Logistics of Space Mining - Red Team

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***Abstract*—The architecture, setup and work on a mining station on the Asteroid 469219 Kamo' oalewa are presented. The spacecraft arriving on site is the mining station that anchors to the surface of the target object by means of a docking ring and microspine grippers. It's a tunnel-based mine: a main shaft is dug though the asteroid and departing from it other veins are excavated. The goal is to extract and process valuable materials such as platinum group elements in order to make the mission profitable. In addition, the regolith covering the surface is also collected using rovers and refined to produce propellant. Astronauts' work is needed to set up the mining system.**

I. Introduction

This paper presents the result of project work conducted in the course Human Spaceflight SD2905 at KTH Royal Institute of Technology in Stockholm, Sweden. The purpose was to investigate and develop a mining operation on the Asteroid 469219 Kamo' oalewa also known as 2016H03 conceptually.

A. Background

In 2020, asteroid mining is still a broad concept, since it requires adapting the knowledge on mining (heavy machinery on Earth) to a gravityless Space environment. To ensure that the mission is fulfilled, the designed systems must be robust enough to mine without needing a very costly manned maintenance mission, but also light enough to reduce the launch cost. Moreover, the absence of gravity requires innovative tethering technologies of which most have been tested already, and all the systems have to be as automated as possible to limit the on-site intervention of humans. As for bringing back the valuables on Earth, the mass budget is also a significant criteria to design a profitable mission. Consequently, to present a first mission concept with a decent technology readiness level (TRL) is a challenge, especially for a mission that will take place in a decade.

B. Assumptions

1) Physical properties: Starting from raw data on the dimensions of the asteroid [2], it is supposed to be a cylinder of 50m length and 30m diameter. Its core is solid and metallic, and is covered by a $30\,\mathrm{cm}$ layer of regolith. Its rotation period is 1 hour [1]. This rotation is slow enough to suppose that we do not consider it during the hovering and anchoring phase.

2) Asteroid composition: The regolith mass consists of 10 % water which is present as powdered water ice. The rest of the soil is not processed, so it is not of interest.

To determine the composition of the asteroid core, a first approach was to copy the general distribution of each mineral in a vein on Earth. Then, to match with the financial analysis of the overall coordination team, a reverse method has been used and adjustments have been made to make the mission financially coherent.

The asteroid core composition is then:

- 10% of the volume consists of Nickel-iron group metals.
- 1% of the volume consists of precious metals (gold, platinum, palladium).
- 89% of the volume consists of rock.

3) Minerals distribution and material properties: The distribution of the minerals is considered homogeneous, so the mechanical properties of the ore is homogeneous. This simplifies the design of mining and processing the ore, making these operations constant in time and space. In reality, the distribution is expected to vary as on Earth, where veins contain a significant amount of certain materials. It makes the mining faster, because only several spots of the asteroid are of interest and contain only a few percents of useless materials such as rock. This expected distribution is considered when designing the mining network geometry. The asteroid core is supposed to be non porous. This assumption makes the design of the water cooling and conveying system easier.

4) Space environment: Micrometeoroids and radiation represent a minor threat to the mining tools or to the communication and control instruments. Consequently, extra shielding in this purpose is not considered. Gravity is assumed to be zero on the asteroid [10].

5) Influence of mining operations: Since only a part of the asteroid is mined, the global structure is assumed to stand still and not collapse. Also, it is assumed that the vibrations caused by the mining systems do not make the regolith fly away from the asteroid because of the absence of gravity: the surface and the core operations are considered to be independent of each other.

C. Mining Archutecture

The scope of the mining mission is to extract resources from a near-Earth asteroid for exploitation in-situ and on Earth by developing a viable option ready for launch by 2030. The mining operation will require multiple techniques to be established to excavate an asteroid of the aforementioned size. The method of extraction is thought to be similar to those used for terrestrial mining. Hence the operations carried out such as boring, excavating, refining and transportation of material are expected to work in a similar manner with modifications to the machinery due to the unique environmental conditions of the asteroid.

First and foremost, one must determine which resources on the asteroid are of interest for space mining and how they can be excavated. There are two distinguishable categories of resources found on asteroids volatiles and metals [1]. Volatiles such as water are of particular interest for inspace applications as they can be used for construction, life support systems, and propellant. It is deemed that these materials can be found on the surface layer of the asteroid, which contains a loose layer of rocks known as the regolith layer. Within the asteroids core, resources with a high market value, such as rare earth metals in particular the platinum group metals, could be transported back to Earth. Both cases will be studied further in this report.

A method is needed to land the mining equipment and human spacecraft to the surface of the asteroid. This was attained using a tethered docking ring to the asteroid using surface harpoons with microspine grippers.

The extraction of the resources will require certain mining operations to be carried out in numerous environments. As aforementioned the regolith retains volatiles material used during the mission. Extraction of this will be done using surface rovers.

Furthermore, due to the lack of appreciable gravity, one must develop a method of excavation which would circumvent this predicament. The considered idea was to excavate the asteroids core from the inside out. By boring a shaft through the centre of the asteroid one could use the inner walls as gripping point, Allowing machinery to work and reach more prominent deposits of high value ore. A major benefit of this approach is that all the material is contained and anchoring is simple.

Additionally, there are two viable option for processing resources from the asteroid. One being transportation of raw material back to Earth, while another option is to process the material on site and bring back refined material. The latter option is the method of choice, due to the high transportation cost for material within space transportation.

