Human Spaceflight Project - Team Blue - Mission and Logistics Report

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***Abstract*—In this article an investigation of the Asteroid Kamo'oalewa, also known as 2016 HO_3 was done to set up an on-site mining system. Platinum group metals present in the surface layer of the asteroid were chosen to be mined and a suitable system for a micro-gravity environment was chosen. The system, consisting of a canopy, remote controlled robots (RASSOR), and annex systems that are installed on the asteroid with a processing station for the refinement of the mineral, was designed to create an autonomous mining station. Different parts of the system were then examined, like the power and mass budget and the set-up of the station by a human mission. With the created mining solution the mining outcome will be 50 t of refined material that will be transported to earth yearly. In the future the design of the canopy and the interaction of the robots, the canopy and the processing station require more research to test it in a space environment equal to that on the asteroid.**
Other mission details consisting of the used spacecraft, the human life support system and the overall coordination can be found in the articles of the project group of Team Blue.

***Index Terms*—Asteroid, 2016HO3, Kamo'oalewa, Mining, Processing, RASSOR, Mirror melting, Canopy.**

I. Introduction

NOWADAYS the demand of rare minerals like palladium, platinum and rhodium have increased due to the usage of them in the industry, like for auto-catalysts or electrical devices, and for the production of jewellery. Looking back on the development of the demand palladium had a production volume of 110 t per year in 1990 and 280 t per year in 2000. Main mining sides on earth are located in South Africa, Russia and North America. The output is usually very low with a content of only 4 - 10 g/t. Additionally the mining is associated with great technical, financial and political risks from geological and technical problems. Some mines can only be exploited while additionally mine another resource like nickel in one of the Russian mines [1]. Asteroids enable another way to mine rare materials with their large source of minerals and can open new ways for future exploration [2].
This article is showing a way to mine a Near-Earth Asteroid to extract rare Earth materials out of the Platinum Group Materials to bring them back to Earth instead of mining them on the Earth. The focus is on the mining solution using the regolith on the asteroid and having an additional refinery station on-site for an affordable transport of the material. The concept is based on a conceptual design of a canopy that is anchored to the asteroid and collects the regolith underneath it [3]. It is combined with a power station on the asteroid surface inside of the canopy and two robots that will mine the regolith. For the on-site processing a station is located at the top of the canopy to refine and store the rare materials. The set-up of the system is done with a human mission followed by an autonomous mining and processing with yearly cargo spacecraft round trip to bring back the material.

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II. Asteroid characteristics

THE 469219 Kamo'oalewa asteroid, also known as 2016 HO_3, is a S-type near-Earth object with a stable quasi-satellite position to earth. It has a diameter of approximately 41 m. The length is not confirmed but is between 40 and 100 m long. The asteroid rotates around its axes with a rotation period of 0.467 $\pm$ 0.008 hours. Therefore the asteroid is classified as a fast rotational body [4]. With these data it is assumed that the asteroid has a length of 100 m.
The classification as an S-Type asteroid indicates a stony material. Referring to Badescu it consists of silicates, sulphides and metals and an anhydrous rocky material [2]. The composition of an S-Type asteroid can consist of up to 80 % iron and 20 % precious metals, like nickel, iridium, palladium, platinum and more. Some can have a mixture of silicates and metallic materials [5]. It is assumed that the 2016 HO_3 is mainly out of iron (30 %) and magnesium-silicate (55 %). The materials that will be mined and refined are platinum (10 %), palladium (2 %) and rhodium (1 %) and some other rare materials (2 %). They are materials of the

Platinum Group Metals (PGM). Main usage of PGMs is in the automotive industry for catalysts, in the electronic industry and for the production of jewellery. The density of the asteroid is calculated to be 5500 kg/m^3. With the diameter and the length the Volume can be estimated to be 132025 m^3. Using this prediction is setting the quantity of platinum to 283800 t, palladium to 31700 t and rhodium to 16400 t in the whole asteroid.
The sphere of influence of the asteroid is calculated with the semi-major axis a, the mass of the asteroid m_A and the mass of the sun m_S. with the equation

$$r_{SOI} = a \cdot \left(\frac{m_A}{m_S}\right)^{\frac{2}{5}} = 398.4\ m \quad (1)$$

