astronauts. Numerous aspects are to be accounted for [30].:

- The dust could darken the surface which would result in a significant increase of radiative heat transfer.
- The Lunar dust has an abrasive nature and could result in considerable wear.
- The regolith may also have a negative effect on coatings, seals and wiring as well as optical lenses [30].

2.7 In situ resource utilization

ISRU contains the collection, processing, storage, and use of materials found or manufactured on other astronomical objects such as the Moon, Mars, asteroids and more. These will replace materials that would otherwise be transported from the Earth. The purpose of ISRU is to provide life-sustaining materials, construction materials, fuels and energy for spacecraft payloads [31].

Today, it is common for spacecraft planetary surface missions to use the solar radiation that is in place using solar panel technology. The use of ISRU in the form of material production is something completely new for humans, i.e., it has not yet been implemented. It is considered that ISRU should be a possible way to reduce, among other things, the mass, and costs of space exploration architectures [31].

NASA wants to plan to introduce sustainable infrastructure that will allow NASA to explore more about the Moon and study more than ever before. This means that astronauts will stay

on the Moon for longer periods. Therefore, more knowledge and a better understanding of what resources are available on the Moon today is needed to support that research and develop the technology that works to process these resources. Living and working on the Moon for months and years can mean that crew members are short of the life-sustaining elements and other important necessities that are readily available on Earth. The longer crew members stay on the Moon, the more important it becomes to create products with local materials [31].

NASA's Lunar Surface Innovation Initiative [32], will develop and demonstrate a technology to use to use the Moon's resources to produce water, fuel and other necessities. The use of sunlight is the most common form of ISRU, and it has been used on spacecraft for decades. An example is the space station, which is equipped with several solar panels to use solar energy and generate a continuous force needed to support crew presence on board the station since 2000 [31].

As space travel through humans evolves toward longer journeys farther from Earth, ISRU will become increasingly important. It is expensive and complicated with supply missions when people become more independent of the Earth. It is necessary to use practical and affordable ways to use resources along the way, rather than carrying everything that is believed to be needed. Astronauts who will be on the Moon will require the ability to gather Moon-based resources and then convert them into water, breathing air, rocket fuel, building materials and more. Some of the most attractive and promising moon-based raw materials that can enable significant mass reduction, cost and even the risk of human space exploration include oxygen and water [31].

Oxygen, hydrogen and water are considered to be the most important products that are most in focus to be able to use on the Moon through ISRU, but there are also other materials that can be at least as important for future missions. Metals and noble gases can become equally valuable resources, especially when they are produced as a by-product of other metallurgical processes (chemical processes). Oxygen is likely to be the first resource produced locally and used to support human missions. It can, for example, find applications in life-sustaining systems and can be used together with hydrogen as a fuel for power and propulsion of operations on the Moon and also future operations [33].

3 Related Work

3.1. Simulate life on Mars

Significant attempts have been made to design and even build a so-called off-world base that will carry important infrastructures, equipment, and supplies from the Earth. Mars' base camp construction from Lockheed is an example of one of several [34]. These designs and concepts are mostly human-focused and have no robot uses. Such projects require careful design and planning to support an exploratory goal. Once an explored goal has been achieved, it is unclear how the base will continue to perform its function and mission. [35] [36].These designs and concepts are mostly human-focused and have no robot uses. Such projects require careful design and planning to support an exploratory goal. Once an explored goal has been achieved, it is unclear how the base will continue to perform its function and mission. [35]- [36].

There are plans to build a human base to gain access to Mars' polar region for future research and data analysis. This project is a similar project to polar research facilities in Antarctica. All accessories such as infrastructure, resources, and operational accessories must be submitted to maintain the base. There are also simulation facilities on Earth to determine how humans adapt and function in these isolated bases. Biosphere 2, see *Figure 2,* located in the desert of Southern Arizona, is an example of a simulation facility on Earth. The purpose of Biosphere 2 is to have a completely self-sufficient base with a miniature support system to help keep a group of people alive for 2 years [37].

Figure 2. Biosphere 2, Habitat and Lung. The "habitat" is where the crew live during the mission. The "lung" is what preserve air pressure inside the structure. (Creative Commons Attribution 2.0 Generic) [38]

These experiments have given mixed results with the goals and purpose of self-sufficiency that have not been achieved. These experiments and results show increased complexity in having a base where it will supply and support humans and other living organisms. Similar experiments have also been carried out outside the United States. The Chinese Space Agency (CNSA) has opened “mars bas 1” that is a simulated Martian bas of operation for future astronauts in China [39].

3.2. Sustaining humans on the Moon

Challenges in sustaining humans and the human-centered facilities in space over the past 2 decades have led to alternative paths. The many challenges of sustaining humans and being human centered from an experimental perspective. It is both complex but also challenging to explore and operate on the Moon as it is today and to take into account human considerations. When it comes to long-term survival, it becomes even more challenging and complex. As for mining on the Moon, it is difficult and very challenging for humans to perform the task. There are several factors that determine that it is very difficult for humans to be on the Moon for a long period of time and perform mining on the Lunar surface. Extreme weather conditions, lack of oxygen, and dangerous gases are some examples that make the job difficult for astronauts to survive on the Moon for a longer period. These factors make robotics a better alternative for the purpose of the task. Over the last 20 years, robotics has developed significantly with very rapid progress, especially in terms of skill, planning, control and vision. The tasks where robotic systems are humanly competitive are

growing. There are also cases where robotics surpasses leading human experts. Today, there are many examples of factories that are fully automated with robots. There is a growing development with self-driving cars, trucks, aircraft and boats. There are also robots where they perform tasks at home, and in workplaces that take over the tasks that are considered dangerous, boring, and dirty by humans [40].

3.3. The Moon base construction

The Moon base construction has been focused on the previous literature for transporting significant amounts of infrastructure and equipment to the Moon. This has been a fundamental role in the construction, mostly for site preparation, open pit mining and the collection of raw materials for the construction [40].

The previous experiments show a lot of deviations that are expected to be used during a Lunar mining process. An example of these deviations is the Moon's low gravity of $1.6m/s^2$ which is of great importance for wheeled vehicles. The low gravity on the Lunar surface leads to a low cohesion of the Lunar surface. It has been shown that wheeled vehicles must be driven slowly in order not to risk losing traction and uncontrolled jumps. This is evident from the Apollo program, after astronauts used the Lunar Rover on the Moon [41]. Previous work has identified bucket wheels as perfectly suitable for excavation in environments with low gravity such as the Moon, this is due to simplified control and improved excavation efficiency. Excavating vehicles such as front loaders and bulldozers have proven to be much less efficient [42].

There are studies that focus mostly on detailed equipment design [43] and conditional comparison of concepts based on industry studies. There are studies where the emphasis is on the driving force and lifting equipment, without focusing on analyzing excavation data in mountain terrain. NASA has conducted a trade study comparing excavation equipment based on the expected ability of them to handle the different types of excavation missions that the Lunar surface faces [44]. This includes qualitative assessment of criteria, a tendency to rely on so-called “nominal data” obtained from equivalent soil conditions. Shimizu Corporation analyzed excavation data such as mining and construction productivity, excavation characteristics, maintenance work and reliability. The productivity details of this analysis are very uncertain, but the analysis is still useful, as it limits the alternatives in a very logical way, which helps to test a smaller list of concepts under the expected Lunar conditions [45]. This includes qualitative assessment of criteria, a tendency to rely on so-called “nominal data” obtained from equivalent soil conditions. Shimizu Corporation analyzed excavation data such as mining and construction productivity, excavation characteristics, maintenance work and reliability. The productivity details of this analysis are very uncertain, but the analysis is still useful, as it limits the alternatives in a very logical way, which helps to test a smaller list of concepts under the expected Lunar conditions [45].

Since 2010, NASA has announced a program called NASA's Lunabotics Competition, which is a competition for university students from all over the United States to build a

mining robot designed to navigate the Moon. The focus is on the robot being able to navigate uneven terrain, mine and deliver simulated regolith. There is also a focus on strict size limits to minimize rover mass, communication bandwidth, energy use and the robot to be autonomous [46].

There are very few examples where the experiment also focuses on the multifunctionality and modularity of the robot that will mine on the Moon's surface. This is where this work differs from the others. In addition to the other challenges that a Lunar mining robot has as part of those discussed here, this project also focuses on the robot's modularity and multifunctionality [46].

3.2. Lunar Rover

The first Lunar rover to move on the Moon was from the Apollo program's Lunar Roving Vehicle, *see Figure 3*. The vehicle was driven by three American astronauts in connection with Apollo 15, 16 and 17. Since then, other Lunar rovers have been sent to the Moon's surface as partially or completely autonomous robots [47]. Lunar Roving Vehicle, also known as (LRV), is a battery-powered four-wheeled Lunar vehicle that was used on the moon during the last three missions of the Apollo program, i.e., Apollo 15, 16 and 17 [48]. LRV is built by the company Boeing, and had a mass of 210 kg, without payload. The vehicle could carry a maximum payload of 490 kg, which included two astronauts, equipment as well as the collected samples from the Moon. LRV was designed for a top speed of 13 km / h, but it achieved a top speed of 18.0 km / h on its last mission which was Apollo 17 [48].

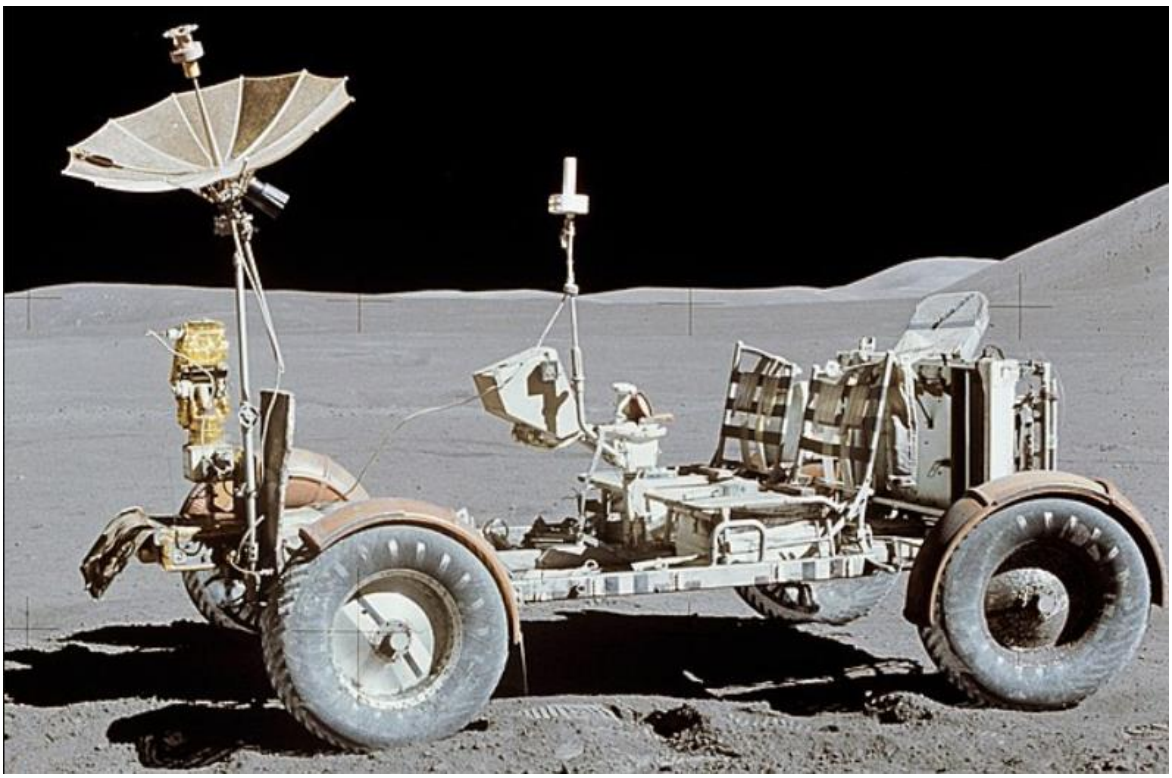

Figure 3. The United State Apollo Lunar Roving vehicle from Apollo 15 on the Moon surface in 1971 (License class: Public domain) [49].

Lunokhod 1 belonging to the Soviet Union was the first of two polycrystalline panel-driven Lunar rovers that landed on the Moon, *see Figure 4.* The space shuttle carrying Lunokhod 1 was named Luna 17 and landed on the Moon in the rainy sea in November 1970. The vehicle was the first moving remote-controlled robot to land on another celestial body [50].

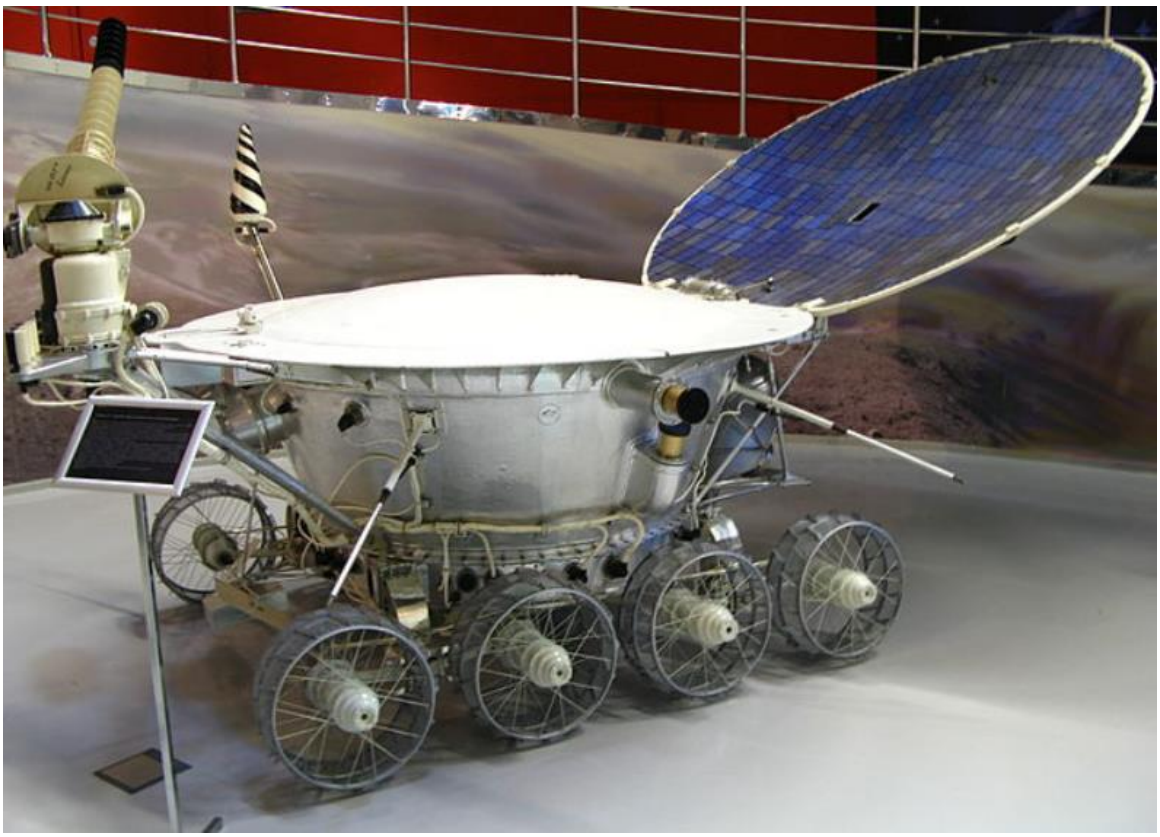

Figure 4.Model of a Soviet Lunokhod program Rover (Creative Commons Attribution-Share Alike 3.0 Unported) [51]

Lunokhod 2 was a monocrystalline panel-driven unmanned Lunar rover that landed on the Moon in 1973 by the Soviet Union. Lunokhod 2 was tasked with collecting images of the Moon's surface, performing laser distance experiments, observing solar X-rays, measuring local magnetic fields, studying the Earth's mechanics of the Moon's surface material, and investigating the determination of light levels to feasible astronomical observations from the Lunar [50].

Yutu is the first Chinese Lunar Rover to land on the Moon on December 1, 2013, by the China National Space Administration (CNSA). Yutu had operational problems already after the first 14-day Lunar night and the robot could not move after the end of the second Lunar night. The robot stopped sending data and performing its operations entirely on August 3, 2016 [52]. Yutu-2 landed on the far side of the Moon on January 3rd, 2019 and is the first Lunar rover to operate on the far side of the Moon [52].Yutu-2 landed on the far side of the Moon on January 3rd, 2019 and is the first Lunar rover to operate on the far side of the Moon [52].

Pragyan was a Lunar Rover that belonged to India's Chandrayaan-2-month mission. Pragyan weighed 27 kg, had six wheels and was to be a solar-powered robot. The mission entered Lunar orbit on August 20, 2019. Pragyan was destroyed along with its lander Vikram when it crash-landed on the Moon on September 6, 2019 [53].

3.3 Future technologies that may be implemented and utilized

3.3.1 Nuclear power plant

For astronauts to be able to live and for operations such as mining to take place on the Moon, energy is needed and there is no electricity network on the Moon today. There are many creative solutions that can help solve energy supply problems on the Moon, but NASA has long seen nuclear fission as one of the most practical energy options for future operations on the Moon. This means that space organizations are taking the next step in making a nuclear reactor on the Moon a reality. Jim Reuter, Deputy Administrator of NASA's Space Technology Mission Directorate (STMD) says that "abundant energy will be the key to future space exploration" [54].

After several years of research and work for the possibilities for the Moon's nuclear fission in previous projects, so-called KiloPower projects, NASA is bringing a new investment and new experiment, this together with the US Department of Energy (DOE) [54].

Both organizations urge US industry partners to submit design concepts for nuclear fission systems that can be implemented on the Lunar surface and be ready to be launched and demonstrate their function and potential within the next 10 years. NASA claims that a small lightweight fission system that can work on a Lunar lander and or Lunar rover should be able to provide up to 10 kilowatts of electricity, which is sufficient to satisfy the electricity needs of several average households in the United States [54].

According to the National Aeronautics and Space Administration and the US Department of Energy report, future fission systems will eventually need to produce at least 40 kilowatts of energy, and this should be able to power about 30 households for up to 10 years according to NASA. NASA says that given the expected levels, there should be enough energy not only to be able to mine on the Moon surface, make a sustained Lunar presence, but also to make it easier one day to allow exploration and even colonization of the planet Mars [54].

3.3.2 Satellites in orbit

The Lunar Reconnaissance Orbiter (LRO) is a robotic spacecraft from NASA that currently orbits the Moon in an eccentric polar mapping orbit. The data that IRO collects has been described as important and fundamental for planning NASA's future human and robot missions to the Moon. LRO has the task of identifying safe landing sites, characterizing the radiation environment, demonstrating new technology and locating potential resources on the Moon [55].

LRO has made a 3D map of the Moon's surface with 100 meters resolution and 98.2% coverage, this excluding polar areas in deep shadow, but including images with 0.5 meters resolution of Apollo landing sites. [55]

4 Method

4.1. Design thinking process

The work that was carried out was organized in accordance with design thinking methodology. It is a well-established process that is used in order to understand users, challenge assumptions, redefine problems and create solutions which are prototyped and tested. The design thinking process is of a non-linear character and sometimes non-sequential and one of its strengths is its usefulness to deal with problems that are ill-defined or unknown. The phases may be summarized as follows below [56] and is visually represented by *Figure 5*.

- The first step is the Emphasize stage. This is done in order to get an understanding of the problem that is of relevance. The most common way of acquiring an understanding is done through research. [56]

- The second step is the Define stage. At this point the accumulated information is analyzed and synthesized into the core problems which are referred to as the problem statements. [56]

- The third step is the Ideate stage. This is the stage where it is time to "think outside the box" and look at the problems from different angles. This is in order to look for innovative solutions for the problem statements that were created earlier. [57]

- The fourth step is the Prototype stage. The goal is to produce simple, downscaled prototypes where certain aspects of interest are investigated to determine if the desired performance is fulfilled. [56]

- Step five is the Test stage. This is where the testing is done. Although this is to be considered the final phase, the learning in this phase is often used to redefine one or several problems. The previous allows for more iterations, alterations, and refinements to produce the best design. [56]

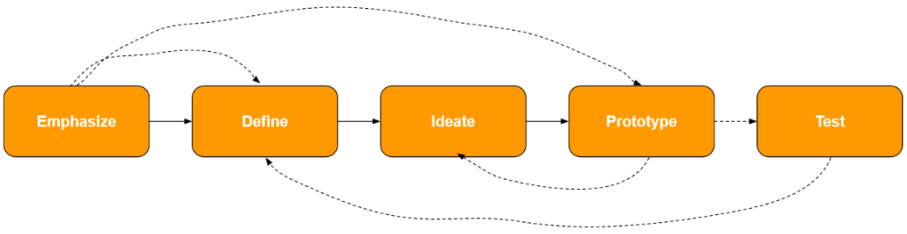

Figure 5. A schematic image of how a typical design thinking process may look like. Adapted from [56].

4.2 Overview and adaptation for the carried-out work

The work has followed the described phases as above. First relevant information was gathered to enable a better understanding of the challenges that the work implies. The information was attained from various sources such as articles, recurring interviews with company experts, books and web pages. All of these provided enough clarity to define the problem and to formulate delimitations and assumptions. Once the previous has been established ideation took place. For this phase, a number of different supporting tools were used, e.g., brain writing and six thinking hats. Brain writing was used to acknowledge as many ideas as possible regardless of deemed usefulness as quality over quantity is encouraged. The six thinking hats tool was used to increase the perspectives of the ideas as sixth different hats are used in order to cover more relevant aspects. Then the ideas that were produced were compared to each other and in dialogue with CSMC a winner was chosen due to its performance in relation to the research question. Once the concept was chosen, the robot structure, regolith collector module and the container module were further developed, and the designs were refined. Then the module equipping module mechanism was chosen to be prototyped due to its novelty and significance of the concept. A rapid prototype was created using various simple materials and tools (see 4.9. for more details). Then it was tested, and central lessons of the test were noted down. Even though some ideas for a second iteration were conceived these were not realized due to the time limiting these endeavors.

4.2.1 Information gathering and needfinding

This part of the report describes the solution methodology used to complete the design concept problem. It has been based on the problem description, project requirements and design criteria that have been discussed in previous sections of the report. This includes literature searches, quantitative analysis of the design criteria, concept generation, sorting and development of alternative designs for the robot's critical functions, design and demonstration of a module. Most of the literature research was online and the sources for these were various databases available on the school library website. These databases were Summon @ BTH, DART, Cambridge Journals Online, Encyclopædia Britannica, IEEE Xplore, Lecture Notes in Computer Science, Google Scholar and more. The websites from which data are taken are reliable sources, such as the European Space Agency (ESA), NASA, GM Motors, Maxon, Lockheed Martin, China National Space Administration (CNSA), Research Gates and more. Search terms used to find the right information were Lunar mining, Lunar, the Moon, Space, mining the Moon, space robots for Lunar, Lunar exploration, robot swarms to mine Lunar and more.