All major systems will be contained within a so-called ”mothership”. Which will house the varies production facilities as well as crew quarters and stored refined ore.

The overall architecture of the mine is depicted in Figure 1.

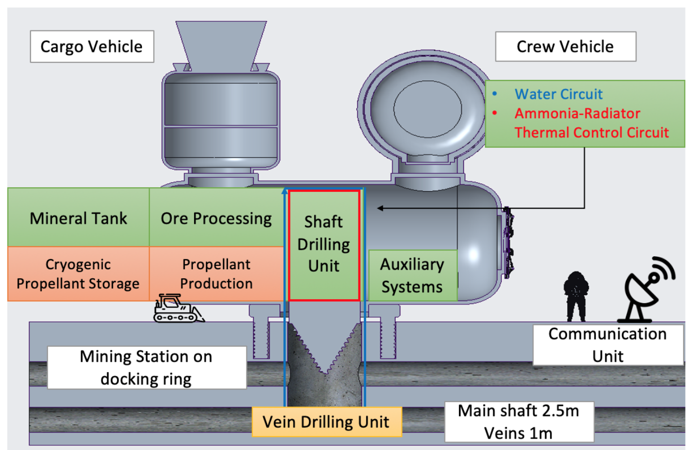

Fig. 1. System Architecture of the Mining Station

II. Anchoring

For any operation that takes place on the asteroid a tethering system to the surface is needed. Due to the small mass of the asteroid its gravity field is so weak (GM estimated to 4.9781e-11 km3/s2 [10]) that even a very small force applied to the surface, even more drilling operations, would cause a reaction force strong enough to escape from the asteroid (Newton’s 3rd law). The system must be automatically deployable since the astronauts will need grip on the surface to set up the mine and the mining station needs to attach itself to the surface as first thing after landing. Since the forces and vibrations produced by the mining machines are consistent the anchoring methods must be robust and strong enough to absorb them and keep a tight grip on the asteroid. At least two different modes of tethering are necessary, a particularly robust one for the mining station and another one that allows movability for the rovers on the surface. Most important anchoring must assure redundancy by using multiple units to produce a fail-safe system.

A. Main tethering system for the station

The single-block mining station is anchored to the surface by means of a docking double ring, based on the technology used to dock spacecraft to the ISS [11], see Figure 2. It consists of a hexapod double ring that allows for soft docking of the spacecraft. The ring is attached to the surface through harpoons, microspine grippers described below. The two components of the system can slightly move relatively to each other and this movability allows the double ring to deaden the vibrations caused by the mining machines.
The docking ring has been chosen as main connection between the station and the surface of the asteroid since it's a reliable and well established technology.

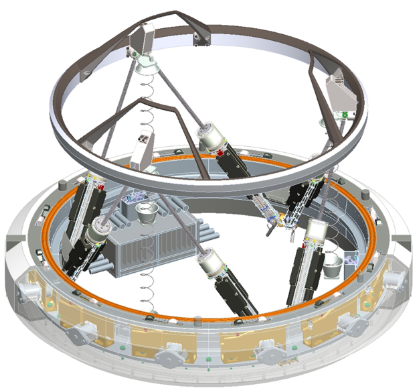

Fig. 2. ISS new docking ring [11]

B. Tethering system to anchor to the asteroid surface

The second anchoring method consists of peculiar harpoons: microspine grippers, which technology is still under development. Different configurations of harpoons are being tested mainly by the NASA Jet Propulsion Laboratory, see Figure 3; the common features of the system are: a central housing for the gripper that will first attach to the surface, microspines with hundreds of hooks are then lowered and attached to the rock underneath in order to assure robust grip. Using a large number of small hooks increases the system safety, even if a partial number of spines attach to the asteroid, they can produce enough force to sustain the loads. The microspine are designed to grip rocky surfaces, but since the asteroid is covered by a thin layer of regolith, as commonly happens, the mechanism needs to be able to penetrate a small depth of loose material, a solution may be imparting a rotary movement to the main harpoon and increasing the tension imparted to the microspines, but this configuration still under development. Due to the large number of spines the system is capable of carrying intense loads that distribute on all the harpoons and each of them reacts imparting a small force, this means that the system can be implemented as a support for mining machinery. The simplicity of the technology allows mobility in microgravity environments and microspine grippers are implemented as tethering method for the rovers that scrape the surface during mining. [12] [13] [14]

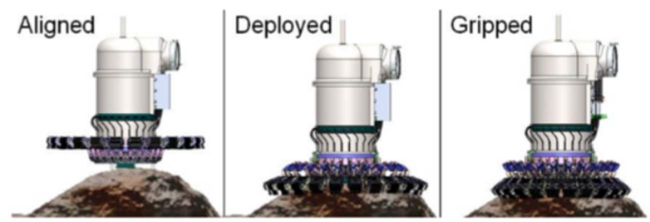

Fig. 3. microspine harpoons grippers [14]

As a conclusion microspine grippers harpoons have been chosen as anchoring system for the docking ring of the station and any other machine that needs to be attached to the surface of the asteroid, and also as tethering method for the moving robots.
The large number of spines and harpoons used guarantees redundancy and increases the safety of the systems. In addition, the anchoring is completely automated, so there's no need for human operations.