and the values 1.0011 AU for the semi-major axis, $7,26 \cdot 10^8\ kg$ for the mass of the asteroid and $1,989 \cdot 10^{30}\ kg$ for the solar mass [6][7][4]. The gravitational force of the asteroid can be calculated using Newtons equation

$$g = G \cdot \frac{m}{r^2} = 5.38 \cdot 10^{-5} \frac{m}{s^2}, \quad (2)$$

which leads to a gravitational force of $5.38 \cdot 10^{-5}\ m/s^2$ for the mass of the whole asteroid in the distance of 10 m and a radius of 20 m until the centre of the asteroid. The universal gravitational constant G is $6.6726 \cdot 10^{-11}(Nm^2)/kg^2$. Because of the small value for the gravitation the influence on the equipment is negotiable and a micro-gravitational atmosphere is assumed.

III. Mining process

HERE are the details of the mining process presented. An overall view of the system and its working principle is presented before going in detail on the process that was used to design each components of the solution, using the software *Autodesk Fusion 360*. Only the 1 m deep regolith is going to be processed in this design, as it is easier to mine and process. Indeed it is already in a form of small particle (dust), hence there is no need to crush it further which simplifies the design and lowers the power needed to mine. At the end of this part, a budget will be set for the power and mass in order to fill the overall power and mass budget to later create the power system and give the overall mass budget for the mining equipment to the space vehicle group. The TRL (Technology Readiness Level) is also going to be mentioned in each subsection for the concerned part, based on scale described in [8] .

A. Operation principle

First of all, Figure 1, shows the overall system installed on the asteroid (grey floor). Each subsystem will be described in detail in later subsections. Here the

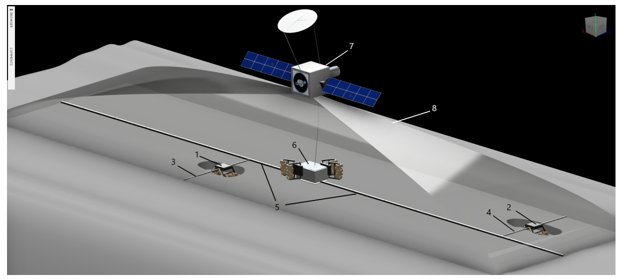

Fig. 1. Assembled design

global principle is going to be explained. At the start of the mission, the components are send in a cargo spacecraft (see space vehicle report), and assembled by humans on site when they arrive. Once that is done, the mining starts. It is now needed to decompose the previous figure in different views in order to have a better understanding. Also, in A, Figure 1 is presented in a bigger format for the viewer if needed.

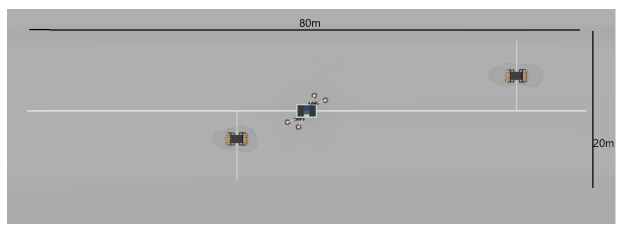

Fig. 2. Assembled design, view from above

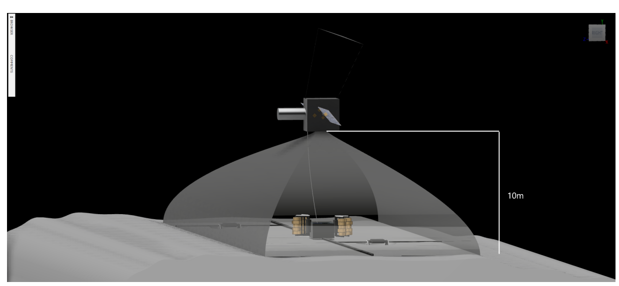

Fig. 3. Assembled design, view from the side

Figures 1, 2 and 3 show the position of the robots (1 and 2) on their rails (3 and 4). The robot's rails can be moved throughout the mined surface thanks to the main rail (5) that passes through the power station (6). The blades of the robots are designed to lift the regolith while aiming at the processing station (7) since the gravity of the asteroid is negligible (see part II), the regolith is going to travel based on the momentum given by the blades of the robot. The canopy (8) ensure that the lifted dust is guided towards the processing station (This is an assumption made during the design, next step of the research process would be to ensure a canopy design that has the ideal shape for supporting the regolith flow). Once the regolith is close to the processing station, a capsule is going to open and fill before closing back inside the processing station for further processing (see part IV for more details). Two more robots (9 and 10) are brought for redundancy in case of failure. The canopy, power station, and main rail (5) are fastened to the asteroid with an anchoring system, more details about this in the subsection III-F. The details for each major component, such as the rails, the robots, the canopy and the power station are going to be explained in detail in their own subsection.