An objective of the literature research was to gather information about the existing technologies that can be helpful that have aimed to achieve a successful, robust design for Lunar mining. A literature review has been conducted on fully autonomous units and some specific technologies used in autonomous units. Another step in the design process is a quantitative analysis of the design requirements. Using data collected through the literature

review, calculations were performed, various concept design proposals, pre and prototype proposals were made to investigate the physical needs of the robot and its modules. The Lunar environment differs markedly from the Earth environment, and this may mean that the Lunar environment may be favorable for non-obvious design solutions and may be counterproductive to standard design solutions that exist on Earth. Therefore, the authors performed analyzes to determine which types of design solutions are most suitable for the Lunar mining concept. Qualitative analyses were performed on the different parts and functions of the concept in order to be able to choose the most feasible alternative.

Throughout the project, the group had continuous contact with CSMC and regularly had meetings with Dr. Marc Donato who is experienced in the development of space technologies. For the meetings mentioned the group had generally come up with some questions or sought some feedback on generated designs. The questions or the designs were written down and/or explained and sent to Dr. Donato at least a day in advance. Then the group met Dr. Donato digitally asked the questions or engaged in a discussion and took note of the dialogue or recorded the session. This provided insights which were utilized in the design in different ways; e.g., the change of steering approach.

4.2.2. Definition of criteria

Several criteria were established of what the concept should be able to fulfill in order to be a solution to the problem in question. The criteria were formulated in accordance with the SMART philosophy. This means that the criteria should be specific, measurable, achieve relevant and timebound [57]. The previous in order to make sure that the developed solution would be appropriate. The criteria were formulated as well as categorized depending on nature and are to be found in the *appdx. 1*.

4.2.3 Idea generation

To produce the best possible solutions, the group used different idea generation methods. This step was an important, because all thoughts, ideas and solutions to different issues come together and then they create the basis for the final solution [58]. Several methods such as Brainstorming, Brainwriting, six thinking hats, exclusion method, combining different ideas and more are used at this stage. The six thinking hats is a method which is used to amplify or strengthen creative conversations. This by making sure that six varieties of viewpoints and thinking styles are accounted for. Using six roles or "hats", allows teams to structure abstract thinking more easily for productive results [59]. Brainwriting is a way of sharing new ideas and encouraging creativity as well as developing new innovative ideas. The tool encourages the users to spend more time formulating their thoughts as they are written and enables them to develop the ideas of others in comparison to traditional brainstorming. [60] One purpose of this was to produce innovative ideas which may not be as obvious. Due to the constraints that had been given to the group several ideas techniques were used to deal with creative blockage and concepts that initially were too similar to each other. One purpose of this was to produce innovative ideas which may not be as obvious.

Due to the constraints that had been given to the group several ideas techniques were used to deal with creative blockage and concepts that were to similar to each other.

With the help of these methods, innovative ideas can be created and developed. The group used different variants of brainstorming, such as brainwriting, sketching, and building on each other's ideas. The method was used by, for example, the group members sitting together and choosing an area within the project to generate ideas on. Then all the ideas that the group members produced were written down. Before the method was used, there were clear rules as follows:

- No ideas should be criticized
- All ideas must be documented
- There are no bad ideas
- Quantity before quality
- The participants help each other to create, adapt and refine each other's ideas
- If an idea does not work, the group should turn it into a successful idea

4.2.4 Benchmarking

A benchmark means the result of continuously testing an application in various forms, for example a website over a period of time. This allows the progress and development of one's product to be tracked when repeating the development. Benchmarking can also be used to compare a product with a competitor's product [61].

Benchmarking was done to examine the market to which the Lunar mining Design Concept belongs. Therefore, alternatives were found and discussed. After each idea that the group discussed, strengths and weaknesses with the different approaches.
In addition, when the group discussed a significant idea or solution, it did benchmark to compare the solution with potential competitors. Many of the similar solutions available online are in the form of video animation and lacks actual data and specifications, which makes it difficult to know how close to reality the concept is if it is materialized.

4.2.5 Concept selection

There are several ways of choosing a concept, e.g., using a Pugh matrix [62]. This was not carried out due to it being hard to put the strengths and weaknesses in relation to each other with aspect to the internecine relation. As such, all concepts were summarized as their strengths, weaknesses as well as key features were noted down. This was used as a foundation of a discussion with Dr. Donato where the group and him ranked the strengths and weaknesses in relation to each other. This was done since one potential issue could be more expensive and implicate more complexity to deal with than another weakness which may be hard to determine without sufficient experience.

4.2.6 Concept and module development

After the concept was selected, the authors began to develop the concept. The first steps at this point of the process were to illustrate the concept through simple drawings. Every idea of the concept was discussed within the group and with Dr. Donato. Several of the ideas have also been illustrated by simple Lego, cardboard and wood prototypes. These have been done to see and possibly test the functions. An example of this is when the group designed and discussed whether the robot would contain six wheels instead of four which were later not chosen due to the complexity that could arise with a robot on six wheels.
All parts of the robot and modules have been developed and upgraded to different versions. This has been based on the requirements that exist on the concept, the features of the designs in question and discussions with Dr. Donato.

Most of the changes and developments made to the modules and the robot have been sketched using CAD-software Autodesk Inventor. Some of these sketches have also been printed in 3D to be able to see certain functions and any deviations.

The Regolith collector module was one of the parts that developed and optimized the most. This is due to factors such as robustness, efficiency, ease of handle and more. Several modules have been designed and all of these have been analyzed within the group and also discussed with Dr. Donato in order to find the strengths and weaknesses in the design in question.

The entire concept, including the modules, has undergone several development phases, changes, optimizations, and improvements. This is so that the concept will meet the existing requirements and to get an optimal result and be able to choose the best solution. The final solution is the result of the optimizations, changes, improvements and studies that have been done. It has been chosen that the older versions of the solution are not discussed and presented in this report. This was because the report would have become longer and the report should focus mostly on the final result.

4.2.7 Functional Hierarchy Diagram

A functional hierarchy diagram is a diagram where it presents all the functions that may be involved in a system. Functional hierarchy diagrams are used to be able to define the elementary functions and how these functions are related to each other. That is, the diagram shows the functions of the system in hierarchical order. It indicates where the function is and it also indicates the subfunctions below it. Then each subfunction is further divided into subfunctions [59]. Functional hierarchy diagrams were made to present the functions involved in the entire Lunar mining process. Here the elementary functions and the relationship between them were defined. This means that *operate on the Moon* is the system itself in this case. To enable this, elements such as *"Perform ISRU- and supporting activities", "Aid robots in need of assistance", "Move on the moon", "Provide communication and remote control capabilities" and "Understand its surroundings and its*

own" are needed. operation ability " are the elementary functions that are interdependent on each other and can enable the Lunar mining operation on the Moon, see *Figure 6*.

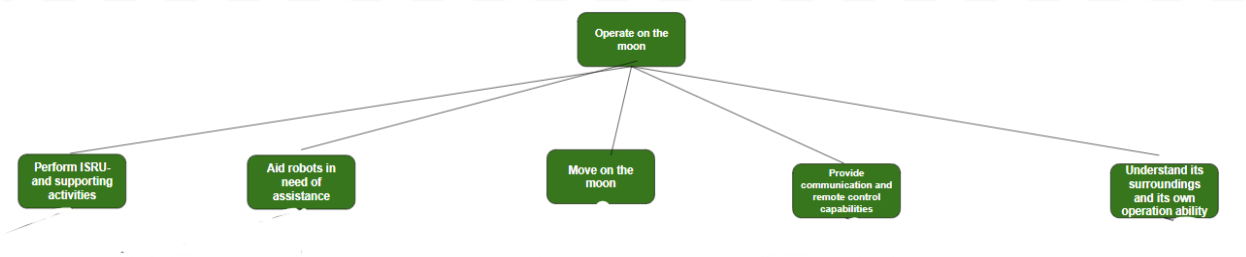

Figure 6. The elementary functions of functional hierarchy diagram for the Lunar mining operation

In turn, the elements mentioned above have been divided into parts to illustrate which elements belong to which and the relationship between them and how they are independent of each other. For example, to enable "*Perform ISRU- and supporting activities" needed "Equip tool module*" and *"Unequip tool module" and then the function of "Operate tool module"* is divided in three elements (functions) which are *"Collect regolith," "Transport regolith" and "Unload regolith" see Figure 7*. Similarly, the entire system has been described with the functional hierarchy diagram. A complete diagram is presented in the results section.

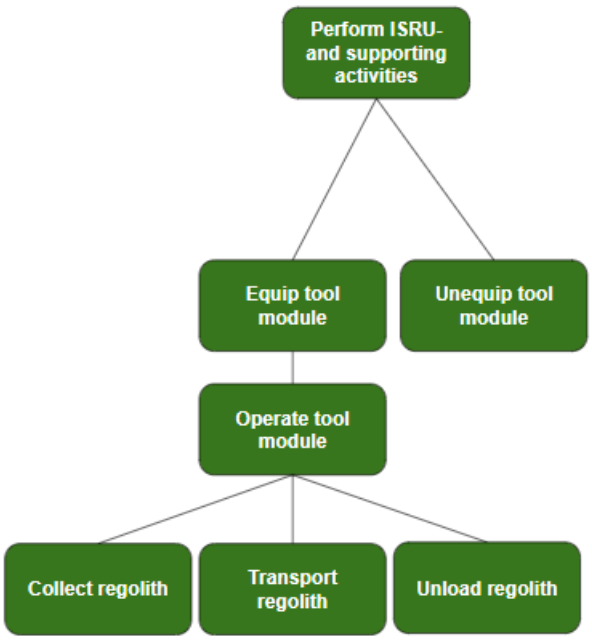

*Figure 7. Functions that are needed and related to "*Perform ISRU- and supporting activities" element

4.2.8 Prototyping

During the process, from the ideation stage to the test phase several different rapid prototypes or prototypes were created. The previous is valid for both physical ones as well as digital renderings. There are several reasons for choosing to protypes features or larger structures. One reason is that the authors intended to use several methodologies for the ideation phase to stimulate a greater variety of concepts due to the variation in approach. Another reason is that some details that are more difficult to image in an abstract form were created physically. The tools and materials varied; it depended on which was deemed to be the most appropriate way to materialize the idea in question. As such, materials such as cardboard, wood, 3D plastics and paper were used. The prototypes were also used to minimize risks to identify problems and weaknesses at an early stage [63].

Moreover, the main aspect that differs the proposed solution in this report from other concepts is the designed solution that enables a robot body to operate different tools. This is since this enables greater resilience to the operation at large since the fleet is more flexible. The previous since the fleet may change its composition if necessary, depending on the case. As such, this was an aspect that was chosen to be prototyped and tested with the goal of determining if this approach would prove to be satisfactory. Since the project deals with concept development, it was appropriate to test the mechanism on a conceptual level of detail. Therefore, the group made a simple prototype of the module holder, in order to test the principle of functionality on the concept.

The module holder equipment was built by using three layers of Masonite board that were glued together forming a base that would mimic the underneath of the robot body, see *Figure 8*.

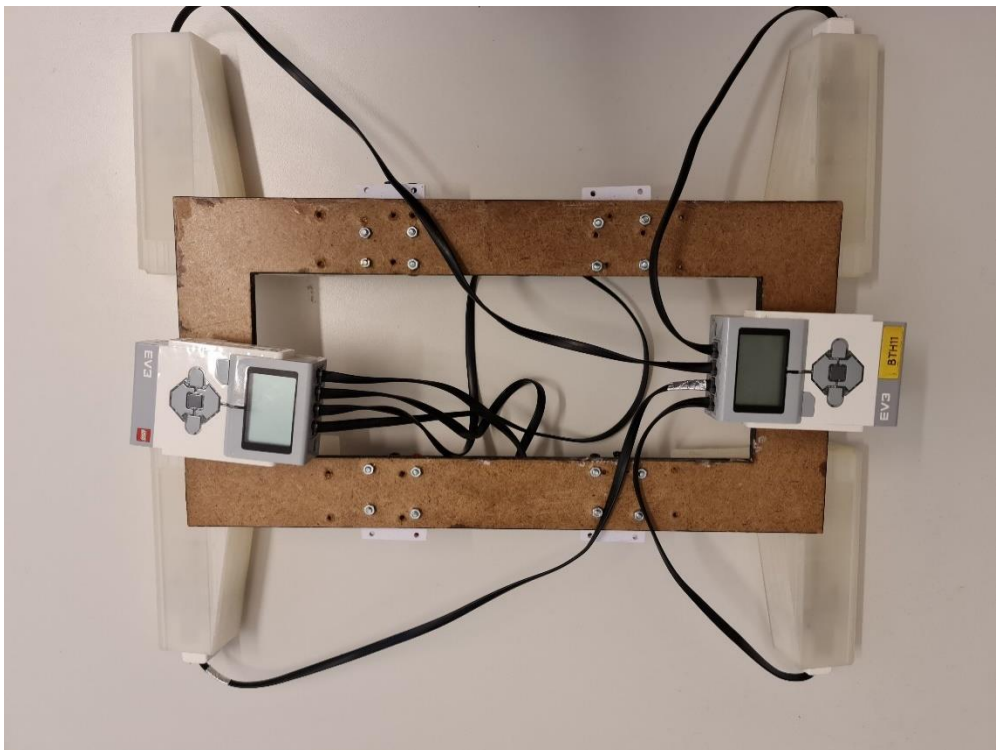

Figure 8. A prototype to illustrate the module holder seen from above

The rectangular Masonite board has lasers cut. The four "arms" that have been screwed into the Masonite board are to hold the motors, which carry the module.

Several LEGO motors were used to achieve the intended movement. A custom attachment for the big motor type was created. This was done by the Autodesk inventor, and it was later 3D printed. The attachment allowed the motor to be connected to the Masonite board as the first mentioned were screwed into the last mentioned and the motors were kept in place by using standard LEGO connectors. Since the big motors are designed to have a cross shaped axis inserted into them one of these LEGO pieces was used and a geometrical shape that allowed such an axis to be inserted into the arms. The arms were designed using the earlier mentioned CAD program Inventor and were later printed in 3D as well, see *Figure 9*.

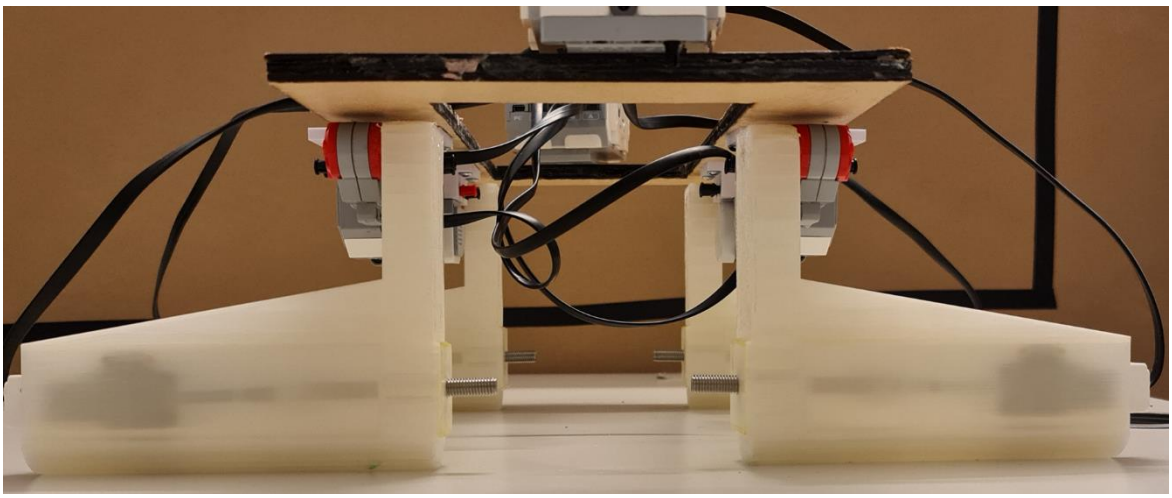

Figure 9. Modular holder, where four arms equipped with motors and screws seen from the side.

In *Figure 9*, the arms that are mounted in the Masonite board and where the small motors that are equipped with screws are mounted in the arms can be seen.

The arms were designed to have a small LEGO motor moving inside, since this is necessary to achieve the screwing functionality. As such, a hollow square was designed at the bottom of the arm. This allowed the small LEGO motor to be placed inside. A hole in the square was then threaded so that a rotary motion would move a screw forward. The screw in question was then connected to a LEGO axis as the parts were glued together using a glue gun. For several reasons the mockup of the container module was a few pieces of Styrofoam that had been glued together to get a reasonable size. This was in order not to put too much strain on the Lego motors since the 3D printed arms were quite heavy. The Styrofoam piece had four holes made, one for each screw. However, these were not threaded due to limitations of the material in question. Then the LEGO motors were programmed to behave in accordance with the necessary course of events. This was achieved by using the intended LEGO Mindstorm developed by LEGO. The big motors were programmed to initially perform some synchronized movements before attaining a 90-degree angle in relation to the Masonite board. Then the small motor would engage, and the screws would go into the Styrofoam part. Then the small motors would stop as the big motors would lift the Styrofoam upwards. All of the tests were filmed in order to be presented to the reader as well as enabling the group to evaluate the result of the design module holder mechanism more accurately.

4.2.9 Testing

Once the prototype was complete it was tested. This was done by putting the concept in its intended scenario. The purpose of the testing was to examine how well it would be able to pick up the container module. Another point of interest was to examine the overall

performance of the screws. However, the design of the container module itself at this stage was insignificant and as such it was simplified.

The software program that had been designed was initiated this engaged the different motors were activated. At first the motors operated the arms were used to get the second set of motors, which operates the screws. The previous in order to enable the screws to find their intended holes. This process is completed by the second set of motors are engaged which causes them to extend due to the transformation of the rotating movement into linear motion.

Several tests were carried out to determine this as the process was repeated seven times. This is in order to attain a trustworthy result. The number seven seemed sufficient since there was only a minor deviation among the outcome of the tests. The tests were recorded to further review the solution in action.

4.3 Verification

Regarding the constructed prototype, the test that was performed concluded that the performance was satisfactory even though there is room for improvement. This is a central part of the verification due to the reason mentioned earlier, e.g., its centrality.

As a means of further attaining a robust performance of the solution a FMEA was carried out but also to objectively evaluate the design and as a foundation for further development. The FMEA is a tool which utilizes a structural approach to discovering potential failures that may be present in the design. It is beneficial to identify failures and risks as soon as possible since this requires fewer costs and implies less complexity to deal with them. As such, a dedicated template was filled out which listed these issues and provided them with a number of severities of failure, probability of failure as well as detectability of failure. It is worth noting that the higher the number the worse the issue. These values are multiplied to a Risk Priority Number (RPN) which is a measure of the listed issue. [64]

The usage of this tool was one way of verifying the design as the most critical failures were identified, and what measures that can be taken in order to minimize or hinder the issue from taking place. If a lot of severe issues would risk taking place, with a high probability of taking place which may be difficult to locate then such a design may most beneficially need to be reconsidered. The result of the design was considered to be satisfactory when the issues were acknowledged given the complexity and task that the project implicates.

5 Design for Lunar mining

Before examining a scenario for Lunar mining, it is necessary to delimit the parameters within which the system should operate. During the last 20 years, a considerable amount of work has been done to conceptualize the idea of Lunar mining, which entails some design criteria for suitable equipment. As such, this chapter is a bridge to the result section.

5.1 Low weight for equipment

Equipment that is designed or to be designed for Lunar mining cannot be mass-intensive, that is, heavy, due to the high costs and possibilities of transporting them from Earth to the Moon. A balance must be struck, for example, between a Lunar mining robot and energy needs [65].

5.2 Flexibility and modularity

Lunar mining robots should be multifunctional that can perform scraping of Lunar regolith, transporting the material to another robot, transporting material to a "further processing station", towing another robot and more [65].

5.3 Simple design and operation

Equipment designed for Lunar mining should be as simply designed as possible. When the design is simple and versatile, the probability of failure will be lower, but it will also be easier to solve different types of changes in the event of any problems in the future [65].

5.4 Lunar environment criteria

This is about the fact that robots and modules must work in the Lunar environment. The loads on the Moon's surface mean a total vacuum, electrostatic dust, and intense radiation in various forms. The robots and other equipment must function and survive in this tough and very different environment than the Earth. The criteria that are counted here is that the robot must have good efficiency. Energy supply systems such as batteries will increase the mass of the robot, therefore it is important that the device has a low power consumption.

It is important that the design is robust to be able to withstand and cope with the Lunar environment. For the robot to be able to move around the Moon's surface, it must be stable. Since everything must be autonomous, it is important that the robot be able to correct itself in the event of any unusability due to the surface of the Moon. While the robot should be able to move in various parts, too many moving parts on the robot should be avoided. Because there is almost a complete vacuum on the Moon, the lubrication of moving parts is a major problem. The vacuum removes the water vapor that acts as a lubricant on the ground.

5.5 Execution criteria

This is about the robot covering the Lunar environment completely without human interaction, i.e., the robot must have a high level of reliability. Since astronauts will not be

on the Moon to repair a broken robot, it is important that the design should have a low error rate. This means that the concept must be modular. A modular design makes it easier to repair components in the robot and the modules. It must also be fully automated. The idea is that the robot will perform its tasks without humans being on the Moon [66].

5.6 System Power Supply

For the robot and modules to be an independent autonomous system and to be able to perform all their functions, they must have an energy supply system. No natural fuel sources exist on Earth, large temperature differences and mass restrictions make it difficult and challenging to find a suitable energy source for the Lunar mining equipment on the Moon. Today, there are various suggestions for energy sources that have the properties required on the Moon. Many of the proposals are not completely ready to be applied today, but they will be ready for application before the operation begins. In order to be able to choose an energy source, the group must assume a constant average power requirement with certain higher peak efficiency requirements. This was done based on the forces required and the mass of all parts of the system.

5.7 Regolith collector

In order to be able to collect regolith and then transport it to the process station, it was necessary for the group to design an efficient module that would mount under the robot and perform the scraping. The group discussed and sketched several alternatives and made simple prototypes until a final solution was chosen.