C. Other solutions considered

Other solutions for the anchoring system have been considered and then discarded:
One possibility was to cover the asteroid with a net in order to have a tethering method along all the surface, the systems would have been attached to the wires of the net and the rovers would have moved along the ropes. The solution has been finally discarded due to the excessive mass required for a net large enough for the target asteroid and for the deployment system.
A second possibility investigated was to build a rail system on the surface to allow mobility also of the mining station. The solution was discarded due to the excessive difficulty of building up such a system, and even harder would be to do it automatically. Moreover, since the mine is based on tunnels a stationary mining station is the easiest choice.

III. Regolith Mining

As stated in section I-B, the regolith of the asteroid is assumed to contain $10\,\%$ water. Although regolith is also made up of minerals which could be extracted, the processing of it is not included in this concept. This is due to the face that the large-scale mining of the asteroid with shafts and vein represents a significantly larger source of ore.
Since there is no point in returning water from an asteroid to Earth, it has to be utilized on spot (in-situ resource utiliztion, ISRU). It can be used for multiple purposes. Major applications are consumption by a crew, usage for oxygen supply, utilization in machines or processing into propellant: liquid hydrogen (LH2) and liquid oxygen (LOx). This is the combination of propellants which is employed in the cargo ship. Therefore, the $4529\,\mathrm{kg}$ of propellant (oxidizer-to-fuel-ratio: 5.8) for the flight from the asteroid to Earth can be saved and additional cargo can be transported to the asteroid. Also, it is a good opportunity for gaining experience with the in-situ propellant production. Therefore, this approach is pursued.
One could think that the mining of a loose material is relatively easy. Although this might be true on Earth - just pick a shovel - this is not the case for a microgravity environment which is present on the asteroid. Amongst others, major challenges are the containment and transport of the excavated material.

A. Regolith Excavation

For the excavation of regolith two major options were studied and compared [5]:

- Grade excavation: scooping, scraping or shoveling
- Closed-cycle pneumatics

The principle of grade excavation is straight-forward: Use a tool with a sharp edge to gather the matter. However, the implementation into a system which can be used on an asteroid is not obvious. The most advanced design is the Regolith Advanced Surface Systems Operations Robot (RASSOR) which is under development by NASA [4]. On the other side, closed-cycle pneumatics represents a technology which requires further explanation. A simple schematic of the functionality is depicted in fig. 4. Highly-pressurized gas is injected into the regolith through an outer tube [6]. Consecutively, the gas is sucked into the inner tube due to the Venturi effect, transporting the loose regolith [6]. It is then guided into a container where the regolith is stored. Hence, it works similar to a vacuum cleaner. This is a cyclic process so that the gas can be reused again [6]. A prototype of this system has already been tested successfully on a rover by *Honeybee Robotics* [6].

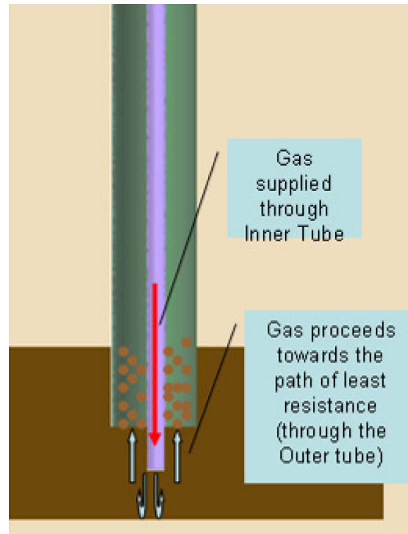

Fig. 4. To be continued.

The key parameters which have been taken into consideration for the selection of the excavation concept are:

- Complexity: impacts the cost for development and reliability
- Containment of the regolith: particular issue in microgravity, drives efficiency
- TRL: impacts the cost for development and reliability
- Excavation rate: limits the potential production rate of the end-product
- Scalability/Adaptability: limits the expansion in production and application on other celestial bodies
- Size and mass: drives launch costs

Note that cost is not listed as a parameter since it is assumed to be taken into consideration in the parameters complexity and TRL. Both drive the cost for development and production. Moreover, it is seen as hard to estimate cost directly since many solutions have not been implemented yet on a larger scale.
The rating of each parameter is given for the two concepts in fig. 4. Since grade excavation is based on a simple principle the system complexity is low. A challenge is given by the necessity to contain the gathered material. Closed-cycle pneumatics is less established in Earth-bound processes, hence the TRL is lower when compared to grade excavation. However, it relies on basic physical principles and on the contrary to grade excavation it does not require moving parts which

increases reliability. The targeted excavation rate of RASSOR is 700 kg/day [4] which is significantly higher than the extraction rate of approximately 144 kg/day [7] of the pneumatic excavator develop by *Honeybee Robotics*. However, it is assumed that the pneumatic system components are easier to upscale if compared to RASSOR which heavily relies on moving parts. Due to the containment of the regolith in the closed-cycle pneumatic system, it also allows for more flexibility for different regolith compositions. Furthermore, the targeted excavation depth of RASSOR is limited to 5 cm [4]. Significantly higher depths can be achieved easily for the pneumatic system by implementing a telescopic system which increases the potentially excavatable volume. Mass and size of both methods are estimated to be comparable and will highly depend on the overall system design.

Under consideration of these points closed-cycle pneumatic system is chosen. In summary, this is mainly due to the following assessment:

- The lower TRL of the closed-cycle pneumatic system is compensated by an increased reliability.
- The higher scalability, adaptability, the easier containment and the higher excavatable volume make up for the lower excavation rate.

Additional advantages of the pneumatic system are low excavation forces and the ability to extract only particles of a certain size by adapting the gas mass flow. [6]

TABLE I
RATING OF DIFFERENT EXCAVATION TECHNOLOGIES

	Shoveling	Closed-cycle pneumatics.
System complexity	+	+
Containment	-	++
TRL	+	-
Excavation rate	++	~
Scalability/Adaptability	~	++
Mass and Size	~	~

B. Regolith Transport & Surface Mobility

When it comes to transportation, the first question that has to be answered is if the implemented system is to be stationary or mobile. Considering a regolith depth of 30 cm (see section I-B), the only feasible solution is a mobile system. It is apparent that the excavatable volume of a stationary system would be too low. The three mobile concepts that were investigated are:

- Rover-based system: The excavation system is mounted on a rover which can move on the asteroid autonomously
- Rail-based system: This would work like an industrial crane which provides mobility in two axis: The excavation system traverses along an adjustable beam. The beam itself traverses along two guiding rails which are fixed on the asteroid.
- Rail-rope-based system: The excavation system traverses along a rail. The rail itself is fixed by a rope which can be loosened and tightened. Thus, it allows for a movement of the rail along the asteroid.

For the choice of the concept the following criteria were considered:

- Cost
- Mass
- TRL
- Extraction rate
- Installation time
- Power Consumption

The method of paired comparison was applied for the selection of the concept with these parameters []. This includes the weighing of the criteria by comparing them to each other. The resulting weights are given in

TABLE II
WEIGHTS OF THE CRITERIA FOR THE SELECTION OF THE CONCEPT FOR REGOLITH TRANSPORTATION AND SURFACE MOBILITY

Criterion	Cost	Mass	Power	TRL	Install. Time	Extract. Rate
Weight	0.2	0.26	0.03	0.23	0.03	0.23

Due to the very low weight of the power consumption and the installation time, these are not considered in the further selection process. However, it should be mentioned that this does not mean that these criteria are completely unimportant but the other criteria are seen as more relevant for the decision-making.
Next, each solution is rated from 0 (very bad) to 3 (very good) with respect to the criteria. The ratings are given in table III. Note, that the cost for the rovers is rated as 'very bad' since it is likely that a multitude of rovers is required. Mass-wise, both rails inherit an extensive and possibly massive infrastructure. The development and design of rovers is a common task in the space industry. Therefore, key technologies is given or can be expected to be developed in foreseeable time. On the contrary, rail systems have never been built in space. Therefore, a large uncertainty exists whether such a endeavour is reasonable in the given context. However,

once such a system is established it can be expected that the excavation unit can be moved quickly from one place to another.

TABLE III
RATING FOR THE SELECTION OF THE CONCEPT FOR REGOLITH TRANSPORTATION AND SURFACE MOBILITY

Criterion	Weight	Rover	Rail	Rail-rope
Cost	0.2	0	1	0
Mass	0.26	3	0	1
TRL	0.23	2	0	0
Extraction Rate	0.23	1	2	2
Rating		1.5	0.67	0.73

With this analysis at hand, a rover-based system is chosen. Additional benefits of it are the accessibility of the entire asteroid and a short installation time. Due to the conceptual character of the study, an already established rover concept was chosen which is presented in [8]. Benefits of the concept are a high flexibility which is given due to the gripper concept for anchoring, the low mass which is estimated with a maximum of $10\,\mathrm{kg}$ and the closed power system.

C. Regolith Processing & Propellant Production

Since this project is a conceptual one, the facility for propellant production is not designed itself. For the purpose of this study, it is seen as sufficient to investigate the power and mass requirements of the propellant production facility. However, the main steps for the production of LH2 and LOx from water are presented. An overview of possibly required devices is given:

- Water extraction from regolith: sublimator, solar reflectors, centrifuge
- Filtering and Condensation: water filter, pump, ventilation system
- Electrolysis: proton exchange membrane (PEM) electrolyser
- Cryocooling: radiative cooling, pulsed tube. [9]

Since LH2 and LOx are cryogenic propellants, they have to be stored in a cryogenic cooling facility for liquefaction. This facility has to store LOx at $90\,\mathrm{K}$ and LH2 at $20\,\mathrm{K}$. Its mass mainly depends on the amount of propellant which is to store. [9]
Alternatively to the production of propellants, the facility should be designed in a way which allows for the production of filtrated drinking water only.

D. Sizing of the Regolith Mining Architecture

The sizing of the regolith architecture depends on the total amount of propellant which is needed and the rate at which the propellant has to be produced. The first is a requirement which is an output of the design of the cargo ship: $4529\,\mathrm{kg}$. The rate is defined by the duration of the stay of cargo ship on the asteroid . Therefore, $29.22\,\mathrm{kg}$ propellant have to be produced per day at the given mixture ratio. For the SEEDS project, it was assumed that $1033\,\mathrm{kg}$ of propellant can be produced from $16.1\,\mathrm{t}$ of regolith per day [9]. A downscaling of the system results in a regolith demand of $700\,\mathrm{kg}$ per day ($40\,\%$ margin included).
Considering the necessity for movement and the uncertainties of the overall system design, it is estimated conservatively that one rover excavates $50\,\mathrm{kg}$ per day. Therefore, 14 rovers are needed. Based on the rover mass presented in [8], the total mass of one rover including the collection system is roughly estimated to $25\,\mathrm{kg}$. Hence, the total mass over the rover-based excavation system is $350\,\mathrm{kg}$.
The power and mass demand of the propellant production and storage facility is also calculated by linear downscaling of the system which was presented in the SEEDS project [9]: the resulting mass is $3.9\,\mathrm{t}$ (tank mass excluded) and the power consumption $11.8\,\mathrm{kW}$. The mass of the tanks was estimated to $2.5\,\mathrm{t}$ by the space vehicle team.