5.8 Bucket

To scrape the regolith from the surface of the Moon, the group designed a module where it is mounted under the robot. The bucket protruding in front of the robot. The regolith collector is a bucket-like tool, where the front is thin and sharp to be able to get good contact with the regolith on the surface of the Moon. At the end of the bucket, a conveyor belt is mounted which helps the regolith to be passed on to the robot, see *Figure 10* which will later transport the regolith to the process station. The bucket that acts as a regolith scraper and collector is about as wide as the robot and it is angled so it becomes an optimal angle for the surface and conveyor belt. It is a compressive mechanism used to enable the bucket to scrape and collect the regolith. That is, when the robot moves forward, a certain pressure is advanced which affects the bucket to be forced to move forward and scrape the surface because it has contact with the surface.

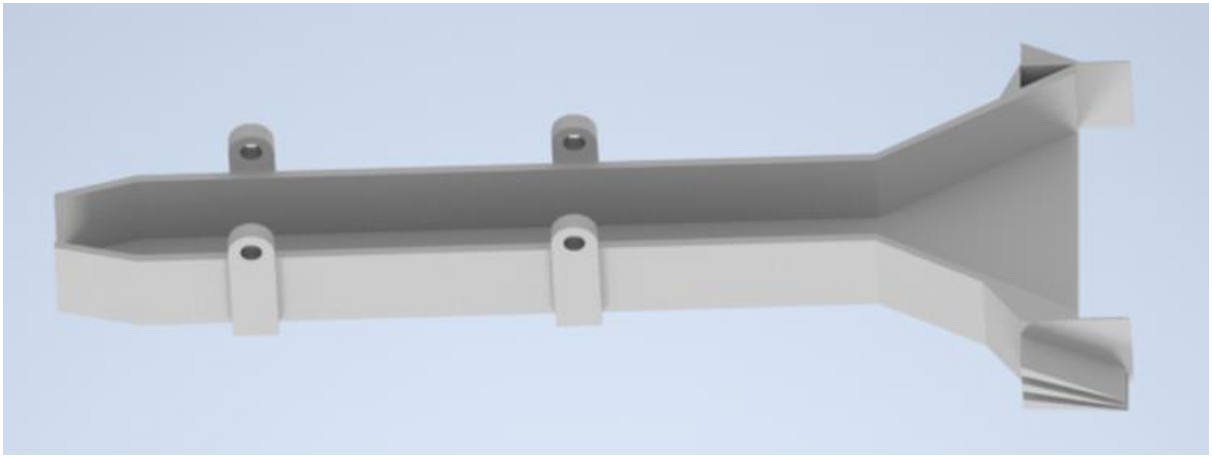

Figure 10. The bucket-like regolith collector seen from obliquely from above.

The advantage of this design is that it is less complicated, and it consists of fewer parts. No motors are required in the bucket itself and the force that propels the robot is used to make the bucket do its job.

The disadvantage of this design is that it requires a lot of power to be able to scrape the regolith. Then there is a great risk that the robot gets stuck in the regolith because the wheels make a stop in the regolith when it tries to drive forward. When the wheels "want to" drive forward and the force is not enough, holes are created in the regolith as the wheels slide on the regolith which in turn leads to the robot getting stuck in the regolith and the whole operation stops. Because this factor can be critical, the group chose not to go forward with this solution.

5.9 Motorized bucket

Another module for scraping that the group designed was a motor-based conveyor belt which on the front is equipped with a rotating roller that has angled grooves around it, See *Figure 11*. The roller is designed in such a way that when it rolls it brings the regolith with the help of the angled grooves in the form of long buckets to conveyor belt which then the regolith leads to the lower part of the belt which in turn transport the regolith to the next robot. The roller is driven by two motors that are mounted on both sides of the roller. The conveyor belt is also driven by two motors, one motor mounted on one side of the conveyor belt´s tip and the other motor is mounted on the other side of the belt´s end, see *Figure 11*.

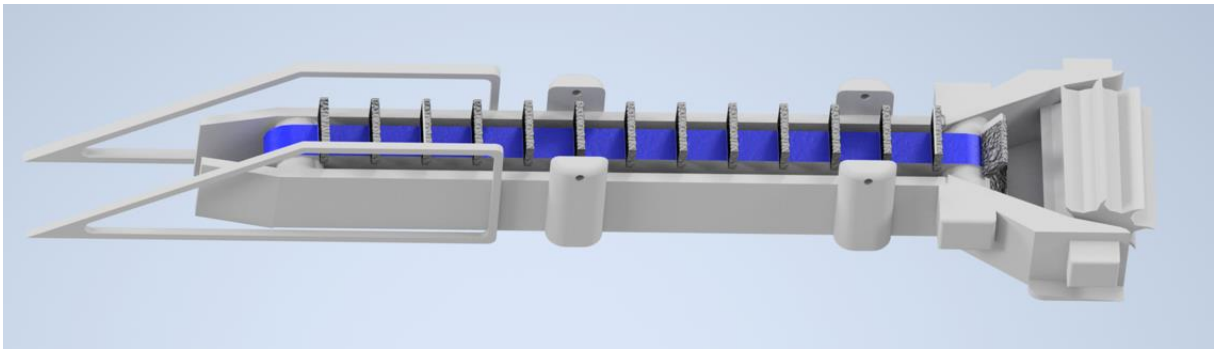

Figure 11. The regolith collector (motor-based conveyor belt) module seen from obliquely from above.

This design is a suitable and applicable design that will handle the operation on the Moon. The risk of the robot getting stuck in the regolith is much less and in the event of any obstacles, the robot can reverse and then control the direction before the robot starts its work again. The roller's mechanism means that it collects the regolith, leading it to the lower part of the belt, which in turn transports the regolith to the next robot.

5. 10 Wheels

Designing the right wheels was one of the most critical parts of the job. Lunar mining robots must meet a range of requirements such as limited transport mass and volume, potential variation in temperature from about -230 to 130 ° C, exposure to solar radiation without atmospheric protection, rolling and sliding contact with unfeathered regolith and dust particles.

5.11 Rotatable wheel steering

Different wheels and steering systems were designed before the final solution was chosen. One of the solutions was that the wheels would move 360 degrees, but also move sideways, see *Figure 12*. This would be done with the help of three motors in each wheel, where one motor would be used for steering, one to operate the lever and one motor to drive the wheel. The advantage of this design was that the wheels could move in all directions and the robot could be steered in different directions without being driven forward or backward. This would help ensure that the robot does not need large areas to turn in different directions. It would also help the robot to cope more easily with any obstacles on the Lunar surface and for the robot to get out more easily if it got stuck in the regolith. The disadvantage of this solution was that it required many motors, and the system was too complicated. The goal is for design to be as simple as possible with fewer complicated parts. A total of 12 motors are needed for the wheels and steering and this contributes to mass increase on the robot. It also makes the system more complicated and the risk of errors increases.

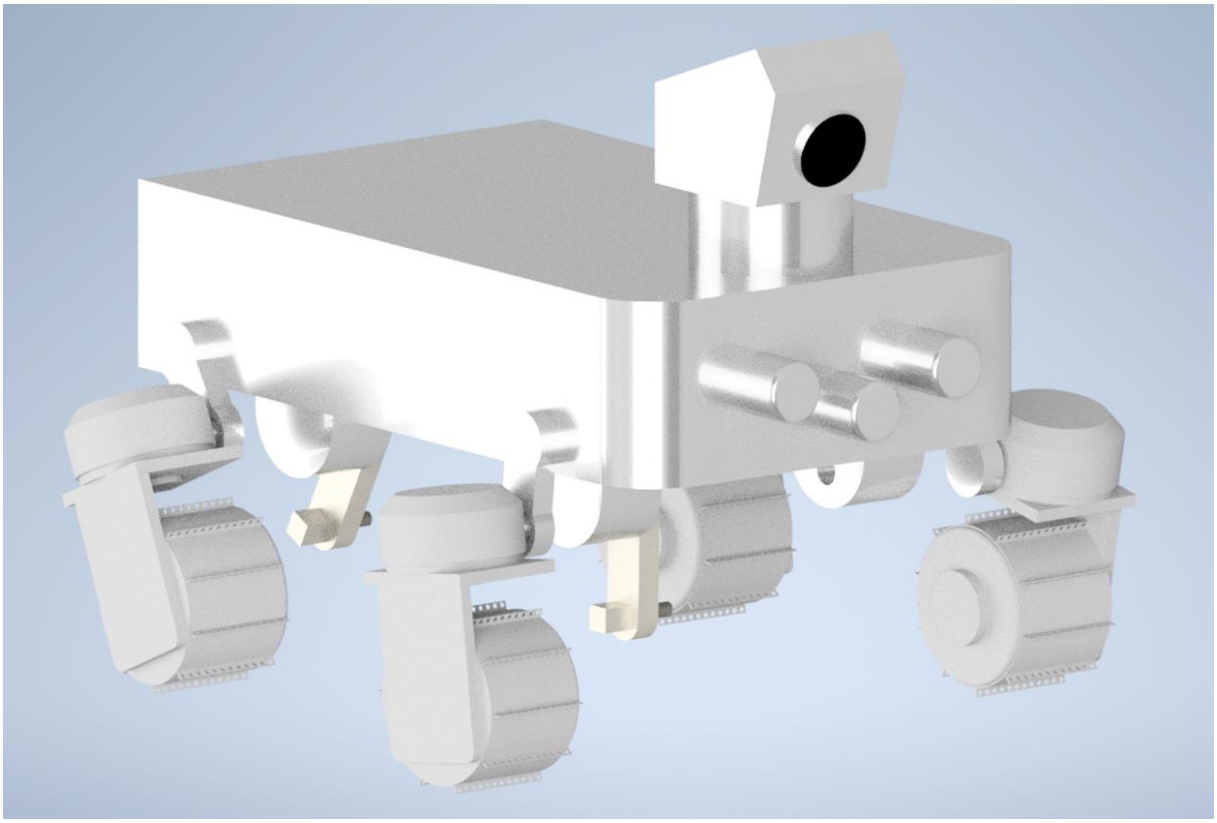

Figure 12. A CAD model that shows the rotary wheel steering design where the wheels and levers are controlled by three motors each.

5. 12 Non-rotary wheel steering

An alternative solution for wheels and steering is that each wheel in the robot would be driven and steered with two motors. That is, one motor in each wheel that drives the wheel and one motor in each wheel that controls the height of the robot. This proposal limits mobility more, compared to the three motors control concept, but on the other hand it is less complicated. A motor sits at the wheel to drive it and a motor sits at the shaft in which the wheel is fixed, see *Figure 13*. The wheel axles are movable laterally, but the wheels are not movable around their own axle. The advantage of this concept is that it is much less complicated, it has fewer moving parts that contribute to less risk of complications and errors, it contributes to mass reduction and uses less energy. After the group discussed and weighed the pros and cons of different proposals for the wheels and the steering, it turned out that two engine steering wheels were the appropriate solution to the concept, and hence this solution was determined as a final solution.

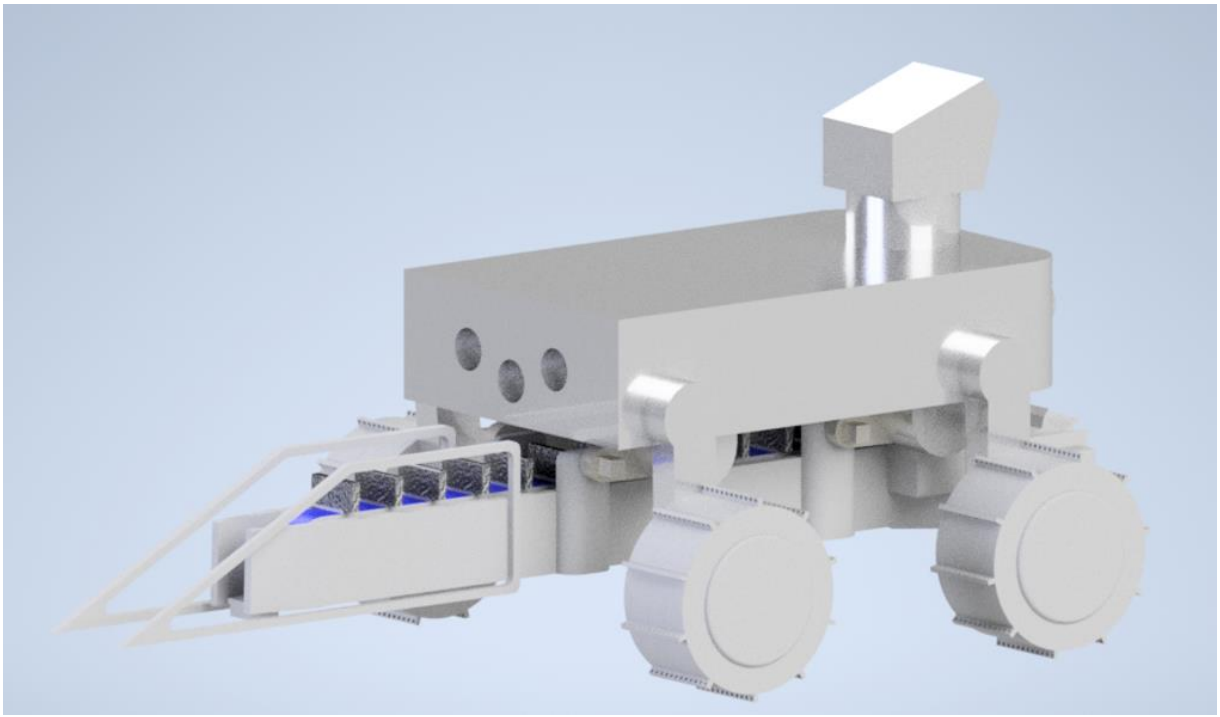

Figure 13. A CAD model that shows the wheels and levers that are controlled by two motors and are mounted in the robot with regolith collector module.

6 Results and Analysis

6.1 The identified requirements

Based on the research, as well as in dialogue with CSMC, several criteria were defined. The requirements are presented in *Table 6*, *Table 7*, and *Table 8, which* are found in *appx 1*. The criteria were defined to ensure that the design would have a performance that would be sufficient. Many of these criteria relate to the actual appearance and what it shall be able to do. The interaction aspect of robots and these kinds of criteria were not defined as this requires too much detailed knowledge for a project of a high-level concept generation nature. The functions themselves are included in the further work as they are a vital part of the concept, nonetheless.

6.2 Functional hierarchy diagram of the robot

In order to get an overview of how all the functions relate to each other a Functional hierarchy diagram was created, this is seen in *Figure 14*. The identified functions are also a result of the research that was conducted. Several distinct activity areas are divided, and its functions are cascaded. These provide a better understanding of how the functions relate to each other as well as which sub-functions are necessary in order to achieve the general functions. As explained earlier this tool also helped to visualize to make sure that all the identified functions are accounted for. Moreover, it provides an overview that is an aid in making sure that no unnecessary functions are present.

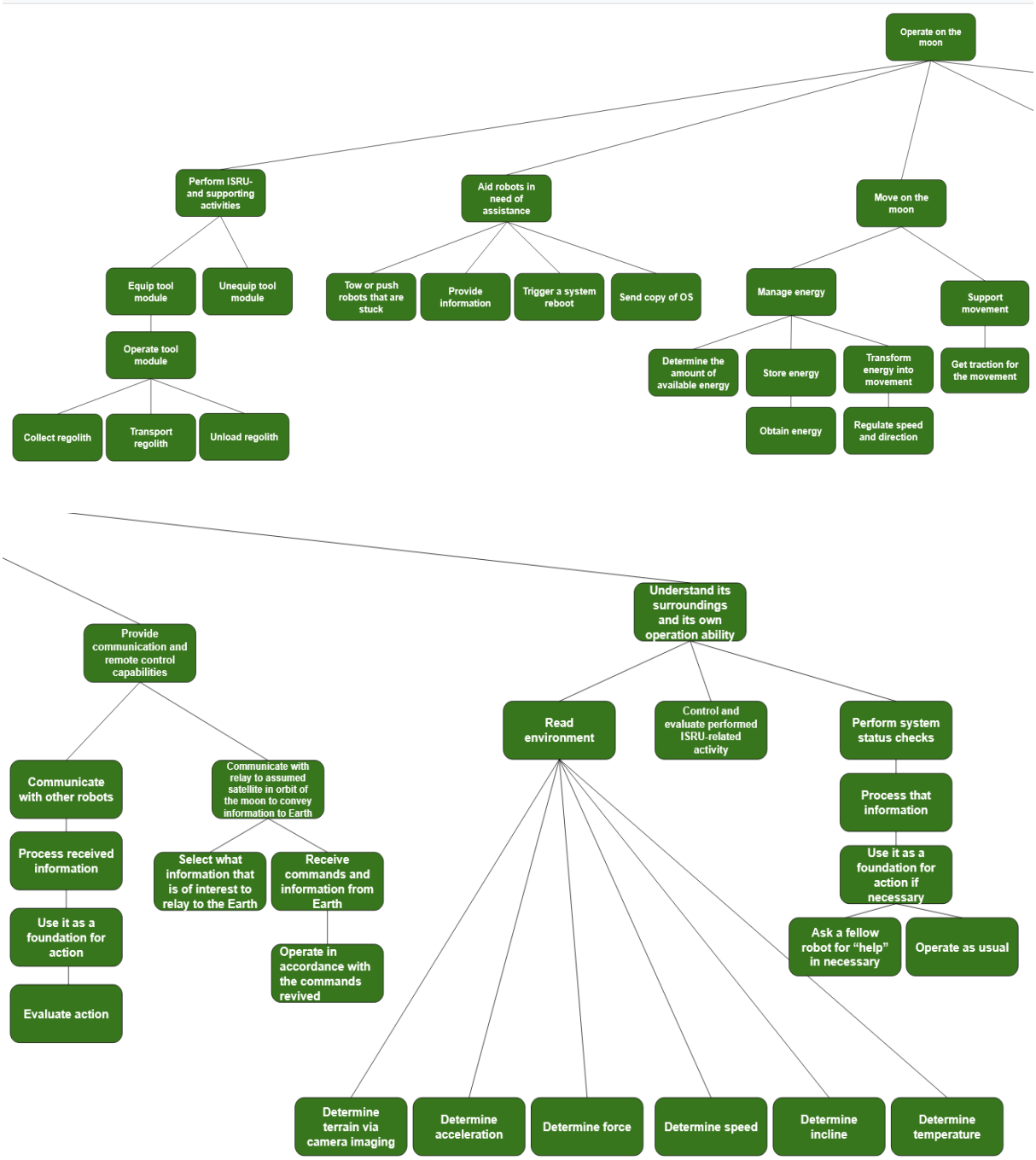

Figure 14. The functional hierarchy diagram of what the concepts shall be able to do (left and right halves respectively).

6.3 Robot architecture

The final solution utilizes several rover-like robots that will operate in a swarm like manner. These robots are designed to be able to seamlessly work together when such is beneficial and on their own when appropriate. The robots are multifunctional due to their ability to operate different tool modules that enable the robots to perform a wide range of ISRU-

relevant operations, necessary to mine and establish a base on the Moon. All of the robots are of the same size. This is beneficial since all robots will be able to operate all modules and there is only a need for one size for all components and spare parts. However, depending on the need for the robots in the future, differently sized robots may be a reality but in the beginning of the endeavor it is recommended that all the robots have the same size and the same system architecture for the previously mentioned reasons. The robot design is shown in *Figure 15, Figure 16* and *Figure 17*.

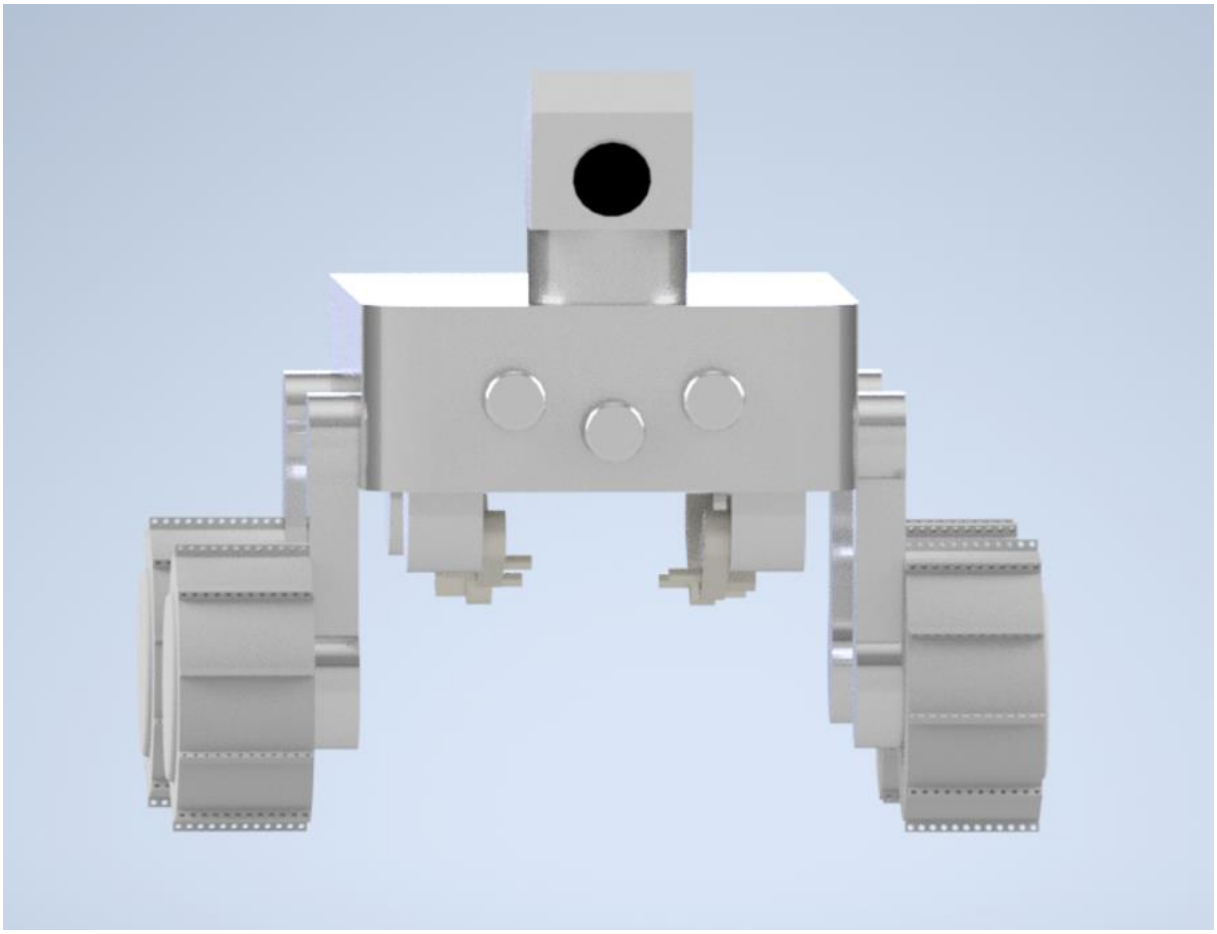

Figure 15. The robot seen from the front.