IV. ORE MINING

A mining station is set up on the asteroid surface in order to extract valuable material. The target of the mission is to make profits and as stated as assumption the composition of the asteroid allows extraction of rocky material including nichel-iron silicates, magnesium and precious materials such as platinum and gold. In addition, part of the regolith layer covering the surface is processed to produce propellant for the cargo mission of phase 3. The quantity of valuables needs to be enough to make the mission worthy but also feasible; while the amount of regolith processed needs to be enough to propel the cargo spacecraft.

A. Ore Extraction

The extraction machinery requirements are robustness, safety and to be autonomous. The machines start working from inside the single-block mining station and dig tunnels, this configuration makes unnecessary an additional anchoring system for the drills, since the side walls of the excavation path will carry the loads produced. The main architecture consists of a bigger shaft dug though the asteroid, as shown in Figure 5, and smaller veins excavated departing from the shaft, as shown in Figure 6. The astronauts won't be on the asteroid for the all mining mission, it would last too long, this means that the system needs to be highly automated and safe, the technology implemented is a well established one for ground operations and must be scaled to space mining. The overall dimension of the mine are stated in Tab. IV and can't be excessive to be feasible, since it's based on tunnelling a requirement is to assure the stability of the asteroid: the total mined volume is 435 m3 and the total mined mass is 1 075 t (1.23 %).

TABLE IV
CHARACTERISTIC OF THE TUNNEL SYSTEM

Tunnel	Length	Diameter	Number
Shaft	50 m	2.5 m	1
Reef	8 m	1 m	30

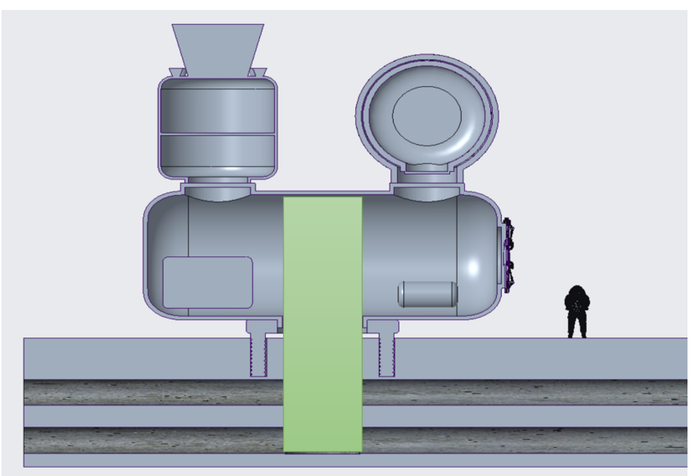

Fig. 5. Scheme of the main shaft

1) Main tunnel: Shaft boring roadhead: The set up of the mine begins with the excavation of the main shaft by mean of an autonomous shaft boring roadhead scaled down for space from the robust and well-established technology of ground mines operations (e.g. Herrenknecht boring machines of Figure7 [15]) and capable of digging into soft, heterogeneous ground and rock. The roadheader consists of a chisel tools attached to a telescopic boom, meaning that the excavator can break the entire cross-section of the shaft. The excavator is lowered using hydraulic arms, feeding itself deeper into the core of the asteroid. This arrangement of the equipment allows work even under tight space

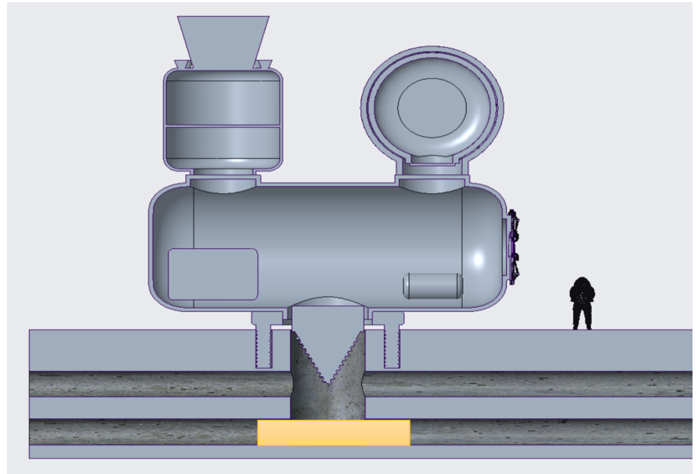

Fig. 6. Scheme of the reef departing from the central shaft

constraints. The system is cooled down using a hydraulic closed system whose water is brought on site from Earth and reused for every cycle. As part of the hydraulic cycle that same water is separated and used as transportation system to bring the ore material up to the station. The extraction capability of the roadheader must be large enough to reduce the time necessary for the excavation of the entire main shaft, during this operation the astronauts will be on site in order to set up the second phase of the mining. Table V shows the extraction rate, mass and power required for the machine and time to excavate the main shaft [15].

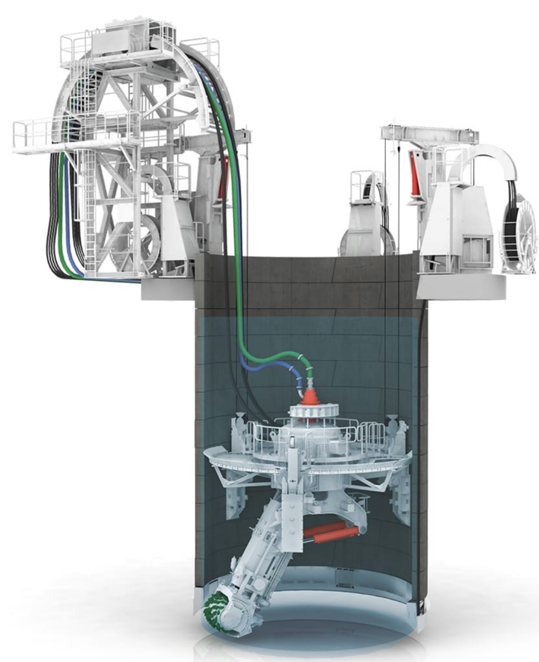

Fig. 7. Shaft boring machine [15]

TABLE V
SHAFT BORING MACHINE

Extraction Rate	Mass	Power	Time
864 mm/day	8 t	40 kW	60 days

2) Veins: Reef boring machine: The second phase of the mining operations consist of excavating smaller veins departing from the main shaft. The set up is brought on by the astronauts but the system must be completely automated once humans have left and remotely controlled if needed. A reef boring machine is implemented to dig the tunnels, once again scaled down for space from the robust and well-established technology of ground mines operations (e.g. Herrenknecht boring machines of Figure 8 [16]). Holes are bored perpendicular to the shaft and the reef system can move along the shaft and drill 360 degrees. The excavator can dig continuously rock material and the compact design is adaptable to confined spaces. The ore is removed via a water suction line that recycles the same water used for transportation in phase one of the mining for the main shaft. Table VI shows the extraction rate, mass and power required for the machine and time to excavate all the veins [16].

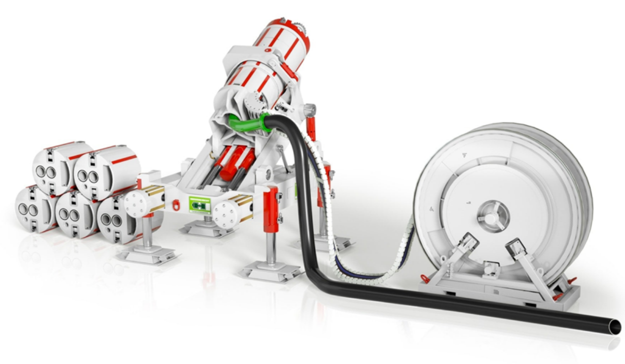

Fig. 8. Reef boring machine [16]

TABLE VI
REEF BORING MACHINE

Extraction Rate	Mass	Power	Time
435 mm/day	2 t	10 kW	280 days

3) Other solutions considered: Another solution for mining operations has been considered and then discarded:
Instead of internal tunnelling excavation a surface mine could have been set up, but additional anchoring systems would have been needed. Internal veins are safer because the side walls of the tunnels guarantee that the machines stay in place and absorb the loads produced during excavation. Moreover, the surface is covered by a regolith layer that would have had to be scraped before starting surface operations, while tunnels go straight inside the rock material.

B. Ore Processing

After extracting ore, it must be processed and refined inside the mining station. Valuable and rare materials such as platinum and gold are produced and stored to be brought back on Earth. The machines selected work under the assumptions that the processing rate equals the extraction rate. The refining part of the station works in parallel with the shaft and reef boring machines so not to have to store the rocks extracted and develop a continuous system.
The processing station must be robust and autonomous, the astronauts will start the system and then leave the asteroid. The machines are kept inside the spacecraft mining station where the material extracted is delivered through the hydraulic transportation cycle, so there's no need for a downloading process from the spacecraft and no additional tethering system on the asteroid for the processing machinery. Finally, water pipes of the transportation cycle bring the products to the tanks.

1) Magnetic Separation: Magnetic separation is a simple and well-established technique of ore processing. The technology selected is based on the one used in ground mining operations, since there are no prototypes for space missions yet, the machinery needs to be scaled down from the heavy ones used on Earth. The working principle is based on the magnetic affinity of the target valuables. By applying magnetic fields of different intensity it is possible to separate from ore minerals with different magnetism ranges [17] [18] [19] [20]. The machine concept consists of a staged magnetic separator; each stage targets a class of materials, the most magnetic first and the less magnetic after them. Permanent magnets with different characteristics are used to create magnetic fields of different intensity in each stage, so there's no need for additional machines that would require additional power consumption to create magnetic fields. The ore passes through the first stage of the machine where a low intensity magnet separate strongly magnetic materials such as iron. Then moving to the second stage a higher intensity magnet reacts with less magnetic materials and so on. A three-staged machine with different magnets allows the separation of the three main categories of materials we're interested in for our mission. Even very low magnetic minerals as

platinum can be beneficiated by means of this multiple magnetic separation technique after the extraction of higher magnetic materials. [21]
Magnetic separators implemented on Earth mines have a very high processing capacity and needs to be scaled down in a space mining system. For the asteroid mining concepts the assumption of equal extracting and processing rate has been made. Table VII shows the processing rates (both during the main shaft excavation and the veins excavation), the mass of the machine and power required [22].