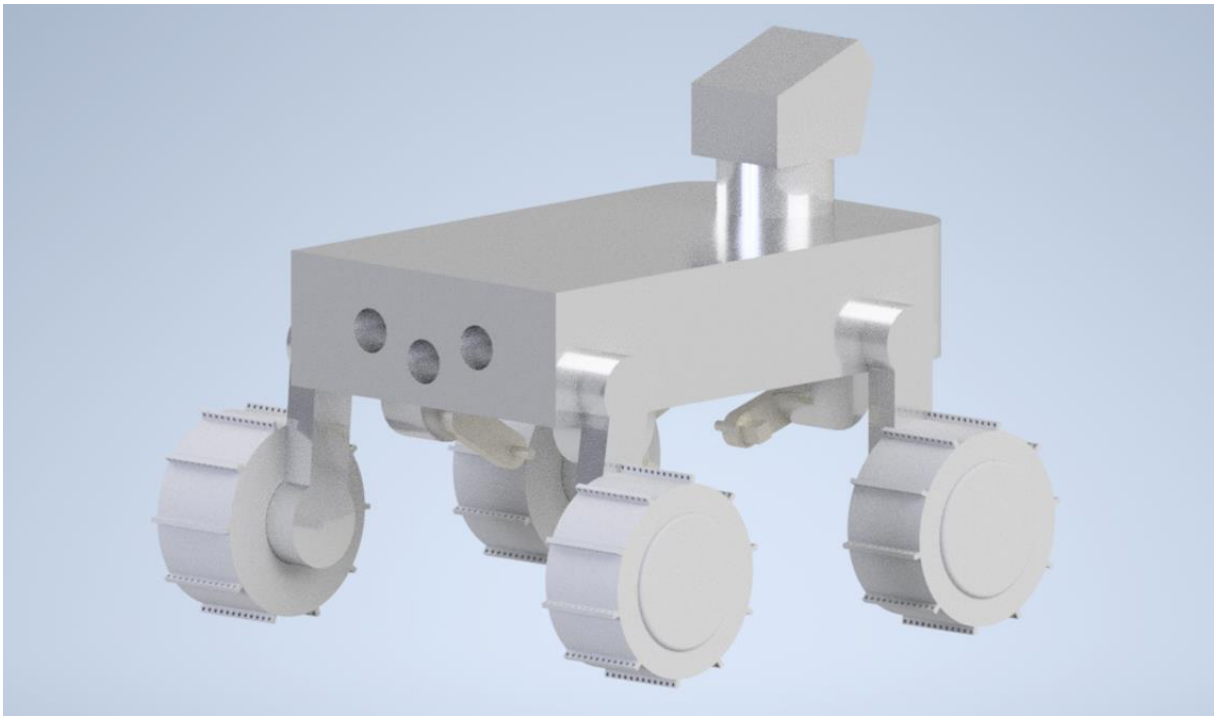

Figure 16. The robot seen from obliquely from behind.

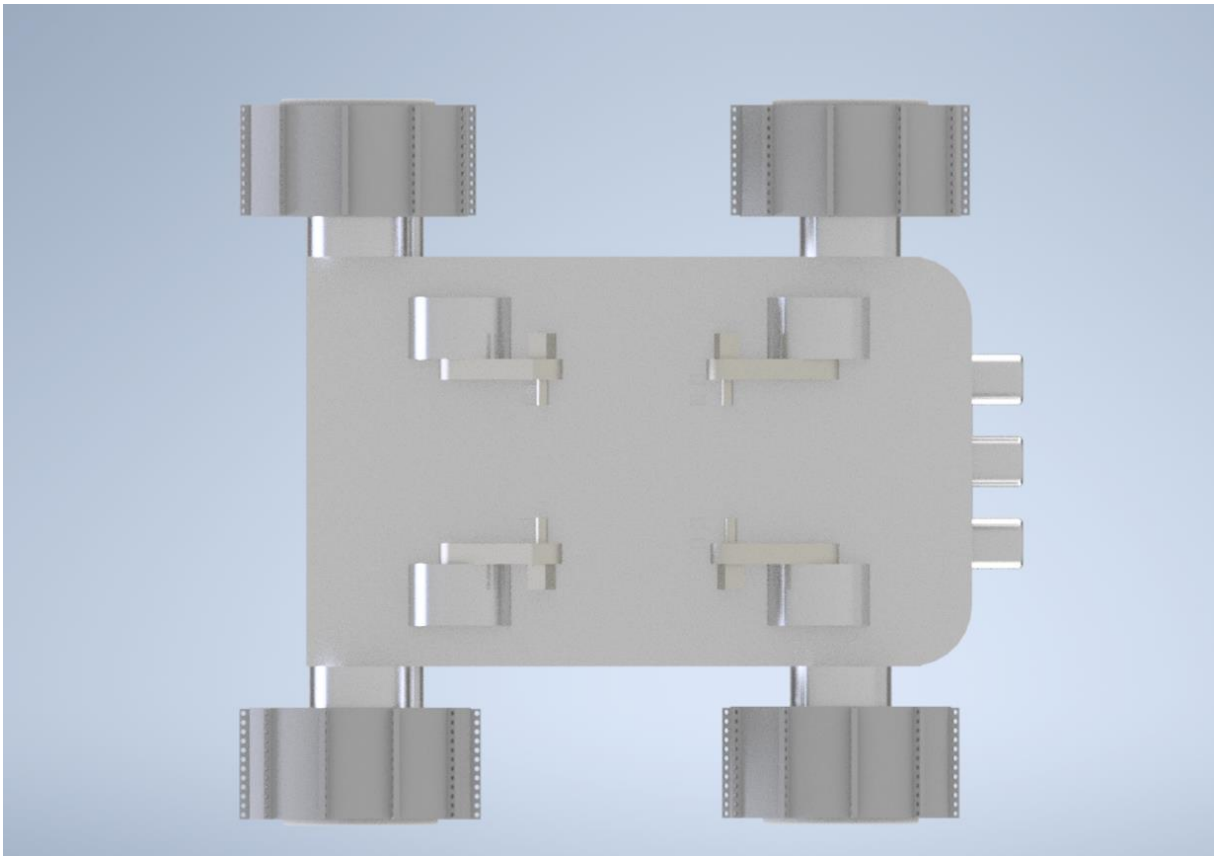

Figure 17. The robot seen from below.

Due to several reasons, such a simple design as possible was aspired to be created. The robots will be easier to build and repair and there are fewer things that may go wrong, which

makes the operation more stable and predictable. Another crucial factor when the robot was designed was the weight. It is expensive to launch something into space (approx. 1-1.4 million US dollars per kg). Therefore, it is important to make the robots weigh as little as possible. There is an issue with this, however. As is familiar, the gravity is a sixth of Earth's, which means that the gravitational force is significantly less on the Moon. This is likely to affect the mining operation since it may be a problem to achieve necessary traction to collect regolith. This impacted the design since it mainly will focus on collecting the top layer of regolith that mainly consists of sand-like material that will be easier to collect rather than "aggressively" breaking material that is more firmly attached and more difficult to mine. There is a risk that the robots may sink into the regolith and not achieve a proper traction to break free. If that would be the case the distressed robot may send an automated emergency signal to the most suitable robot or robots to come to its aid. The robots have the possibility to connect to each other and operate as a single unit which allows them to benefit from an increased number of wheels creating the movement that significantly increases the probability of breaking free.

The robot itself consists of 17 motors. The four motors that will operate each of the four wheels enabling all-wheel drive. These motors are also responsible for steering. A turning motion is accomplished by one side driving forward as the opposite side is reversing. This enables the robot to turn without the need for any additional motors. Another four motors will operate motors that connect the body to the wheels. These motors will be able to change the height of the robot. Another four motors operate the "module holder arms" and another four are connected to the solutions that will firmly attach the robot with the module. This will be done by the last-mentioned motors connected to a screw which will move in a threaded environment which will enable it to move the screw outwards. Since the motor is connected to the screw and is movable in a track it will follow the screw seamlessly. As the modules are equipped with appropriate holes and corresponding threading this will enable the screws to fasten into the module. To detach the equipped module all motors simply must reverse to let go. Rotary fastening mechanisms are preferred since they are easier to seal among other things. The previous results in that all types of linear actuators are to be avoided. [15] The motors operating the height of the robot will also be engaged to reach a suitable position to attach/detach the modules in an efficient way. The last motor will enable the front mounted camera to rotate which is necessary to get an understanding of the environment it is operating in. Since the multifunctionality aspect of the robots, i.e., the ability to use different dedicated tool modules has not been used to the knowledge of the authors and is a key feature of the solution this was prototyped and is presented later in this section. This with the purpose of verifying that the idea of a conceptual level to establish if there is any potential for further development.

Furthermore, the robot is powered by a lithium-ion battery. This is since it has the highest energy density [15] as well as also surviving the temperature that it will be exposed to. The battery type has previously been used in space applications with varying purposes. The direct size of the battery depends on the maximum cost of launch. There is a trade-off since

larger batteries will result in the robots may operate longer but at the same time the cost will be proportional to the weight increase.

A computational processing device will be used in order to make sense of all information that the robot will be exposed to, e.g., imaging processing, enabling communication, operating the motors etc. In regard to software and software problems, it is thought that each robot will be equipped with an emergency system reboot switch in order to deal with eventual software malfunction. If that would not work, a robot should be able to send a copy of its own OS to the malfunctioning robot to restore functionality.

The robots will also utilize a number of sensors. It will have a sensor that measures electrical current since this will tell how much power is used, acceleration and force. A battery sensor will also be used so that the robot knows how much power that is left and when it needs to go to recharge. A high-resolution camera will be used for the robot to understand where it is and how the terrain ahead looks like. A gyroscope is preferably also included which enables an understanding of the direction, which is beneficial since the lack of conventional GPS capabilities. Furthermore, a temperature sensor will have to be used in order to know when it needs to activate its electrical heating capabilities. A tilt sensor may be beneficial to have since this reveal important additional information about the terrain. The data from the previous provides data necessary for the robot to operate the ledges and thus alter its center of gravity.

In order to get a better understanding of the sensors, actual products have been chosen in order to show how a plausible setup might look like. The suggested products are presented in *Table 2*. However, it is worth keeping in mind that the following equipment is not space graded but intended for everyday use.

Table 2. Necessary sensors for the proposed robot (not space-grade equipment).

Sensors		
Type of sensor	Function	Reference
The electronic battery sensor (ESB)	The ESB measures the current, voltage and temperature of batteries with precision. An algorithm is used to calculate the current and predicted state of charge as well as function of the battery from these base parameters and indicates battery aging effects.	[67]
Current sensor (CS)	A current sensor is a device which detects and converts current to a measurable output voltage. This output voltage is proportional to the current through the measured path.	[68] [69]

Camera	The camera will collect enough images for the computational processing device chouse as a foundation for choosing a suitable route.	[70]
Gyroscope (digital)	Uses the principle of the conservation of angular momentum to provide information regarding direction.	[71]
Temperature sensor (TS)	The so-called thermopile sensors are designed to measure temperature from a distance by detecting an object's infrared (IR) energy. This means that the higher the temperature, the more IR energy is being emitted. The thermopile sensing element, composed of small thermocouples on a silicon chip, absorbs the energy and thus produces an output signal.	[72]
Tilt sensor (TS)	A tilt, sensor or sometimes referred to as inclinometer, is an instrument used for determining angles of slope, elevation, or depression of something with respect to the direction of gravity direction.	[73]

The robot shall operate autonomously by default but should be able to be controlled manually by the ground control if deemed necessary. Such occasions may happen if exceptionally difficult terrain lies ahead. It is intended that if one robot is driven in a specific way by an operator then the other robots may be instructed to follow the exact same route without having to control them manually.

Furthermore, energy transfer to the modules will be supplied via a connection that is established when the modules are firmly attached. When the screws are completely inserted the back of the screws are connected to circular surface and act as an electrical conductor. This enables electricity to be transferred from the robot to the module. The conductor in the module has corresponding optimized measurements to fit the first one thus “closing the circuit.” The previous can be seen *in Figure 18*.

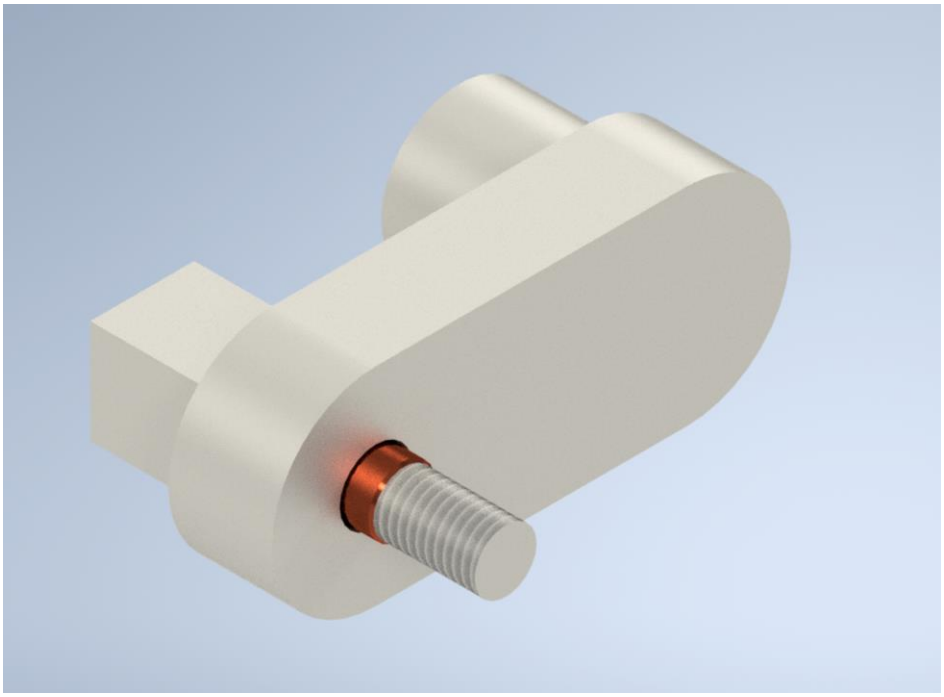

Figure 18. The module holder arm with its screw and electrical conductor.

The electrical conductor has a larger diameter in the socket ("the hole is bigger") which prevents the threaded screw from touching it if it is inserted straight. However, it might be affected by the moment of the screw and therefore it might need to very resistant to wear. A material which fulfils the following demand as well as the demand of being resistant to wear shall be chosen. A material with suitable properties might be the alloy "C18000 COPPER CHROMIUM NICKEL SILICON" [74]. The Socket is shown *in Figure 19*.

With the purpose of minimizing the connections as well as sockets it is intended that the module holder arms will be used for recharging the robots as well. This will require a charging adapter whose design is beyond the scope of this project.

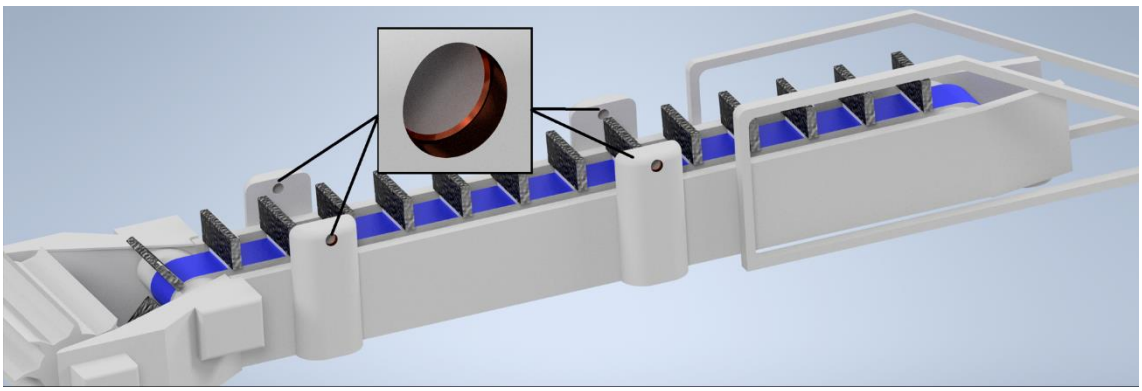

Figure 19. The socket in the module holder.

Moreover, it is important to control how hard the module is operating, and this may be done by simply regulating the electricity that is being provided by the robot [75]. There is no additional data that is critical to be conveyed and this results in no CANBUS or similar is needed in the module. This does not mean that there is no data that may be of interest but in order to keep the solution as simple as possible, such functionality will not be implemented due to the complexity it implicates.

6.4 The module architecture

The main reason to implement a module-based solution operable by every robot is because this strengthens the robustness and resilience of the operation. The robots are equipped with several mechanisms to prevent critical failures. However, if an event that disables a robot would take place assuming that the modules that it was equipped with are unaffected, then that module might be equipped by another robot. This enables the second robot to complete its intended task while a third robot equips a dedicated repair module which is dedicated to repairing damaged robots to get them fully operational again. If the robot were damaged beyond repair or would be retired for another reason, then the components that are still operational might be salvaged and used as spare parts. The components may furthermore be used in any of the vehicles since there is only one functional system architecture. It is worth acknowledging that the repair modules will also be able to repair other modules as well. Since it is easier to repair modules than robots, since the modules consist of fewer components with less complexity this is also to be considered a strength with the solution. If all robots had a built-in tool or several such, any eventuality might result in severe complications since the operation is more dependent on several robots if not an oversized fleet operates. If only a few robots exist with a number of tools built-in any damage may limit or hinder the efficiency of the operation. This is an issue that the modularity solution intends to avoid with the described functionality and operationality.

6.5 Designed modules

6.5.1 Overview

For this work two modules were designed, and several others were envisioned. If the module has a reasonable size, weight and the correct attachments for the robot's module arms then there is a great design freedom for what a module might look like. As such, if a problem would be experienced or a certain functionality is discovered to be desired then it is easier and cheaper to send up such a module in comparison to sending up a dedicated robot designed from scratch. Moreover, there is no reason to limit the module design to only one robot if that sizing would not be enough. If necessary, the modules might be operated by two or potentially even more robots if that would be desired.

6.5.2 Regolith collector

In order to collect the desired regolith a tool for this is needed. The excavating process requires two robots. One robot operates the regolith collector module and the other one operates a container module. Once the container module is full that robot will transport it to the processing facility. Meanwhile another robot with an empty container module will take the delivery robot's place in order to get regolith from the excavating robot. This is done in order to achieve an acceptable efficiency for the process.

At the front of the module there is a rotating wheel with sharp and slightly bent teeth. These will detach any rock that might be stuck in the regolith and make sure it goes inside the module and make sure that it moves along it. The previously mentioned becomes evident in *Figure 20.* This is achieved by a conveyor that scrapes the regolith along the bottom all the way until it is transferred into another module, namely the container module. The regolith collector module is powered by several electrical brushless stepping motors; two at the rotary wheel at front and two for the conveyor (one for each conveyor wheel placed at opposite sides). The regolith collector module is powered by the battery of the robot as it is not equipped with a battery of its own.

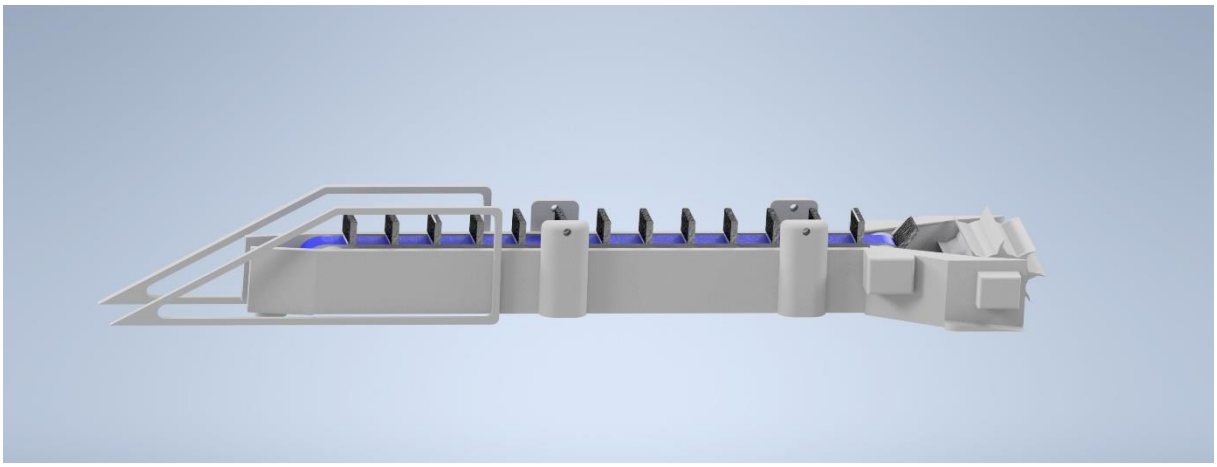

Figure 20. The regolith collector module seen from the side.

At the front sides of the regolith collecting module there are two fins that will help stabilize the module and generate some equivalence to down force with the goal of improving the traction. The rotary wheel at the front will also help to improve the traction thanks to its “rotary digging movement” which will help to move the equipage forward which minimizes the risk of the wheels getting stuck. This is evident in *Figure 21.* The scraping wheel is expendable which was deemed necessary since this part will be affected by tear. The rotary wheel along with the rest of the module is visible in *Figure 21.*

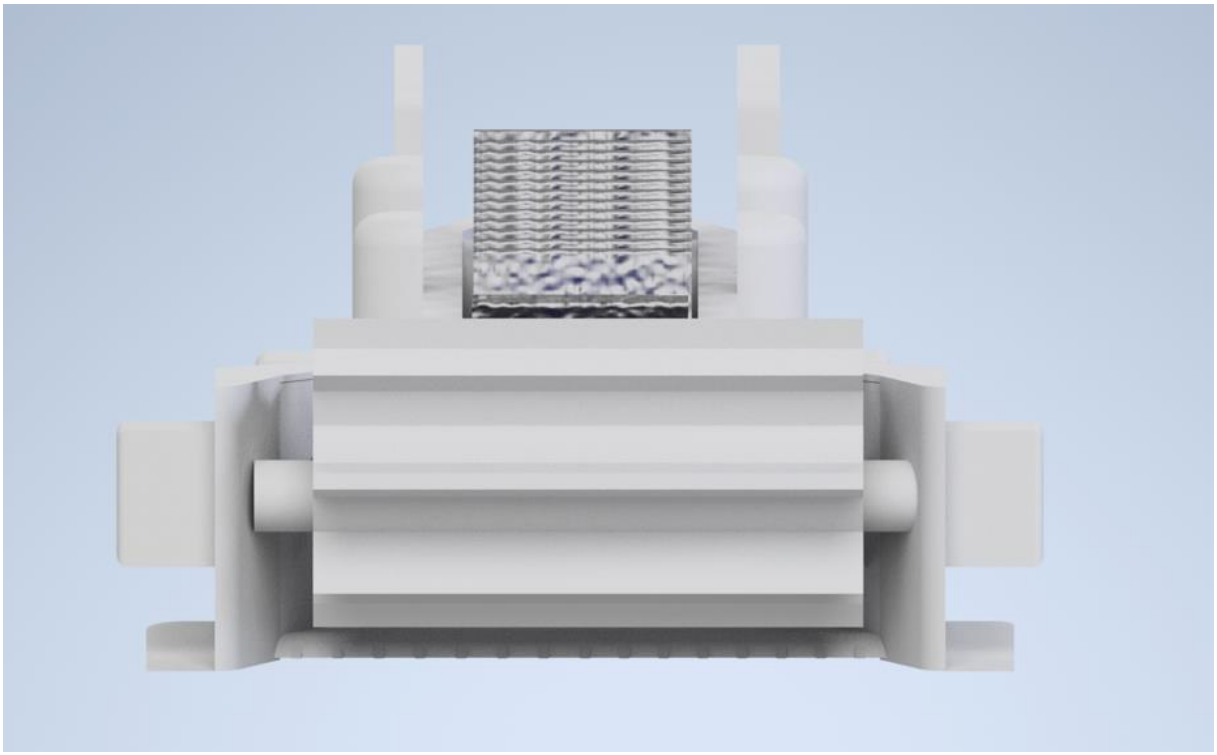

Figure 21. The regolith collector module is seen from in front.