TABLE VII
MAGNETIC SEPARATOR

Processing Rate	Mass	Power
Shaft extraction rate: 10 t/day Reef extraction rate: 1.6 t/day	2.5 t	5 kW

2) Other solutions considered: Other solutions have been considered for the processing phase and then discarded:
Electrostatic separation: this technology is also well-established in ground mining. The process is based on electrostatic charges to separate by mass the materials. Even if it's commonly used on Earth this solution has been discarded due to possible charging problems. System maintenance is reduced at its minimum and it must be highly safe for the mine.
Chemical processing: this solution is based on separation of mineral based on their chemical affinity to reactants. The solution has been discarded due to its complexity, since we're interested in different material with different chemical properties and affinities. Moreover, the chemical reactants needed would have been carried on site by the spacecraft increasing safety concerns.
It has to be pointed out that also the possibility of not performing processing on site but bringing back the ore to Earth or on a closer orbit to a separate station has been considered. After a comparison analysis brought on with the other groups the on-site refinement proposed has been selected as the easiest and most advantageous solution.

C. Transportation and storage system

The main transportation system for the extracted ore is hydraulic. The water is brought on the asteroid from Earth by the spacecraft and flows in extendable pipes that connect the boring machines and the processing unit inside the station and then the refining separator with the tanks. Pumps modelled from the ones operating in ground mining are implemented to keep the water flow [23]. The water cycle of the mine is a closed one and it includes also the water coolant system for the boring machines.
The final products of the mine are stored in inflatable tanks on the outside wall of the mining station. The selection of inflatable storage allows for mass and volume reduction, while the tanks are filled with processed ore they expand to the outside so there's no need to include their volume inside the spacecraft.

V. Astronauts Operation

Before developing a task schedule for humans during their stay at the asteroid, a rough estimation of the available hours of EVA was needed. Our crew is composed by 3 members and they will stay at the asteroid for 112 days. We assumed that astronauts will need 2 days at their arrival and 2 days before leaving in order to dock/undock to the mining station, therefore 108 days of work time are available. One of the crew members needs to direct operations from the asteroid due to the communication lag caused by the huge distance between the asteroid and the earth, that leads to a 70 seconds delay. Having said that, only 2 astronauts can perform EVAs at a time. Before performing every EVA astronauts need to prepare their body, the suit and every tools (pistol grip tool, tetherer, e.c.) that he is going to use during work operations. Therefore we assumed that between two consecutive EVA 3 days are needed, considering as well a day to let astronauts rest. Looking at the ISS data, it is possible to find out that a reasonable EVA duration is close to 7 hours. Taking everything into account, 378 hours of EVAs are available during the whole 112 days at the mining facility.
Once that the amount of EVA time is available, the goal is to develop a work schedule. First of all the inflatable ore tank needs to be deployed. Following that, the regolith mining system needs to be started. In order to find out what needs to be done to start the mining operations, terrestrial mining systems have been considered. Both mining systems need to be positioned and then attached to water pipes and wires. In addition, the gravity of the asteroid is quite negligible, astronauts thus needs a reliable way to move and to tether along the drilled shaft, therefore an handrail is required.
Knowing tasks and the amount of time available it is possible to develop a work schedule. Operator 1 (OP1) and Operator 2 (OP2) are the astronauts performing EVAs, while Operator 3 (OP3) stays inside of the mining station directing operations and controlling machinery. The following list shows the operation phases and their duration. In every phase the different tasks are shown

together with who accomplish them and how many hours of EVAs are needed.

a. Setup operation (28 days)
   1) OP1 and OP2 deploy inflatable ore tank (28h)
   2) OP1 and OP2 position SHaft boring machine (SBM) (35h)
   3) OP1 connects SBM to power system (7h)
   4) OP2 deploys the SBM water pipes (14h)
   5) OP3 starts the SBM and turns on the refineries
b. Shaft boring machine (SBM) drilling (52 days)
   1) OP1 deploys and starts the regolith mining system (63h)
   2) OP2 installs handrails along already drilled shaft (63h)
   3) OP3 stops the SBM and turns off the refineries
c. Reef boring machine (RBM) set up (28 days)
   1) OP1 unplugs the SBM and collects its pipes and wires (14h)
   2) OP2 deploys and positions the RBM(49h)
   3) OP1 lays RBM electric cables and connect them to the power system (14h)
   4) OP1 connect the RBM to its cooling system (14h)
   5) OP3 starts the RBM and turns on the refineries

The amount of EVA hours scheduled is 301, out of the 378 available. The remaining EVA windows are spread along the 3 different phases to overcome malfunctions and incorrect work time predictions.

VI. Risk assessment

Risk Analysis is a process that helps you identify and manage potential problems that could undermine the mission goal and increase the costs by a huge amount. To carry out a Risk Analysis, you must first identify the possible threats that you face, and then estimate the likelihood that these threats will materialize. In order to do that we created table VIII which rates from 1 to 5, the impact of a potential risk in two different ways: schedule delay and cost. The overall risk rate is the average between the two values. The final risk value, found in table IX, is the product between mean risk value and probability.