The back part of the regolith collector module will be able to go on the inside and the delivering robot will move slightly forward in order to better use all the available space in the container. This may be seen in *Figure 22.*

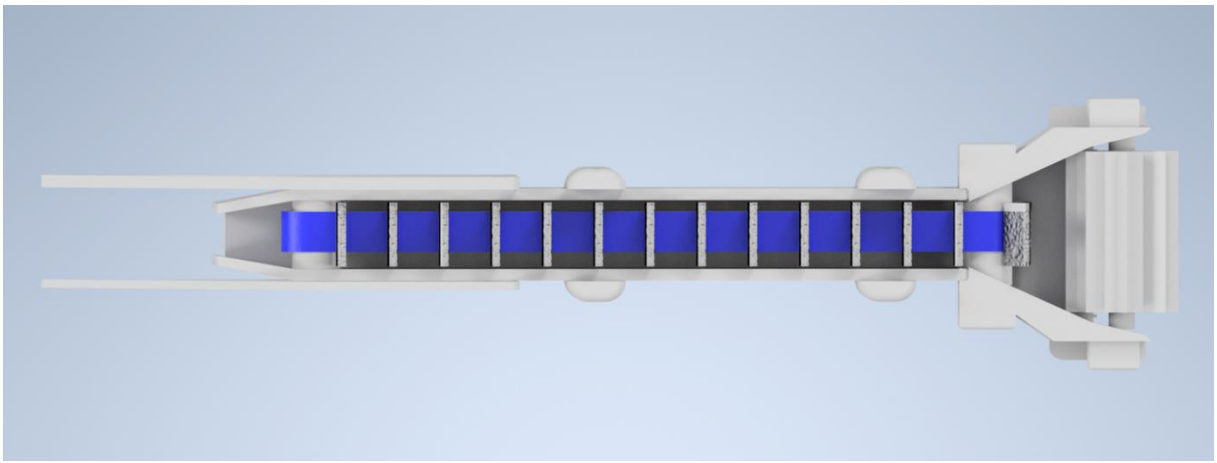

Figure 22. The regolith collector module seen from above.

6.5.3 Container module

The group has strived for the concept to be designed as simply as possible and with as few electronic components as possible. Therefore, the group has avoided designing containers (the module in which the regolith is transported) without motors.

The container is in the form of a square box that has similar dimensions as the other modules, for obvious combability reasons, which can be seen in *Figure 23*, as well as a suitable width fitting the attachments. The container module was designed to transport regolith but depending on how the operation evolves it may potentially be used to transport other items or resources.

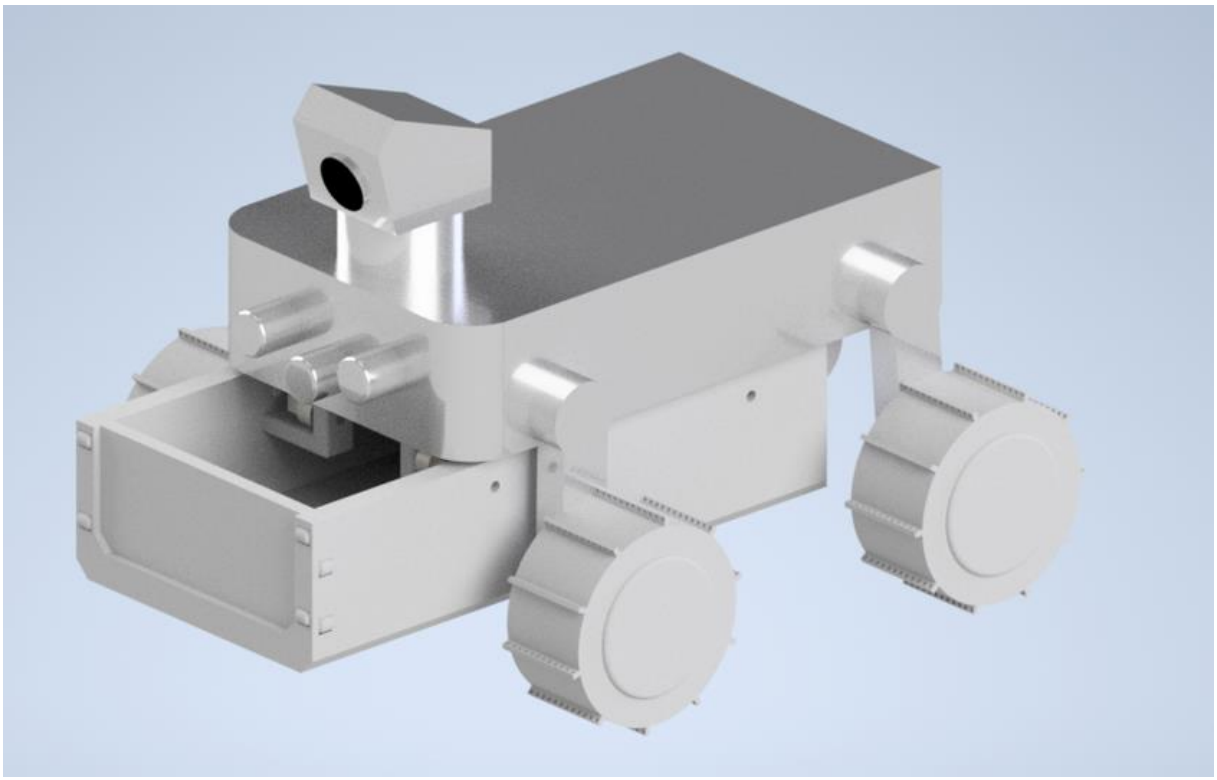

Figure 23. A CAD- model that illustrates the robot that is equipped with the container module.

To determine the dimension of the container module, calculations were performed to ensure that the determined amount of regolith that is 50 kg can be accommodated at the same time as the regolith collector can be run in to hand over the regolith. The first step is shown by (1).

$\rho_{regolith} = 1350\ k/m^3$ [76].

$m_{regolith\ to\ be\ hold\ in\ the\ container} = 50\ kg$

$$V_{Regolith} = \frac{m_{regolith\ to\ be\ hold\ in\ the\ container}}{\rho_{regolith}} = \frac{50}{1350} = 0.037\ m^3 \qquad (1)$$

$V_{regolith} = 0.037\ m^3$

However, since a part of the regolith collector will need to enter the container for the transfer the volume needs to be greater than that. This is in order to fit both the regolith as well as the module. Therefore, the group dimensioned the container in order to fit appropriately and to utilize the available space below the robot.

With the adjusted measurements the volume of the container is

$$V_{Container} = 0.085\ m^3$$

$\rho_{regolith}$ is the density of regolith, $m_{regolith\ to\ be\ hold\ in\ the\ container}$ is the mass that is to be contained in the container and the robot is to transport it. $V_{regolith}$ is the volume of regolith that is to be held in a container and then transported to the process station. $V_{Container}$ is the total volume that the container can hold. $m_{Which\ container\ can\ hold}$ is the total weight that the container can hold.

As such, the container may theoretically contain 115 Kg in accordance with (2)

$$m_{Which\ container\ can\ hold} = V_{Container} * \rho_{regolith} = 0{,}085 * 1350 \approx 115 \qquad (2)$$

$m_{Which\ container\ can\ hold} = 115\ kg$

However, this will not be the case due to the aforementioned reason. It will leave more than enough room for the desired quantity of regolith. Partly, due to provide good transporting quality for other application which was mentioned above.

At the end of the regolith collector are mounted two triangular opening mechanisms, see *Figure 24*. The purpose of this is to cooperate with the container module's door to be opened when handing over regolith.

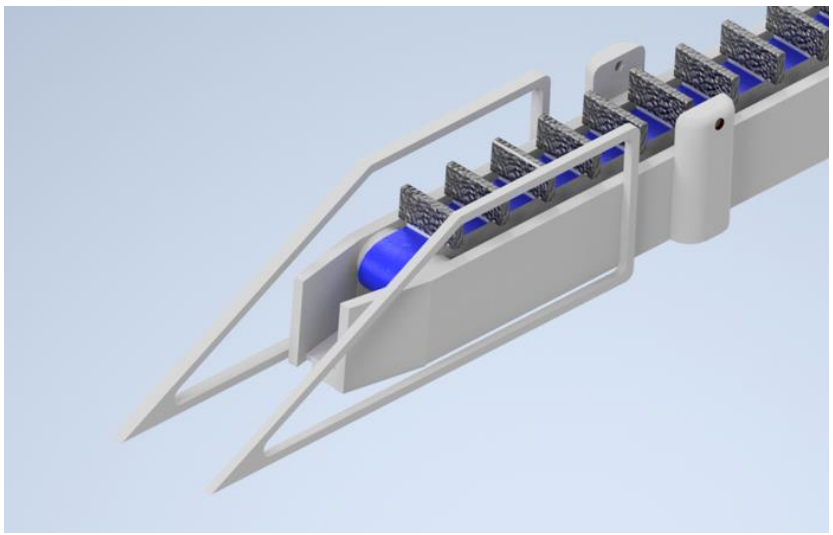

Figure 24. Triangle mechanism that is mounted at the end of regolith collector

As mentioned before, the container door is designed in a way so that the door is in a track see *Figures 25.* On the sides of the track are 12 wheels that help the door to be moved up and down, see *Figure 26.* The opening and closing of the container door are mechanically designed and works in connection with the regolith collector handing over the regolith to the container. That is, when the tip of the triangle mechanism which is mounted at the end of the regolith collector is placed at the edge (end of the container module door) of the container module door, the door is moved upward by pushing the regolith collector into the container.

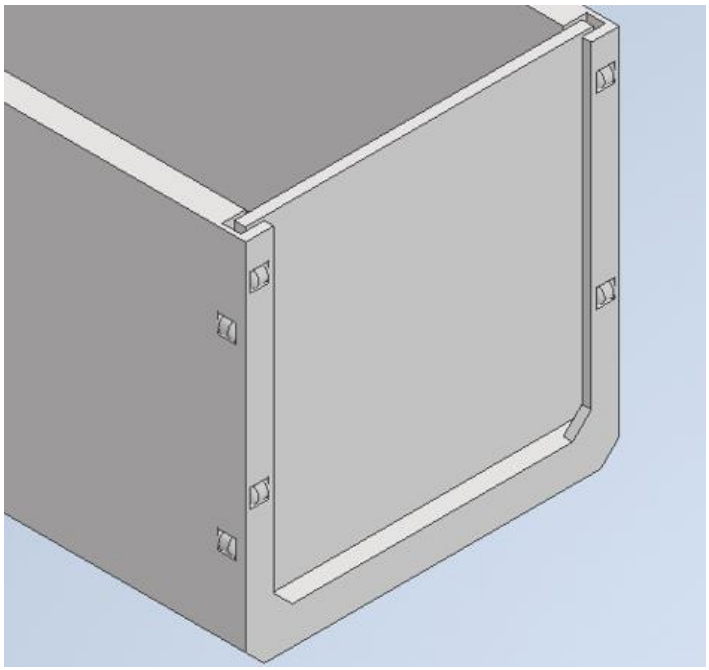

Figure 25. A CAD module that illustrates the container door that sits in the grooves at the end of the container

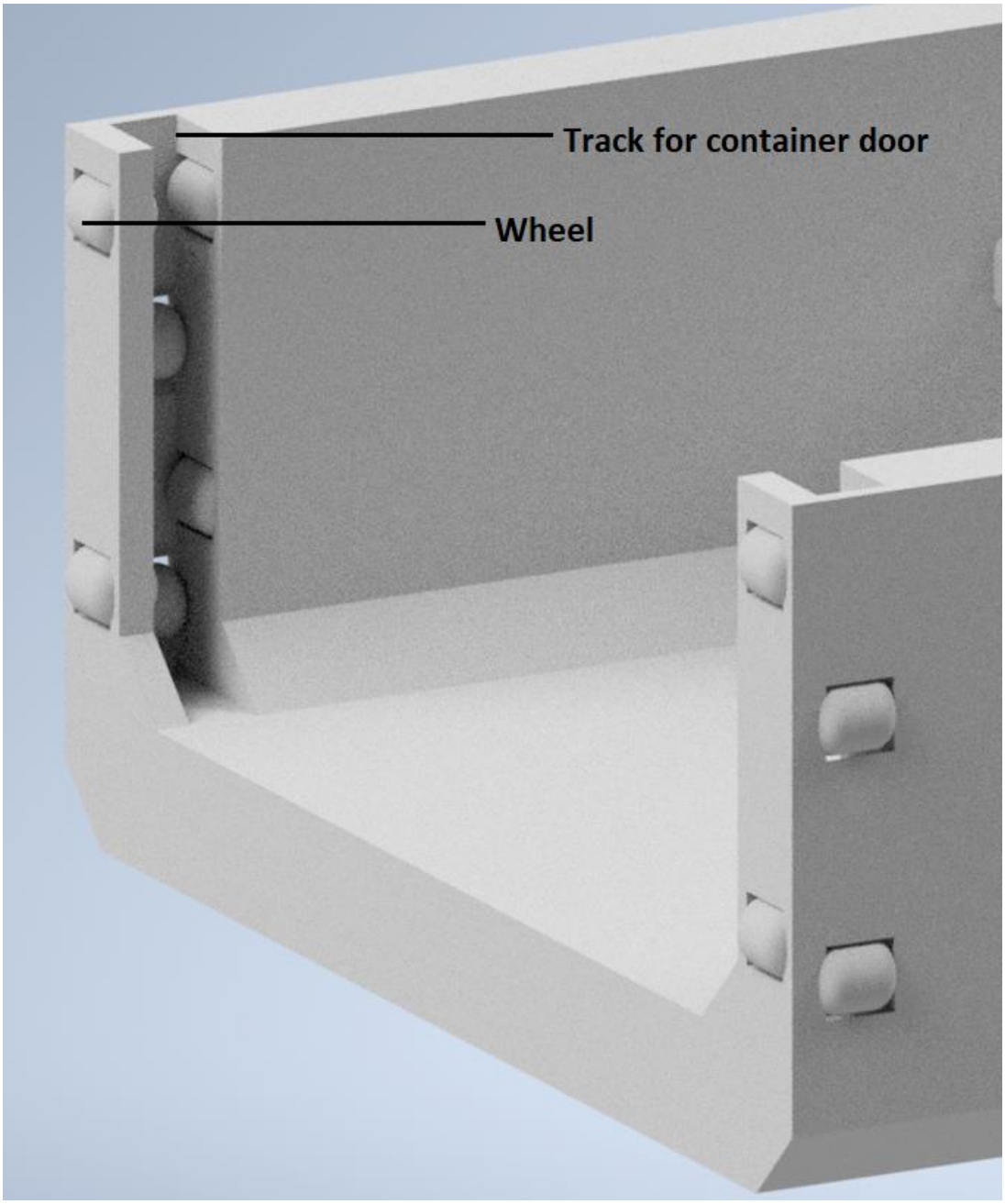

Figure 26. The track with the wheels with the container module, where the Container door is to be placed.

For the robot with regolith collector to hand over the regolith, it drives backward so that the triangles at the end up under the door on the container, see *Figure 27*. Then the robot continues to reverse, and this contributes to the door moving upwards, which can be seen in *Figure 28*. After the regolith collector has handed over the regolith, it drives forward and then the door moves downwards. When the regolith collector has left the container, the door has been closed and the container is closed.

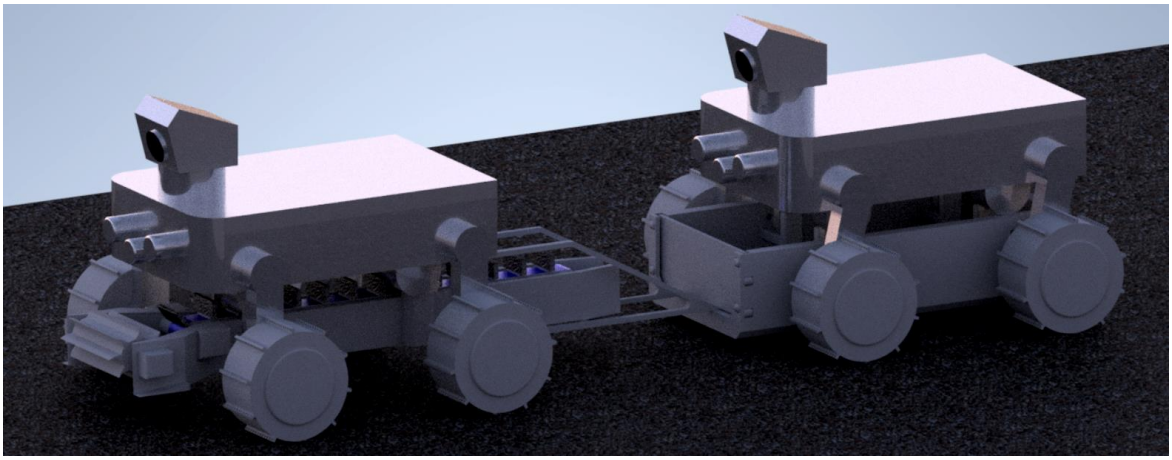

Figure 27. An illustration of triangle mechanism that placed under the container module door

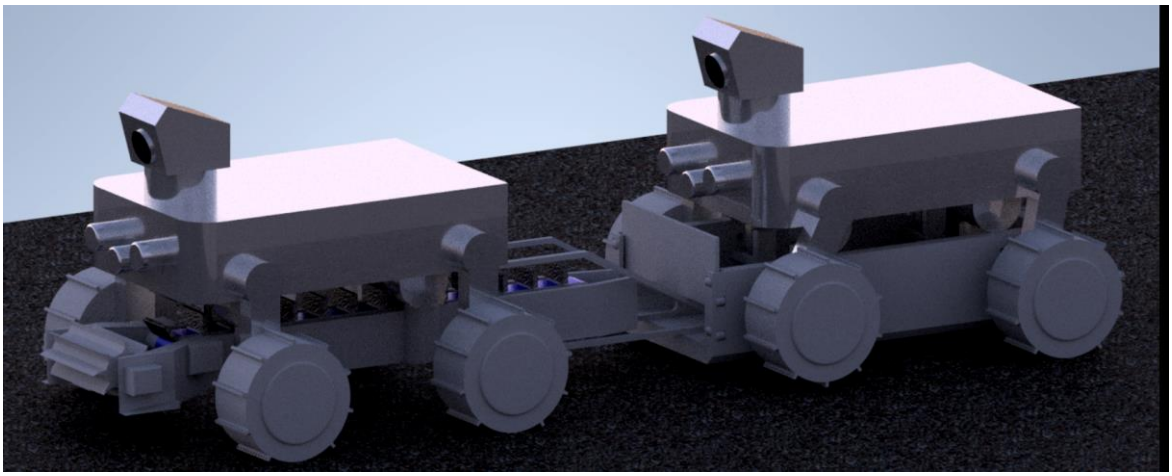

Figure 28. An illustration on how container module door moves up, while robot with the regolith collector reversing into the container module.

The robot that is equipped with regolith collector cooperates with the robot that is equipped with container, this through communication between them. For the regolith collector to be able to drive into the container, the height and angles are adjusted with the help of the equipment that the robots are equipped with. *Figure 29* illustrates a scenario where both robots and their modules cooperate so that the regolith collector hands over the regolith as it is scraping to the container so that the robot with the container will then transport the regolith to processing station.

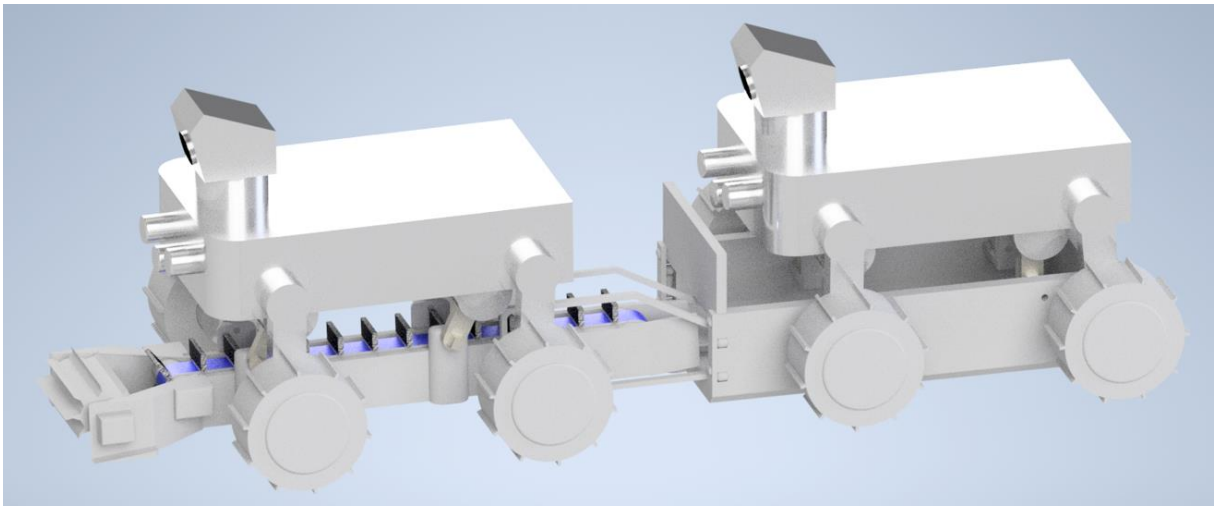

Figure 29. A scenario where cooperation between two robots (regolith collector and container) is illustrated.

6.6. Identifying potential problems with the designs using FMEA

In order to provide prerequisites for a robust design the tool failure mode and effect analysis was used. The result of this is presented in *Appendix 4*, *Appendix 5* and *Appendix 6*. The result of this established that there are a number of things that can go wrong. This knowledge is important because this allows for the design to be prepared for the described issues and provides better prerequisites in order to overcome the issues. Generally, it can be established that the Lunar regolith is a major source of problems that may affect many systems. Furthermore, physical damage is also an issue that may occur and result in severe consequences for every system. It may be hard to avoid this since damage may occur on many occasions but however there are preventative measurements that may be implemented in order to limit the damage and to make sure that it may handle such. Also, the temperature is a factor which may impact several systems. The preferred design control method is testing and in the absence of that possibility simulations may be used. Calculation is also recommended to be used in several occasions when appropriate. Prior to the actual testing simulation is recommended to be used even though this is not explicitly filed out in the template.

The most severe problems include:

- Design and manufacturing issues
    - Modules and dedicated equipment mismatch
- Electronic malfunctioning
    - Battery failure
    - Motor failure
    - Sensor failure
    - Software and communication failure
    - Charging failure

    - Power transfer issues
- Geographic and environmental obstacles
    - Getting stuck in the regolith
    - Turning over
    - Taking a fall or similar sudden damage
    - Extensive regolith build-up
    - Taking a hit by space debris
- Module failure(s)
    - Motor failure
    - Power transfer issues
    - Stop in the regolith collector module
    - Problems finding the opening of the regolith container module

In the FMEA several actives are listed to deal with and minimize the risk of the issues taking place. Many of these concerns the actual design and construction as there is a limited range of activities that may be carried out on the Moon by the robots.

6.7 Verification of the module holder solution

In order to perform a series of tests regarding the functionality of the module exchange mechanism a basic prototype was constructed, which can be seen in *Figure 30*. The goal with the prototyping part of the module holder was to evaluate if a solution as such could pick up a “module” and lift it upwards. The conducted tests differ quite a lot from the intended scenario on the Moon. The circumstances under which the module holder is intended to operate in when it comes to temperature, gravity as well as the obvious lack of regolith differ quite a lot.

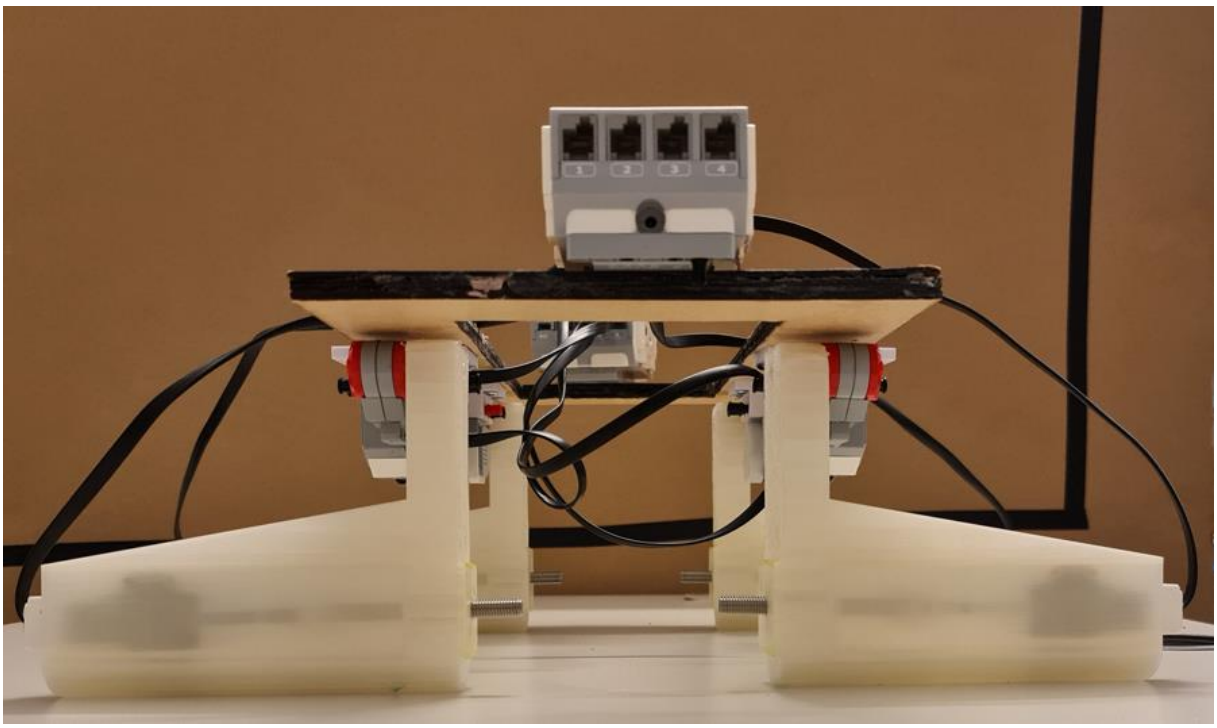

Figure 30. A basic prototype of module holder.

This was a simplified first prototype with the objective of evaluating the solution on a conceptual rather than testing a solution for a proposed finished product. This is something that is important to keep in mind. For an actual application all equipment used would be different; different motors would be used, the arms would be made of a different material, and they would also be of a different geometrical appearance. Nevertheless, the overall principle remains the same.

To summarize, the prototype consists of:

- Four small Lego motors (operating the screws)
- Four big Lego motors (operating the arms)
- Four 3D printed arms with dedicated room to fit the motors and screws
- Four M8 screws with a glued Lego axis fastened to the screw head
- Four regular Lego axis (for connecting the big motors and arms)
- One rectangular base plate made up of three layers of Masonite wood glued together
- Two Lego control units (so-called “Bricks”)
- Eight wires
- Four 3D printed big motor attachments
- Sixteen Lego connectors
- Sixteen screws and nuts

The test concluded the following that the described module indeed could be picked up by the arms. The used motors were operating in a synchronized manner and the screws were efficiently moving back and forth depending on which way its connected motor was

rotating. However, it was noticed that there were some problems with the screws finding the holes. This is mainly attributed to the choice of using degrees as a base of how much the motors should move. This affected the performance since it was hard to get an exact starting position which would be absolutely the same every time. This deviation resulted in some occurrences where the screws simply started to bend the arms backwards when they could not move forward anymore, which can be seen in *Figure 31*. The group had some fears that this could be the case prior to testing. There are certain things that can be done in order to deal with these problems. However, this requires an additional use of components which will increase the complexity of the overall solution. As is familiar, the design philosophy of this project was to seek the easiest and less complicated ways of achieving an acceptable performance. As such, any potential improvement needs to be put in relation to the additional level of complexity that it entails. However, using more sophisticated motors, it is likely that the problem that the group encountered will not take place and that there is a greater ability to control the position of the motors in a way which is not possible with the LEGO motors. Therefore, it is suggested that a more accurate replica of the actual module holder is to be built and tested in a similar way. If the described problem still occurs, then it is likely that some sort of mechanical solution needs to be included to help the screws find the holes in the intended way.

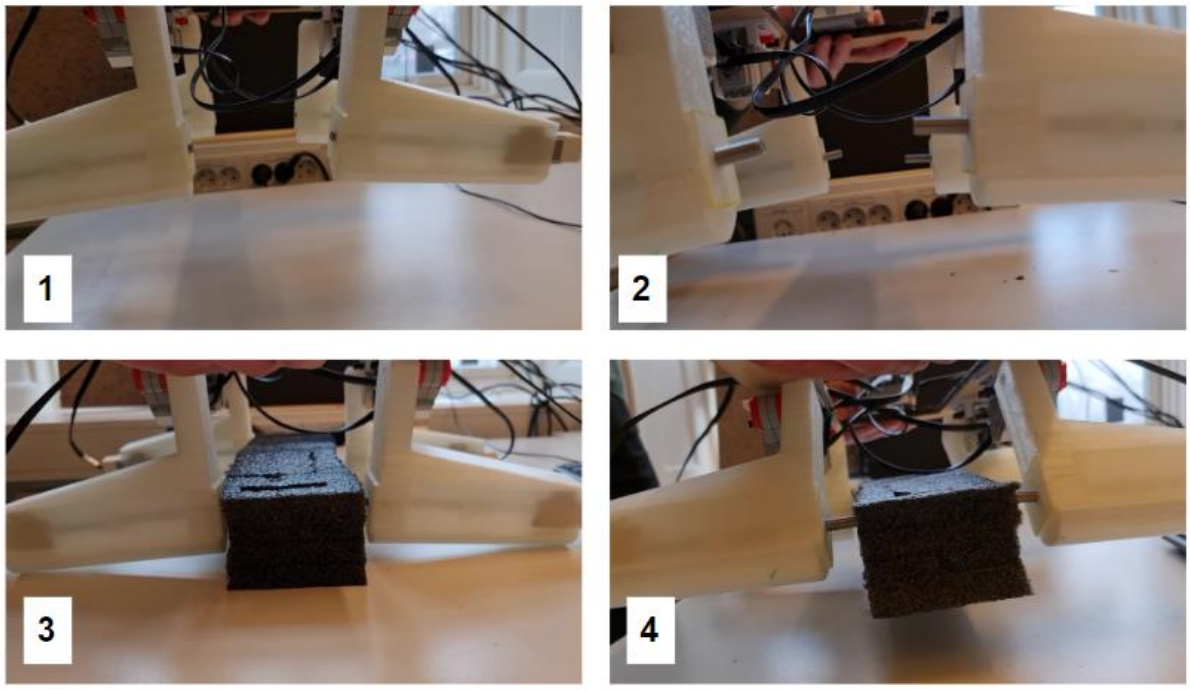

Figure 31. Four snapshots of the module holder prototype in operation which highlights the screw extending in length and picking up the module.

Figure 31 shows the module holder picking up a mockup of the container module. In the first picture, the arms of the module holder position themselves appropriately. The second picture shows when the screws of the arms engage to grip the module. Picture three shows the arms that have gripped the module and the module is attached. The last picture shows where the module holder holds the module.

In order to illustrate how the different functions of the prototype relate to each other a FAST diagram was created. The diagram is seen as *Figure 32*. A fast diagram is a way of visualizing how certain functions are carried out and why [77]. This highlights the fact that a lot of the different functions that indeed are necessary to achieve the desired functionality may not be as obvious at an initial glance. This is since they arguably support the more obvious functions. Moreover, as simple as the test was all these functions are needed even if the material and motors would be changed to accomplish a setup that is suitable for space application. This is something that is worth keeping in mind. However, it is also worth remembering that the actual module holder solution has more functions than the diagram shows. Examples of the previous include providing ground clearance and lowering the center of gravity. These functions are not included in the diagram due to the boundaries set by the prototype test.

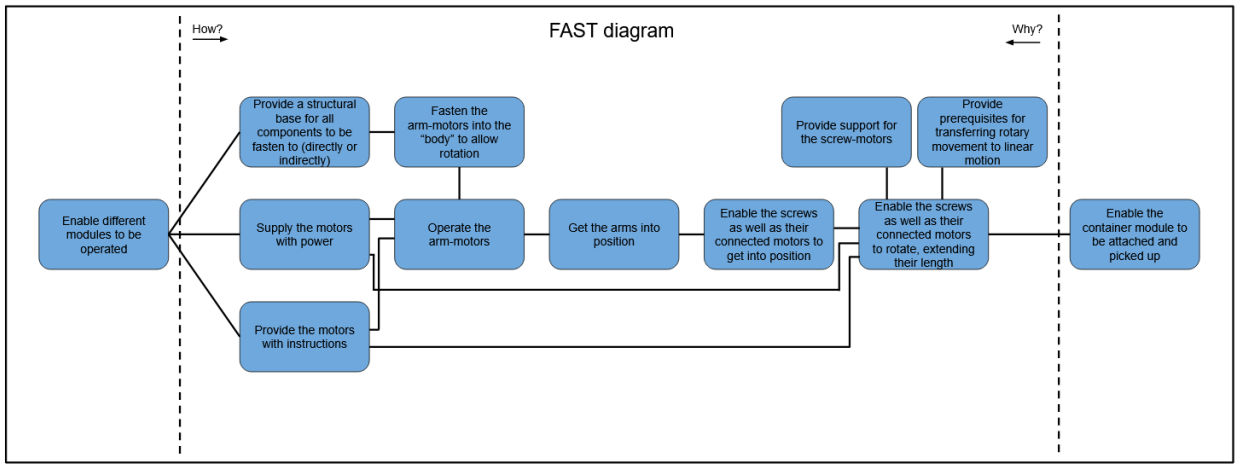

Figure 32. Fast diagram of the tested prototype.

The purpose of the diagram is to represent the logical relationships between different functions of the module holder on the robot and its modules. The diagram is constructed from left to right and answers the questions “how” and “why.” That is, how to "enable different modules to be operated" and enable the container module to be attached and picked up.

On the left side of the diagram, the main functions are at a higher level and represent the "why", the need. These are Provide a structural base for all components to be fastened to (directly or indirectly), Supply the motors with power, Provide the motors with instructions.

The sub-functions and technical functions are on the right, these are at a lower level. These functions represent how the main functions are performed to achieve the desired results. These functions in the system are, provide support for the screw-motors, provide prerequisites for transferring rotary movement to linear motion, Enable the screws as well as their connected motors to rotate, extending their length.

The functions that have a link are on top of each other, these represent the common dependence and simultaneity, “when.”

7 Discussion

7.1 General

The idea to mine the Moon has been around for many decades and various approaches have been suggested by different scholars, entrepreneurs, and enthusiasts. There are great challenges that need to be overcome in order to establish any meaningful operation on the Moon. As mentioned earlier in the thesis, many of these but others as well relate to the environment that the operation shall take place in. The temperature variation is an area that implicates problems for the electrical components and devices that the robots shall be equipped with. However, there are ways to handle these difficulties, one of these includes the strategy to equip the robots with heating loops to keep all electronics at a survivable temperature. The thesis does not claim that this is the best way to handle this problem but does however claim that this is a plausible and reasonable way to achieve the goal. The method is mature and has been used successfully in the past.

Another extensive problem is the Lunar dust itself and how it interacts with the robots. The dust is abrasive and has the potential to get stuck and thereby hinder movement. It is also challenging to travel in the regolith itself and there is a risk of getting stuck due to insufficient friction and sinking. Therefore, the robot will need to be cleaned regularly in accordance with the assumption explained earlier. To combat the sinking problem the robots were designed to be able help each other either by pushing or towing. The previous as a means of utilizing the grip of one or several other robots.

The most important feature of the proposed concept is undoubtedly the way that all the robots handle the operation of the tools. Many of the other concepts available on the internet rely on tools that are built-in into the robots themselves. It is also common that there are several sizes of the robots themselves. There are benefits with this approach as it is significantly easier to design a solution that has a narrower problem scope. This makes it easier to get a more optimized performance for the solution in question. However, doing the earlier mentioned makes the entire solution system architecture a lot more vulnerable. This is since if one or several of the dedicated robots may be affected by some sort of disaster or an unforeseen event then the entire operation is at risk. This is since some necessary activities may not be performed, which basically makes all the other activities useless in that context. For instance, say that all dedicated regolith mining robots are destroyed at a crash landing then the robots that have tasks that relate to that process are useless since they cannot perform their intended tasks. A previous scenario as previously mentioned is something that is sought to be avoided with the interchangeable modular design. This is because it minimizes the dependency of the robots themselves. Yet the dependency on the tool modules still exists. However, there are ways to accomplish a more resilient approach concerning these as well. Actions such as providing a few extra modules and spare parts are actions that are recommended. Also implementing a modular design on the tool modules, themselves is beneficial since it enables reuse of all functioning components if a module

would need to be discarded. A dedicated repair module is intended to be designed which will be able to repair all robots and modules. It may be argued that sending more material and tools to the Moon is unnecessary and a waste due to the very high prices of launching something into space. However, it needs to be put in relation to the lost time that the process is operating at a limited capacity or stands still as a worst-case scenario. While it is difficult to calculate the exact number of the previous at the current time due to a lot of uncertainty, it is recommended by the authors that such a calculation should be executed. This is since it provides an understanding of how much "redundancy equipment" that it makes sense to send along. It will be necessary to provide spare parts since several of the components will be affected by wear, e.g., the rotary wheel on the regolith collator module and the screws. Therefore, it will be required to have some redundancies of these in order to prevent downtime due to component shortage.

Another strength with the proposed concept is the fact that the fleet may be rearranged to perform a specific task at a maximum capacity of the modules if necessary to then perform another activity at the maximum capacity of the modules. This creates greater flexibility compared to the scenario where the fleet needs to relate to the number of built-in tools. However, the full capacity of the benefits limits how many modules are acceptable to have on the Moon at the same time as well as the total usage percent of all of them. Depending on how far the mining takes place from the imagined processing facility their higher ratio between container modules and regolith collecting module needs to be. This is since it takes more time for the robots to get to the processing facility and empty their regolith. Therefore, a greater number of containers needs to be active in order to make use of the regolith collecting time in an effective way. The fact that the greater the distance from the processing facility, the more container modules are needed for efficiency reasons may be considered a weakness with the design. This may be the case, but nevertheless it is more efficient than if a robot would collect all regolith and then travel on its own to the processing facility. Even in the case where a lot of robots do the aforementioned, the process would still be even less efficient due to the fact the majority of the time will be getting from the digging site to the processing facility.

7.2 Features that were considered for the design but discarded

It is important to keep in mind that this project ultimately resulted in one concept being suggested even though a lot of alternatives were discussed in the earlier stages of the project. There are many ways a solution that fulfills the described objectives could look like, all of them will have different strengths and weaknesses compared to the other and these were put in relation to each other in the earlier phases of the thesis.

The solution architecture of the robots themselves was also an aspect that was given much consideration. Different approaches ranging from rovers that operated completely independent from each other to a system where a lot of identical smaller robots would operate in a swarm like manner was put in relation to each other. The individual rover approach had the strength that it was very resilient to unforeseen events as a failure would

not affect the system any way other than productivity losses. Nevertheless, this results in the fact that the mining operation will be inefficient. For instance, if a robot mines far away in relation to the processing facility, then the transportation will take a lot of time. This is because the robots cannot drive that fast, partly to the terrain as well as using more power. A robot that would operate completely independently could beneficiary have all tools built-in and would not need to have any interchangeable tool modules. This is a benefit since this eliminates the need for the changing procedure which simplifies the operation. However, this instead increases the robot design itself as a result of the previous described. This will also limit the functionality since all functions have to be built prior to launch and when the robot is up there then "it can only do what it was made to do." The meaning of the previous is that no new functions or activities may be performed. This contrasts with the interchangeable tool design where the functionality may be improved since new modules may be designed and launched as long as they relate to the same design framework. This is an aspect that is of utmost importance since it provides long-term operation resilience and flexibility.

The other extreme scenario where the fleet consists of smaller work robots also has its strengths and weaknesses. The design approach would minimize the dependence of the robots themselves assuming that there are more robots than a skeleton crew. It is worth mentioning that this design alternative also utilizes an interchangeable tool module approach since it would be too expensive and complicated to equip all the swarm robots with a complete setup of tools. The design of these may implicate problems. It would be beneficial to make these as small and lightweight as possible. This is, as familiar, due to the limited launch space and the cost of it. This might, however, result in several problems e.g., traction problems. Once again, it is necessary to keep in mind that the gravitational pull of the Moon is only one sixth of the one of the Earth. This significantly reduces the normal force of the robots and thereby in extension also the friction force. This might become an issue, especially when the regolith collecting activity is performed. It is worth mentioning that this fact could be compensated for with the design of the regolith collector approach itself. As is the case with the proposed design, it is equipped with a rotary scoping device which "helps" the robots moving forward since the rotary movement facilitates the process and helps the equipage moving forward. It may be argued that the approach also yields several benefits such as improved efficiency due to the extensive collaboration aspect. However, these benefits do not outweigh the disadvantages.

The proposed solution may as such be considered to utilize a principle that is somewhere in between of the two described scenarios. This enables the solution to take part of the benefits from both scenarios.

7.3 Technologies that were incorporated into the robot design

For this project, several technological features were implemented rather than designed. This is since it was beneficial to use the maturity of that technology in comparison to designing such a feature from scratch. An example of such a feature is the wheel design which was

heavily inspired by the design of the latest Lunar rover which was designed by NASA. The group saw no need to, literally, “reinvent the wheel” as the latest design by NASA would be based on the latest available data provided by their satellites and research equipment. Needless to say, the staff at NASA also has significant experience as well as a specialized level of competency to accomplish the design in an adequate way.

The choice to rely on heating coils is also a feature that is used today and has been achieving positive results. It is arguably the easiest way to provide prerequisites for the electrical components to survive the harsh climate. However, it is not a perfect solution since it consumes a significant amount of power. This raises the question whether more efficient solutions should be implemented. It is unlikely to be a reality in the near future but a scenario where the robots could operate an entire Lunar day and spend the Lunar night charging in a more optimized environment such as a dedicated facility would be more beneficial. However, even more beneficial would it be if the robots could operate the Lunar nights as well. This would probably require another fundamental design approach.

7.4 Comments regarding the dimensioning of the robot

As mentioned briefly earlier, the robots will all be of one size. The sizing of the robots is a process that requires a great amount of work. This is also a trade-off situation. The efficiency of what a robot may be able to when it has a greater size stands in relation to the practical implication of that such as construction and launch cost, higher energy consumption etc. Therefore, it is important to consider these facts when the exact measurements are established. The measurements provided by the group must be considered as guiding suggestions since all the necessary data is not known. For instance, it is hard to estimate the worth of a specified volume of regolith. Moreover, it is not possible to say how much it will cost to operate this processing facility as well as the cost to recharge the robots. It is important to remember that this depends on the nuclear power plant that is intended to be sent up. If there were problems concerning this power plant, then the cost would probably be a lot higher. There are alternative ways to provide stable power to the Moon, however currently the feasibility of these is questionable. One of these approaches intends to use solar cells on satellites in orbit and then later convey this power to the Moon. All these factors make it hard to provide actual calculations. However, it is possible to provide and foresee several plausible scenarios.

7.5 Anticipated problems that the robots might encounter on the Moon and strategies to deal with them

The surface of the Moon is a challenging terrain to operate in. However, as described earlier, there are a lot of valuable materials which makes the effort worth it. It is worth keeping in mind that launching equipment from Earth is complicated, not to mention extremely expensive. Therefore, is it desirable to use the available resources located on the Moon and use them in order to provide relevant materials such as water and hydrogen etc. However,

in order to achieve the previously mentioned, the regolith needs to be collected, transported and processed. Since the processing is out of this project's scope the challenges regarding these will not be discussed.