Looking at the different final values we can see which unfortunate events we should focus on, with the highest rated risk being more dangerous for the mission. The most dangerous off-nominal case is the docking ring tethering failure, which can be handled by adding a secondary anchoring system. Other high-risk situations are the SBM failure and its cutter breakage. In both cases the unscheduled hours of EVA should be used to repair the system, therefore a crew member needs to know deeply the machine. The EVAs director should also have a overall knowledge of the mining station subsystems, allowing him to repair them while the other crew members are getting ready to go outside. In case of an astronaut light injury that will prevent him from doing EVAs, the operation director should swap its job with the injured crew member. If a cargo s/c failure happens during the outbound trip, a back-up should be kept ready for departure. In case of a failure during the return, if the payload may be saved a recovery mission should be organized. If the RBM stops, which is still quite unlikely, there are not so much options to follow because of the absence of astronauts on the mining station. A reasonable option could be developing a debugging software, that may be able to resolve minor failures. Lastly, if the mining or refining speed is slower than expect it would be enough to delay the cargo return, causing only a shift in the timeline, but still not endangering the mission completion.

TABLE VIII
Risk Values

Rate	Cost	Schedule Delay	Probability
1	0-10M	7 days	1%
2	10-100M	8-30 days	1-3%
3	100-500M	30-60 days	3-5%
4	500-1B	2-6 months	5-10%
5	1B+	>12 months	>10%

TABLE IX
Risk Analysis

Risk	Cost	Schedule delay	Probability	Final value
Tethering fails	5	5	3	15
Subsystem damaged during travel	2	2	2	4
Landind site non available	3	5	1	4
SBM failure	4	5	12	9
SBM cutters breakage	3	1	4	8
RBM failure	5	5	1	5
Astronaut gets injured	3	5	2	8
Mining speed lower than predicted	1	2	3	4.5
Cargo s/c failure	5	3	2	8

VII. Time Schedule

The timeline for all the on-site logistics-related operations can be found in figure 9 in the appendix.

VIII. Mass and Power budget

Table X and Table XI show the overall mass and power budget estimation of the mining equipment needed for the mission.

TABLE X
MASS BUDGET

Subsystem		Mass [Kg]
Rock Mining	Shaft boring machine	8 000
	Reef boring machine	2 000
	Pumps and pipes	500
	Water tanks (full)	1 121
	Ore refining machinery	2 500
	Ore tanks (empty)	2 000
Regolith mining	Regolith Rovers	350
	Propellant Production Facility	3 900
	Cryogenic Storage Facility	2 500
Structure	Fuselage	6 380
	Landing gears	2 400
	Anchoring system	3 000

TABLE XI
POWER BUDGET

Subsystem		Power [kW]
Rock Mining	Shaft boring machine	40
	Reef boring machine	10
	Pumps and pipes	5
	Ore refining machinery	5
Regolith mining	Propellant Production and Storage Facility	11.8

IX. Conclusion

In this project, the logistics team focused on adapting on-Earth mining systems for space purpose and on using technologies from already operating spacecraft, in order to present a coherent mining station in term of technology readiness level, cost and durability. However, as asteroid mining is a new concept, some technologies that are used are still under development. For instance, the suggested tethering system would be the bigger ever designed for a spacecraft. In parallel, the team had to focus on off-nominal scenarios, including redundancies and safety margins to fulfill the objective. Active communication was done with the other groups to advance in in the team work. A retroactive method was often used to match the requirements or preferences of each group, thus resulting in an optimal system.

X. Division of work

The writing of this report was done by every member of the group. The high-level decisions, e.g. the mining architecture, have been made together and were based on literature research conducted in parallel. The consecutive tasks have been shared equally between the team members. Alexander mainly worked on the concept of the regolith mining. Florian looked for the asteroid composition and drew the timeline of the operations. Harparan studied the mining methods to come up with the shaft and reef drilling machines. Marco focused on the astronaut operations as well as the tethering systems. Finally, Martina designed the refining systems and the tethering systems.

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APPENDIX A
ON-SITE OPERATIONS TIMELINE

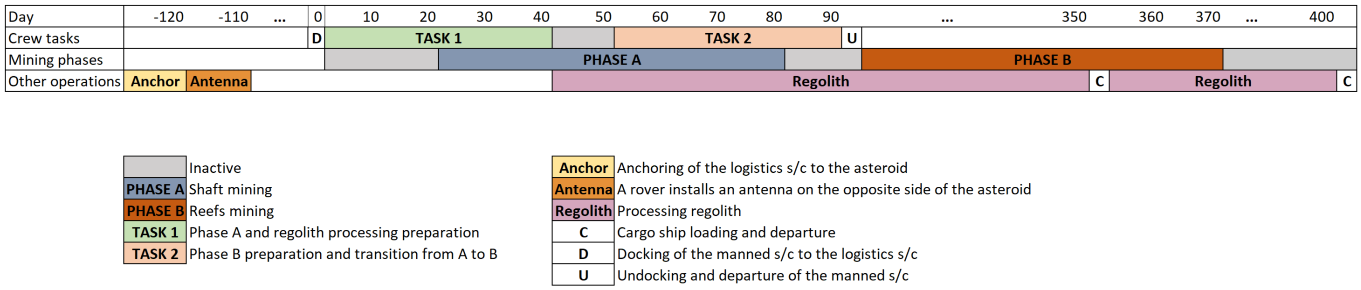

Fig. 9. On-site operations timeline