The regolith is made from fragments of crushed meteorites which gives it a texture close to that of a mix of gravel and sand. The composition of the previous varies depending on the location of the Moon. In areas that may be described as more sand-like, the risk of robots getting stuck emerges; especially when the robots travel uphill. If a robot gets stuck, it shall be able to ask one or several other robots for help to either be pushed or towed, whichever option is the most beneficial given the circumstance of the robot getting stuck. The robot has a geometrical mechanism that allows the robots to interconnect which strives to get better traction which is beneficial for the equipment to escape the fate of getting stuck forever. Needless to say, the process of using other robots to free the distressed robot affects overall productivity. However, this must be put in relation to the case of losing a robot as well as a tool module permanently. The process of using appropriate robots may as such be compared to a long-term productivity investment. The problem of a rover getting stuck is a very real one and has affected NASA. This took place on Mars but nonetheless it may take place on the Moon as well. This highlights the need to have a strategy to deal with the problem as described earlier in the paragraph.

There are also creations on the Moon which contain materials that may be of interest. However, getting access to their riches is very complex and complete accessibility to all such crates is impossible. The robots are equipped with four motors connected to dedicated levers with the purpose of increasing the ground clearance which is intended to be able to handle more uneven and challenging terrain. Furthermore, the arm that holds the equipped modules may be placed in a horizontal position which raises the module and increases the ground clearance even further. The described feature is intended to provide better prerequisites for the robots to travel to geographically less accessible locations including the Moon crates but not limited to them. The designed equipment is intended to scrape the more accessible, top layered surfaces at firsthand in order to collect regolith. Nevertheless, it makes sense to see beyond that since it will become tempting to get to the more challenging locations later. Then this needs to be accounted for when it comes to the robot design. This is in order to avoid potential and send up a brand-new robot design material which needs to be designed, built and launched. It takes a lot of time as well as a lot of money. The group is no stranger to the idea of launching several sizes of the robot fleet. This type of highly specialized robot may be one of these "sizes." Nevertheless, the group stands by its position that only one robot size should be used at the earlier phases of this undertaking due to the advantages that were mentioned in the dedicated section. It may be hard to foresee all needs at this stage. Therefore, certain alterations and adaptations of the design may need to be implemented. That being said, it is strongly recommended to have as few variations and not make any design changes if it is not deemed to be absolutely necessary.

Another possible issue that could become a reality is the overturning of the robots. This would be very unfortunate. The major actions that have been taken concerning this topic have been of a preventive nature. It is worth keeping in mind that the gravity of the Moon is weaker than the one on Earth; one sixth of Earth to be precise. In this instance it is to be considered an advantage since it reduces the probability of the robots turning over in the first place. The motorized levers are also a design feature that strives to minimize the risk of the described topic taking place. The back pair may be raised or lowered or vice versa depending on the scenario. This is since they enable the center of gravity to be shifted which may be used to compensate for traveling along inclines. If a robot nonetheless would overturn it has to rely on a fellow robot managing to push it back into a correct position. This approach may be considered to be impractical. However, it needs to be put in relation to the risk of overturning taking place. Due to the action described concerning the ledges as well as the weak gravity providing an advantage, the risk is to be considered small when travelling along the highline. This motivates the choice not to design a specific feature to deal with if such a scenario should take place. This is since it provides another level of complexity to the overall design, and it is costly. The cost may be considered to be even higher if all robots are equipped with a specific feature that never or extremely rarely is used. The previous motivates the rationale for the chosen approach.

Another problem that could occur and cause problems is malfunctioning software. It is not rare that software spontaneously malfunctions, freezes or crashes. This is a reality that needs to be taken into account. The robots will not be equipped with a lot of software compared to other products. Nevertheless, the software is critical for its operation and therefore problems concerning this need to be taken care of as soon as possible. The implementation of the details in this section is something that is left unsaid due to the complexity that they implicate. Nevertheless, the following envisioned features are being proposed to deal with any software-related problems that could seriously affect the operation. As a first step the software should be diagnosing itself constantly to make sure that everything works as intended. If not, then the system should be able to restart to fix any problems relating to freezing. If any files or programs should be damaged, then measures to repair this should be possible and carried out. If the actions described would not be sufficient then one robot where everything is working as it should be able to send a copy of its system to replace the malfunctioning system of the robot described. In order to achieve the described functionality some delicate work is required to be performed. This will take time and money as well as result in a quite advanced system software architecture. Nevertheless, the solution is something that the group advocates since it provides a level of software resilience which is necessary to have in order to operate in a setting as the described scenario. It is worth keeping in mind that even small failures are extremely hard to correct since the robots operate on another extraterrestrial object. Alternatively, it might be of interest to implement a similar approach that is used for critical systems found in airplanes, to have redundancies which actively does the same thing independently of the others [78]. It is worth acknowledging that this approach drastically increases complexity and thereby costs as it significantly increases robustness. Such a scenario is a trade-off situation with major

consequences for the design. A possible approach might be to back the most critical aspects while ignoring others and choosing alternative approaches.

The module exchange mechanism is a feature that may present some problems as well. The greatest risk is considered to be problems related to the screws finding the holes. The thought is that the robots shall lower themselves using the levers in order to find an appropriate position and then activate the motors in the module holders. This makes the screw rotate which enables them to move forward. The execution of this is conceptually identical to the built prototype. In the design there is no solution that makes sure that the screws are perfectly aligned to their corresponding holes. The thought is that motors will be able to make sure the module holder arms are completely vertical. It is believed that this solution shall be able to provide enough accuracy to make sure that the screws find their holes. However, this is an aspect where the authors recommend that an actual arrangement is properly built and tested. The arrangement in question shall be made from the intended components since it has been established since the mechanisms on a conceptual level works.

7.6 The goal of the solution and what it enables

As mentioned before in this report the overall objective of the project was to enable prerequisites for colonization of the Moon, initially mainly for research purposes. Also doing so without the need of launching extensive material from Earth due to the complexity, cost and risks that implicates. The risks primarily relate to the fact that if humans are present on the Moon and shipments of resources such as water, for instance, unsuccessfully make it to the Moon then the crew is put at risk. Therefore, is it highly desirable to minimize all the launches and shipments from the Moon. This, however, depends on the fact that the resources that the Moon possesses actually; in other words, a successful ISRU strategy is needed.

The robots along with the interchangeable tool modules all serve their purpose of achieving a functioning in-situ resource management procedure. The robots serve as the general enablers of all activities as they operate and control the modules. Then the regolith collecting module, as the name suggests, collects regolith. The regolith is then transported via the container module to the processing facility. At the processing facility regolith is processed and desired chemicals such as water, hydrogen as well as oxygen among others are produced.

All the earlier mentioned chemicals simplify the research operation as the need to provide this from the Earth is no longer necessary. Long term, the Moon might function as a stopover on a journey to Mars. While on the Moon the travelers to Mars might resupply rocket fuel (“hydrogen”), water and oxygen then launch again heading directly for Mars. This time the launch takes place under preferable conditions due to the lack of air resistance as well as the significantly weaker gravity, making the process considerably cheaper and more fuel efficient. The point of the previous is that the design of the robot fleet may simplify humanity's effort to send crewed flights to Mars as well.

There are more activities that need to be executed in order to provide necessary living and working conditions on the Moon; especially since it involves putting humans there. This is something that the group acknowledges, and it has always been known from the start that it would not be possible to design all the necessary tool modules. Nevertheless, as mentioned before the solution infrastructure that was developed allows for additional modules to be designed and used by the robots. In other words, prerequisites for using the developed framework allow other actors of the CSMC to design the modules that are considered to be necessary. As mentioned before, the solution infrastructure also allows for new modules even post-launch which may be beneficial and necessary since a greater understanding of the Moon is attained when the robots have been investigating the environment more closely.

7.7 Fulfillment of the research question and criteria

The thesis asked the following research question:

- "How might a concept that is enabling Lunar resources to be gathered and transported look like?"

The result of the question is presented as the robot and the two designed modules. The design also fulfils the other demands that were presented by CSMC. This is as the concept is multifunctional (with the possibility of more functions being added as long as they fulfil the constraints that exist) since either robot may equip either module. The robustness criteria are also met as the minimalistic design approach resulted in a simpler design where fewer errors may occur. The fact that every robot may equip every module also guarantees a robust operation since there is greater resilience and flexibility. The operation may furthermore be scaled up to a time frame that is determined by CSMC.

Moreover, by going over the requirements it becomes evident that all are accounted for in accordance with Table *3*, *Table 4* and *Table 5*.

Table 3. The identified functional requirements

Functional requirements	Fulfilment of requirement
The robot shall operate the different tool modules.	The module equipping mechanism enables the different designed modules to be equipped.
The robot must avoid obstacles that occur on the Lunar surface e.g., irregular terrain. Obstacles of	The wheels are dimensioned to allow it to roll over obstacles such as rocks. Also, the arms of the module equipping

maximum 15 cm shall be able to be overcome.	mechanism allows the height clearance to be increased by letting the arm horizontal position.
The robot shall be able to supply the modules with power.	The design of the module equipping mechanism has a feature that allows power to be transferred.
The robot shall be able to gather data concerning its direction.	The robot is equipped with a sensor providing this information.
The robot shall be able to gather data concerning its inclination.	The robot is equipped with a sensor providing this information.
The robot shall be able to gather data concerning the Lunar temperature.	The robot is equipped with a sensor providing this information.
The robot shall be able to gather data concerning its energy consumption.	The robot is equipped with a sensor providing this information.
The robot shall be able to gather data concerning its electrical usage and to convert this data to other relevant information e.g., force exposure.	The robot is equipped with a sensor providing this information.
The robot shall be able to gather data from its immediate surroundings. The dedicated equipment shall be able to move 360 degrees.	The robot is equipped with a sensor providing this information.
The robot shall be able to turn 360 degrees.	The robot may turn 360 degrees by letting one side rotate in the opposite direction in relation to the other side.

Table 4. The identified performance requirements

Performance requirements	Fulfillment status
The robot shall excavate regolith.	The regolith collector module enables the robot to do so.
The robot shall be able to acquire a sufficient mining position and angle itself appropriately using its levers.	By using the levers, the robot may adjust its position in order to achieve a more efficient mining process.
The robot shall be able to pick up a tool module and mount it on its itself as well as detach it.	This is something that the module equipping mechanism can do in collaboration with the motors adjusting the levers.
The robot's battery must sustain at least 20 hours of operation before it must be charged.	The calculation in *appdx. 2* shows that this is possible.
The robot shall be able to measure its power supply to measure its power consumption and its force exposure.	This is being done by using the data from the current sensor.
The robot will be able to physically connect to other robots.	The three cylindrical knobs at its front as well as the corresponding holes at the back fulfill this requirement.

Table 5. The identified design requirements.

Design Requirements	Fulfillment status

The robot and its sensor equipment (excluding batteries) shall weigh a maximum of 80 kg.	The calculation proves this in accordance with *appdx 3*.
The battery weight shall be maximum 30 KG of Lithium-ion type.	The calculation proves this in accordance with *appdx 3*.
The robot shall be made from a material approved for space application.	Aluminum T3 is the specified material of the construction, which is space graded.
The robot shall withstand the temperature on the Moon, i.e., -230 to 130 ° C.	Aluminum T3 fulfills these criteria.
The robot's container module shall be able to fit a weight of at least 50 Kg.	The calculation proves this in accordance with appdx 3.

8 Conclusion and Future Work

8.1 Conclusion

The conclusion of this work is that the concept that was developed is one appropriate way to enable Lunar mining as well as other activities that are required to establish a scientific presence on the Moon. Due to the open nature of the question, there are alternative ways to answer it. The circumstances of the project presented some major challenges that significantly affected the design as well as how it operates. For viability as well as feasibility reasons, all necessary components and systems including their subsystems were always envisioned in their easiest execution. In other words, a “less is more” philosophy was implemented throughout the duration of this work which caused some consequences, e.g., some reduced performance in favor of simplicity for the steering solution.

Furthermore, the proposed concept utilizes a swarm approach of a specially designed Lunar rover for the purpose, simply referred to as ”robot” throughout this work. The robots are designed to operate together when that is necessary as well as independently when suitable, depending on the relevant task at hand. These arguably give the most potential for a flexible operation on the Moon. The most relevant features for these have been established and are motivated in the report.

The key feature of the design is that it is not the robots themselves that perform the tasks but instead they carry interchangeable tool modules that enable the fulfillment of the tasks. This is motivated since it achieves a greater mission resilience, however at the cost of providing a surplus of modules. It also likely reduces wear on the robots since it is the modules that get more exposure due to them performing the work, e.g., the regolith collects scraping regolith and loosens any rocklike material. Another highly significant aspect is the fact that the solution actively provides an infrastructure that enables new activities to be performed post-launch. If the presumptive newly designed modules do not conflict with the geometrical constraints that the robots implicate. It is possible to use the infrastructure to design modules that use more than one robot. This enables greater flexibility for the robots to perform a wider range of activities. This is valid prior to launch as well as post-launch. This detail might however be even more significant post-launch since there may arise circumstances where the gained knowledge concludes that a module operated by multiple robots might be highly desirable. This is an aspect that also contributes to an increased mission resilience. It is also worth mentioning that the robots themselves are intended to change and equip the modules on their own, without any involvement from the ground control; even if the possibility to intervene manually even if that opportunity exists.

The robot structure is designed to be propelled by four wheels. These wheels are connected to a lever that in turn is driven by four motors which enables the robot to adjust its height when it is necessary. The most prominent occasion for this is when the robot shall equip itself with a module. Then the height is automatically adjusted as the module equipping

mechanism is engaged. As all modules are fitted with threaded holes this allows the specially designed screws of the module holder mechanism to fasten themselves thus getting a firm grip of the module in question. By reversing the screws, the module is subsequently released. Furthermore, the robot is equipped with a camera that is used to understand its surroundings as its feed is processed onboard the robot, which is done by its CPU.

Two interchangeable tool modules were designed along the robot structure. These are the regolith collector module and the container module. All the previous modules share the same principal philosophy in being as minimalistic as possible as well as providing prerequisites for a robust and resilient operation. The purpose of collecting regolith is to use this as a resource since it can extract e.g., oxygen, hydrogen from it. which significantly facilitates a human research endeavor on the Moon since this practically eliminates the need to provide these from Earth. To launch anything from Earth to the Moon is extremely expensive and the cost of doing so, per KG launched, is between 1-1.4 million US dollars. Therefore, the operation is not feasible without the possibility to extract these kinds of resources from the surface of the Moon. The regolith collector module is, simply put, designed as a kind of conveyor that will transport the top layers of regolith that are loosened by a rotating “wheel” at its front. Then the regolith will end up in the container module that is operated by another robot than the regolith collecting module. A unique solution enabling a simple transition is also designed that utilizes a geometrical looking principle.

The overall conclusion of the work is that it has resulted in a result that may be used as a foundation for further improvement. It is to be kept in mind that this work concerns the development of a high-level concept that shall be able to create prerequisites that are necessary to utilize the resources that are present on the Moon. This is since they are de facto necessary to sustain a realistic research endeavor of the Moon. What the previous means is that more work is needed in order to transition the solution from a concept stage to a product level. This undoubtedly has to do with the complexity that designing something intended for an extraterrestrial as well as inhospitable environment presents. Nevertheless, the group has identified and acknowledged some of the most important aspects that require further development.

8.2 Future work

8.2.1 Overview

Due to existing limitations, the group has not been able to create a complete and functional physical prototype. These limitations are time, materials, knowledge and other resources. Design Consideration, more comprehensive analysis, detailed CAD modeling and software development are among the areas that future teams can work with this concept to build a finished prototype.
The following are some parts that can be done in the future to be able to develop a functional concept design:

- The software part can be included, and the relevant parts can be programmed
- A detailed energy supply plan can be created
- A closer to reality prototype can be built
- A more detailed construction design can be created
- More focus on the modules can be added

8.2.2 Software

The group in this project consists of two mechanical engineering students and has limited knowledge in software engineering. This is one of the reasons why everything belonging to the software part has been neglected. These parts are such as the communication between the robots, communication between the robots and the Earth, the communication between the robot's internal parts such as sensors, camera, and other devices, but also communication between the robot and its modules. This is an important and interesting area that can be worked on in the future in the further development of the concept. However, this requires experts in the field, such as people who have knowledge and experience in software engineering and programming. This is about simply automating the robots and their modules. The concept can be developed by focusing on the integration of mechanical and electronic systems by implementing mechatronics parts. For less advanced software development, applications such as C ++ and Raspberry Pi can be used. The group has used a simple programming platform, Lego Mindstorm, to control the devices so that they behave as they should. This can be developed by using more advanced programs that can perform the work better and more efficiently.

8.2.3 Energy system

The group has developed a simple energy system and energy source, following restrictions that existed. This is also part of the concept that can be worked on in the future. A detailed plan is required for how much energy is required for the concept to be able to operate. A detailed wiring diagram is required where it shows how much electricity different parts of the concept require. It should also include how the electricity should get to different appliances in the concept. For future work, a base power distribution system must also be performed, where the number of volts, number of ampere hours, suitable battery type, the margin for capacity and how many watt hours are required for the time the robot is to perform the work must be determined. All these must be tested separately before they are included in the prototype.

8.2.3 Material selection

As described earlier in this report, the Lunar environment differs markedly from the environment on Earth, so it is important that the materials used in components on the Moon are adapted to the Lunar environment. The robots and their modules are mostly made of aluminum, but materials other than aluminum are also used, for example in electronic parts, such as motors, chips, cables, and batteries. Here it is necessary that the future group that

works with this concept identifies these materials and their properties. A sharing material can be tested and verified on a "Moon-like environment on Earth". A problem that exists on the Moon is, for example, that lubricants cannot be used on the Moon due to vacuum. In future development, alternative materials can be discussed and tested. There are already materials used for similar objects by, for example, NASA and ESA. These materials can be researched where the right material should be selected for the right component.

8.2.4 Prototype

A physical prototype can be built that will contain several components that the group has discussed during this project. Examples of these components are various sensors that have been mentioned in the report, a camera, communication system and more. The prototype can be built by using aluminum instead of plastic and wood. This can also help to be able to test and verify several parts of the design. To begin with, a less advanced prototype can be made using materials that are more similar to the actual materials to be used for Lunar mining robots. More focus should be on the modules that have been discussed in the report. For example, the group has designed the regolith collector and made 3D modeling and simple 3D printing from plastic, wood and corrugated cardboard. This can be developed by building better prototypes. Conveyor belts that are part of the regolith collector module can be built so that it is functional and can be tested. but also verified. for example, there are several options for what kind of plastic can be used on the Moon, therefore, a suitable plastic variety can be selected and then a prototype can be built by using the right material or material that is as close to reality as possible.

The group has developed a good foundation on how the concept should work, but when it comes to deeper details, more work and experts from different areas are needed. What the group has come up with is a good foundation for the next group so they can build on that and focus on more details on a deeper level. Everything that has been addressed by the group for the concept is based on the needs that exist and on the facts on which it is to be based. This will help future groups build a functional prototype that can be developed later.

8.2.5 Verification

The group has verified some parts of the concept which consists of using 3D printer materials, plywood, metal shafts and Lego motors. In future work with this concept, this work can be performed with more suitable materials that are closer to reality than these. For example, the group has suggested using Maxon motors for the possible final result. Therefore, Maxon motors can be used to verify different parts of the concept. The arms which should hold the modules that the group has used are made of PLA material and have been built within 3D printers, but these can be made of aluminum because aluminum is the material to be used for a possible finished product on the Moon. To demonstrate the function of the robot working together with the module, the group used Styrofoam that would correspond to one module. Instead, a better prototype equivalent to a module can be built. This can be done by using the right dimensions that fit the robot's module holder and correspond to the weight that the robot is intended to carry. This can provide better data as

a result. In future work with the concept, all parts of the concept must be tested, optimized, and verified until a finished prototype can be presented.

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Apendixes

Appendix 1 – Identified requirements

Table 6. The identified functional requirements

Functional requirements
The robot shall operate the different tool modules.
The robot must avoid obstacles that occur on the Lunar surface e.g., irregular terrain.
The robot shall be able to supply the modules with power.
The robot shall be able to gather data concerning its direction.
The robot shall be able to gather data concerning its inclination.
The robot shall be able to gather data concerning the Lunar temperature.
The robot shall be able to gather data concerning its energy consumption.
The robot shall be able to gather data concerning its electrical usage and to convert this data to other relevant information e.g., force exposure.
The robot shall be able to gather data from its immediate surroundings. The dedicated equipment shall be able to move 360 degrees.
The robot shall be able to turn 180 degrees.

Table 7. The identified performance requirements

Performance requirements
The robot shall excavate regolith.
The robot shall be able to acquire a sufficient mining position and angle itself appropriately using its levers.
The robot shall be able to pick up a tool module and mount it on its itself as well as detach it.
The robot's battery must sustain at least 24 hours of operation before it must be charged.
The robot shall be able to measure its power supply to measure its power consumption and its force exposure.
The robot will be able to physically connect to other robots.

Table 8. Identified design requirements.

Design Requirements
The robot and its sensor equipment (excluding batteries) shall weigh a maximum of 80 kg.
The battery weight shall be maximum 30 KG of Lithium-ion type.
The robot shall be made from a material approved for space application such as aluminum T3.
The robot shall withstand the temperature on the Moon, i.e. -230 to 130 ° C.
The robot's module holder shall be able to carry a weight of at least 50 Kg.

Appendix 2. The estimated energy usage per system

Motor system

The motor system is estimated as follows in table 9. The total consumption is estimated to be 54.5 MJ per day for one robot. This is a high number but is realistic since the motors are moving forward for the entire duration of its operation. The estimated numbers are average values for both collecting regolith and transporting it. One reason for the high numbers is that the designed concept shall travel at higher speeds than existing rovers that are of a more research nature as well as it more heavy duty oriented.

Table 9. Estimated energy usage of the motors of the robot

Motor energy consumption						
System	Purpose	System quantity	Energy consumption per second for entity [W]	Total energy consumption per second for system [W]	Estimated usage time during a day [H]	Energy consumption [MJ]
Propulsion motor system	Enabling movement.	4	60	240	24	20.7
Lever motor system	Keeping as well as adjusting the position of the robot.	4	40	160	24	13.8
Module mechanism motors -arms	Adjusting the position of the module. May be used for increased ground clearance.	4	40	160	5	2.8
Module mechanism -screws	Used for attaching and detaching the modules.	4	20	80	0.05	0.01

Camera motor	Used for rotating the camera.	1	10	10	0.1	0.04
Sum		**17**	**170**	**650**	**59**	**37.4**

Table 10. Estimated energy usage of the motors for the Regolith collector module.

System	Purpose	System quantity	Energy consumption per second for entity	Total energy consumption per second for system [W]	Estimated usage time during a day [H]	Energy consumption [MJ]
Regolith collector module -Front	Gather the regolith.	2	40	80	24	6.9
Regolith collector module - Conveyor	Transport the regolith along the module.	2	30	60	24	5.2
Sum		**4**	**70**	**140**	**48**	**12.1**

CPU and sensor systems

It is assumed that the energy usage of the CPU and the sensors will not exceed 5 MJ. The most sensors will be active the entire day, but the devices are highly efficient and are considerably smaller compared to the motors. [15]

Appendix 3. Weight and volume calculations

Table 11A table concerning weight and volume of the concept

Entity	Available volume [m^3]	Required volume [m^3]	Weight [Kg]
Robot structure	0.12	-	62
CPU and sensors	-	0.03*	4*
Battery	-	0.02	34
Motors**	-	0.01*	4*
Additional motors	-	-	6*
Sum	**0.12**	**0.06**	**110 (76)*** **

*Estimated value.

**Concerns the ones operating the arms of the module as well as the ones operating the levers.

***Excluding battery weight.

The weight of the robot

The weight of the robot rectangular is used by calculating the total volume and then multiplying with the density of aluminum. This, however, gives mass for the entire homogenous rectangle. It is assumed that 90% of it will be hollow in order to fit with equipment. As such, the previous weight is multiplied by 0.1. The previous is given by (4).

Aluminum density ρ: 2700 $\frac{Kg}{m^3}$ [15]

$$m_{rc} = 1 * 0.6 * 0.225 * 2700 * 0.1 = 37\ Kg \quad (4)$$

For the levers it is assumed that the entities are made of aluminum as well and they have a volume of 0.001 m^3. This enables the weight to be calculated in accordance with (5)

Weight of the levers, $m_l = 4 * (2700 * 0.001) = 11\text{Kg}$
(5)

The weight of the wheels is calculated by calculating the volume of one wheel then assuming that 90 % of it is hollow before multiplying with the correct number of entities.

The weight of the wheels, $m_w = 4 * (\left(\frac{0.324}{2}\right)^2 * 0.162 * \pi * 2700 * \ 0{,}1)) \ = 14$ Kg

The total weight approximation of the robot structure (excluding equipment) is approximated by (6).

$$m_t = m_{rc} + m_l + m_w = 37 + 11 + 14 = 62\,Kg \quad (6)$$

Volume requirement for battery

Energy capacity of the battery, E_C: 2830 MJ/m^3 [15]

Required energy amount, E_R: 54.5 MJ

Required volume: $V_{battery}$

$$V_{Battery} = \frac{E_R}{E_C} = \frac{54.5}{2830} = 0.02\,m^3$$

(5)

In accordance with the assumption that 90 % of the robot structure will be hollow this means that the available volume inside will be as shown in (6).

$$V_{robot} = 1 * 0.6 * 0.225 * 0.9 = 0.12\,m^3 \quad (6)$$

By comparing $V_{Battery}$ to V_{Robot} it becomes evident that there is enough room to fit the battery thus fulfilling the criterion while at the same time leaving plenty of room for the sensors, CPU and motors.

Appendix 4. Drawing of the robot

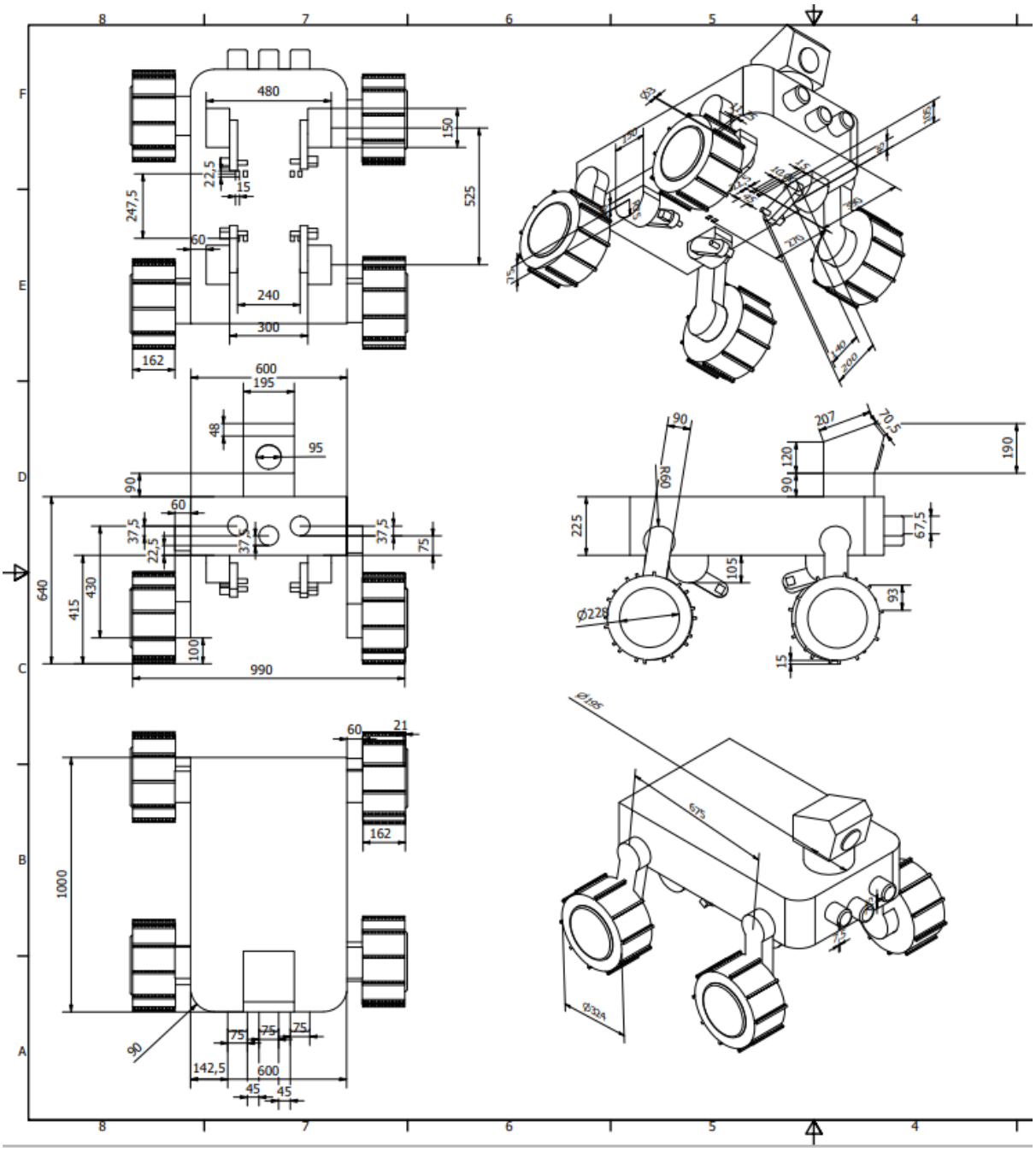

Figure 33. Drawing of the robot

Note: for any missing measurements of an object that are present of another identical object symmetry is to be assumed. (All measurements in mm)

Appendix 5. Drawing of the container module

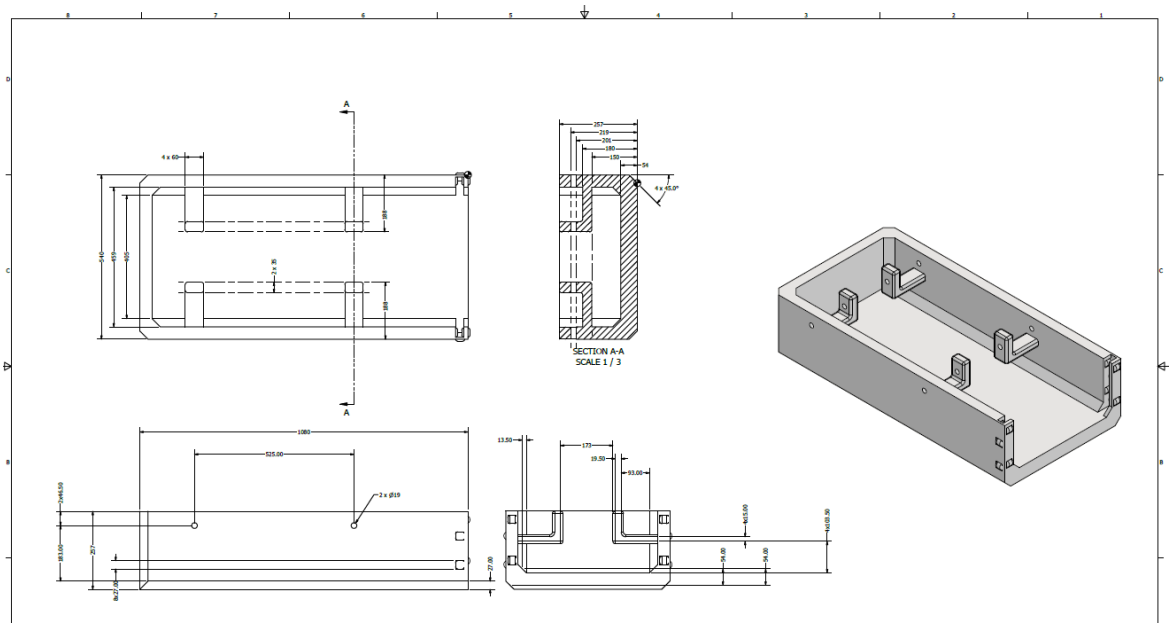

Figure 34. Drawing of the container module

Appendix 6. Drawing of the regolith collector module

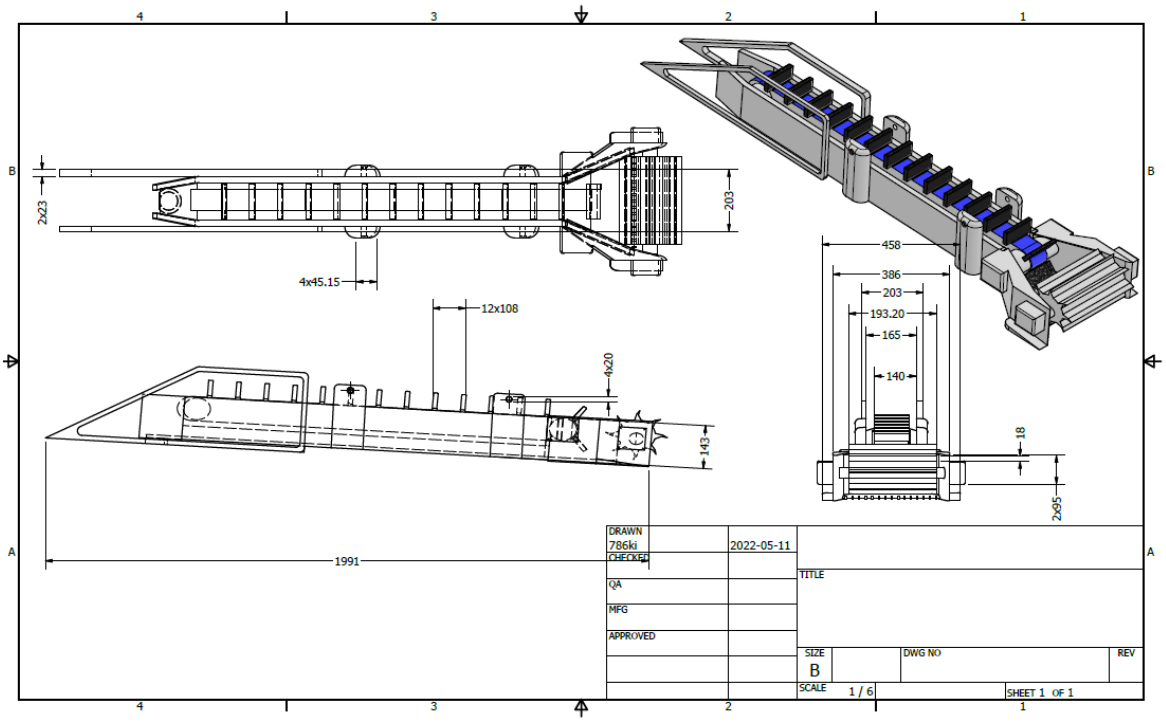

Figure 35. Drawing of the regolith collector module

Appendix 7. Failure Mode and Effect Analysis (FMEA) for Robot

Table 12. FMEA for robot

Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Prob	Current Design Controls	Det	RPN	Recommended Action(s)
Chassi	Structural body	Robot not operationa-ble	10	Crash	7	Calculations, simulations	2	140	Make sure that the landing takes place in a safe and controlled way.
Chassi	Structural body	Internal damage, robot may get severely damaged	10	Accidental damage (e.g., fall damage)	5	Calculations, testing	5	250	Make sure that the robot may handles impacts. Make sure that the robot can make a safe route to avoid falls.
Chassi	Towing/ pushing system	The robot cannot tow or push another robot	6	Deformation, damage to threads, rigorous exposure to Lunar dust	4	Testing	2	48	Make sure that the materials used have a resistance to impacts. Develop an anti-Lunar dust strategy.
Chassi	All systems	One or several internal devices comes off	10	Crash, accidental damage, poor fasting methods	4	Testing	1	40	Make sure that all the necessary equipment in the robot is fastened in an adequate way.
Chassi	All systems	Sealing failure	9	Crash, insufficient sealings	6	Testing	2	108	Make sure that the sealings are tight and robust.
Wheels	Drive system	Wheel fails to get enough traction (no movement)	9	Poor surface quality, structural damage	6	Calculations, testing	1	54	Testing, make sure that the imaging system can determine surface quality and incline.

Wheels	Drive system	Affected movement	4	Repeated exposure to structural obstacles resulting in damage	3	Testing	1	12	Make sure that the wheels can resist shocks and other types of external effects.
Wheels	Drive system	Wheel falls off.	9	Repeated exposure to structural obstacles resulting in damage, faulty shaft	4	Testing, simulations	1	36	Make sure that wheels and shafts are robust.
Propul-sion motors	Power propuls-ion	No motion	9	Crash, extensive use for a long period, no power	5	, Calculations, testing	3	135	Implement an effective measuring method.
Module arm motors	Height adjusting	Modules cannot be equipped; the CoG cannot be compensated for, Ground clearing problems	8	Crash, extensive stress for a too long period, no power	4	Testing	1	32	Implement an effective measuring method.
Screw motors	Module equipping mechanis m	Modules cannot be equipped or unequipped	8	Crash, extensive stress for a too long period, no power	5	Testing	2	80	Implement an effective measuring method.
Camera motor	Camera movement	The environment cannot be controlled properly; problems with determining appropriate routes	8	Crash, extensive stress for a too long period, no power	2	Testing	1	16	Implement an effective measuring method.
Battery	Energy supply	The robots' functions are hindered due to no power transfer	10	Physical damage, connection problems	3	Testing	10	300	Make sure the battery is in a safe, insulated environment and secluded environment. Make sure heating and cooling systems work.

Battery	Energy supply	Insufficient performance	5	Exposure to high or low temperature, physical damage	3	Testing	2	30	Make sure that sensor data is accurate to avoid hazardous temperatures.
Battery	Charging [for robot]	No energy transfer	9	Poor wires, battery failure, short circuit	5	Testing	1	45	Make sure the chosen wires are of sufficient quality.
Power socket	Energy transfer to module	Affected of no performance	6	Poor wires, short circuit, Lunar dust buildup, wear	6	Testing	4	144	Make sure that the power socket is robust and that no regolith finds its way inside. Replace regularly.
Softw-are	Spontane-ous crashes	The robot cannot function	10	Unknown	6	Testing	10	600	Provide prerequisites for robots providing support for each other and use resilient software.
Communi cation	Inter-robot commun-ication	Robot cannot receive or provide aid	8	Spontaneous malfunction, damage to communica-tion device	4	Testing	2	64	Use resilient software, make sure that the hardware is well-protected.
Commu-nication	Earth-robot commu-nication	The robot cannot receive manual commands	4	Damaged hardware, statics	6	Testing	5	120	Use resilient software, make sure that the hardware is well-protected.
Module screws	Module equipping mechanis m	Modules cannot be equipped	7	Deformation, damage to threads, Lunar dust exposure	5	Calculation, Testing	5	175	Make sure that the materials used have a resistance to external impacts.

Module screws, module arms	Module equipping mechanism	Modules cannot be equipped, or the module cannot be equipped in a reasonable time frame	7	Insufficient reliability in fining the holes due to damage, miscalculations or software problems	5	Testing, calculations	2	70	Ensure that the arms and screws find the place even when affected by external factors.
Camera	Imaging system	The robot cannot move safely since the camera is not working	6	Exposure to Lunar dust	9	Testing	2	108	Equip the camera with a function which may clean the lens.
Battery sensor	Informat-ional data system	The robot is not provided with accurate data and its operation is compromised (might result in robot failing to get to charging station)	10	Physical damage, spontaneous malfunction-ion, wiring problems	3	Testing	2	60	Make sure that the sensors are reliable and have a strong resilience towards damage.
Current sensor	Informat-ional data system	The robot is not provided with accurate data and its operation is compromised (might not understand how hard it is working)	8	Physical damage, spontaneous malfunction, wiring problems	3	Testing	2	48	Make sure that the sensors are reliable and have a strong resilience towards damage.
Gyrosc-ope	Informat-ional data system	The robot is not provided with accurate data and its operation is compromised (might result in trouble navigating)	10	Physical damage, spontaneous malfunction, wiring problems	3	Testing	2	60	Make sure that the sensors are reliable and have a strong resilience towards damage.
Temper-ature sensor	Informat-ional data system	The robot is not provided with accurate data and its operation is compromised (might be exposed to dangerous temperatures)	10	Physical damage, spontaneous malfunction, wiring problems	3	Testing	2	60	Make sure that the sensors are reliable and have a strong resilience towards damage.
Tilt sensor	Informat-ional data system	The robot is not provided with accurate data and its operation is compromised (might potentially tip over)	7	Physical damage, spontaneous malfunction, wiring problems	3	Testing	2	42	Make sure that the sensors are reliable and have a strong resilience towards damage.

Appendix 8. Failure Mode and Effect Analysis (FMEA) for Regolith Collector Module

Table 13. FMEA for regolith collector module

Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Prob	Current Design Controls	Det	RPN	Recommended Action(s)
Conveyor and front motors	Power Propulsion, Lunar mining system	No regolith may be collected	7	Physical damage	4	Testing	2	56	Make sure that the motors are resistant to shocks etc.
Conveyor and front motors	Power Propulsion, Lunar mining system	No regolith may be collected	5	Lunar rocks blockage somewhere in the module	6	Testing	1	30	Implement reversing feature after a time of no forward movement
Conveyor and front motors	Power Propulsion, Lunar mining system	Reduced performance	7	Exposure to high or low temperature	5	Testing	4	140	Make sure that the robot knows when it is time to activate heating/cooling systems
Power cables incl. connection	Power Supply	Limited or no operation performance	9	Physical damage, poor wiring conductivity, socket obstacle	4	Testing	2	72	Make sure that the cables are robust and resistant to external factors.
Container opening solution	Regolith transferring system	The regolith cannot be transferred	5	Physical damage, poor dimensioning, problems finding the right approach	6	Testing	1	30	Ensure that the robot finds the correct distance and approach as well as the robots communicate with each other working together.

Conveyor belt	Regolith transferring system	The regolith cannot be transferred	6	Damage to the belt and or its “teeth”, extensive Lunar regolith buildup	6	Testing	3	108	Make sure that the relevant parts are replaced when necessary as well as making sure that components that are used have a long lifetime.
Sealings	All systems	No regolith or a lesser quantity may be collected due to reduced performance	7	Poor sealing quality, physical damage, long-term wear-down	6	Testing	2	84	Make sure that the sealings are robust and changed regularly to avoid failure.
Module attachment	Module equipping mechanism	The module cannot be equipped, thus the activity cannot be performed	9	Damage to the structural bearing parts, insufficient dimensioning, excessive regolith buildup	4	Testing, calculations	1	36	Control that the bearing parts withstand the stress and use a sufficient safety factor.
Module attachment	Module equipping mechanism	The module cannot be equipped, thus the activity cannot be performed	8	Physical damage, Lunar dust in the threads, inaccurate dimensions	5	Testing	2	160	Make sure that the screws always find their way into to their intended attachments, even from slightly wrong starting position. Evaluate if necessary to develop a solution that cleans the holes prior to insertion.
Entire module	All systems	Reduced or no regolith collecting performa-nce	8	Crash, or unintended object impact	4	Testing	1	32	Make sure that all systems are well-anchored and resistant to shocks and collisions.

Entire module	All systems	Module unusable	5	External impact causes the entire module to flip over	2	Testing	1	10	Investigate the best approach to get the module in the correct position again. Make sure that nothing is damaged even if the module gets upside down.
Entire module	All systems	Module unusable	10	Equipment destroyed due to rocket crash	7	Simulation, calculations	2	140	The landing sequence is a risky procedure and therefore it is important to calculate and simulate to make sure that the landing takes place in a safe and controlled manner.

Appendix 9. Failure Mode and Effect Analysis (FMEA) for Regolith Container Module

Table 14. FMEA for regolith container module

Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Prob	Current Design Controls	Det	RPN	Recommended Action(s)
Entire module	All systems	Module unusable	10	Equipment destroyed due to rocket crash	7	Simulation, calculations	2	140	The landing sequence is a risky procedure and therefore it is important to calculate and simulate to make sure that the landing takes place in a safe and controlled manner.
Entire module	All systems	Module unusable	10	Accidental damage	5	Testing	5	250	Make sure that the robot may handle impacts. Make sure that the robot can make a safe route to avoid falls.
Opening mechanism	Locking mechanisms	No regolith transfer	5	Triangle fails to find the correct position, wrong start position, damage	5	Testing	4	100	Ensure that the triangle accurately will work even if the starting position is a bit off. Also, make sure that it handles shocks well whit affecting its performance.
Closing mechanism	Locking mechanisms	No regolith transport	5	Debree in the way, the locking mechanism, poor moveable parts	6	Testing	4	120	Make sure that the closing robot carrying the container understands when it needs to use its arms to shake/ or move it. Ensure that the

									components are robust.
Module attachment	Module equipping mechanism	Bearing structure fails	9	Structural damage, miscalculation	3	Calculation, testing	1	27	Make sure that the parts in question are designed with a reasonable safety factor.
Module attachment	Module equipping mechanism	Screws fail to find their intended place	8	Damage, worn parts, Lunar dust in threading	5	Testing	3	120	Ensure that the screws are resistant to wear. Investigate whether the screws need to be regularly cleaned for satisfactory performance.

Faculty of Engineering, Blekinge Institute of Technology, 371 79 Karlskrona, Sweden