B. Canopy

The canopy presented in the previous figures was transparent for viewing purpose. However, in the design process, its material has been chosen as being a carbon fiber silicon resin for its property. Indeed, since this component is going to be fold during shipment and mounted on site (see subsection VI-B) it needs flexibility, hence silicon is chosen a a suitable resin. Its dimension are going to be 4 mm thick, 80 m long, 20 m wide and 10 m high, as shown by Figure 4, giving an overall weight of 14.4 t with a 20 % margin. Its TRL is probably the lowest of the system, as it is between 3 and 4 right now. This idea is inspired by a concept found in [3]. Figure 4 also shows the geometry of the component with its 1x1 m opening at the top for the processing station. It is also important to note that a guiding system for the

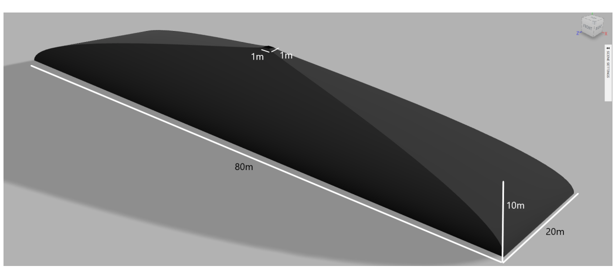

Fig. 4. Canopy design

robot's rail (3 and 4 on figure 1) is needed at the bottom of the canopy but not showed on Figure 4. Last but not least, the canopy is anchored thanks to 10 harpoons: 4 on each 80 m sides plus 1 on each 20 m sides. The dimensions of said harpoons are dependent on the mass of the canopy. The design process of these harpoons will not be covered in this paper, the technology however will be described, as said before, in section III-F.

C. Robots

The robot design is inspired by the design of the Regolith Advanced Surface Systems Operations Robot (RASSOR) 2.0. This robot is planned for a mars mission and consists of two bucket drums in the front and back connected to a mobility platform. It has a mass of 66 kg and an average velocity of 27 cm/s. Its dimensions are $1.9\ m\ x\ 1.5\ m\ x\ 3\ m$ The two bucket drums can excavate a mass of 2.7 $metrictons/day$ with a power of 4 W/kg of regolith. They rotate in opposite directions to enable counteracting excavation forces what leads to a net zero horizontal excavation force. It is therefore suitable to work in a low gravity environment. A day of excavation consists of 16 hours of mining and 8 hours of recharging at a power station. On board of the robot is a stereo and hazard camera that will scan the surface and create a virtual map for the mining, these characteristics and the robot are detailed in [9].

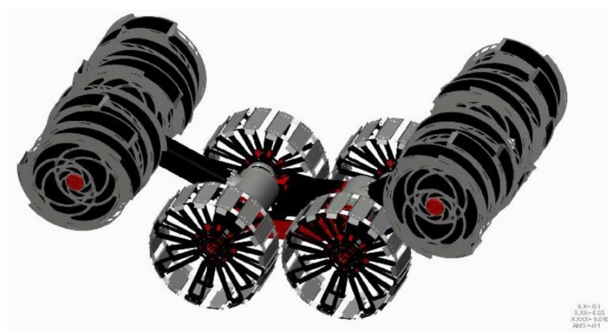

Fig. 5. RASSOR 2.0 CAD model

Because of the different conditions on the asteroid (i.e. with almost no gravitational force compared to the gravitation on mars) the design of the robot needs to be adjusted to these conditions. Fist change is at the collection of the regolith. For RASSOR it is collected inside of the bucket drums and transported to a station where it can be deposited at the lander. In our case the regolith storage inside the drums is not necessary because it is planned to scoop the regolith upwards inside of the canopy with a sufficient velocity to collect it at the top of the canopy. Hence the scoops will be constructed to give the optimal upward drift for the mined regolith. It is assumed that the drums are turning with the same velocity as on mars and the mining output

Fig. 6. RASSOR 2.0 CAD model, adapted

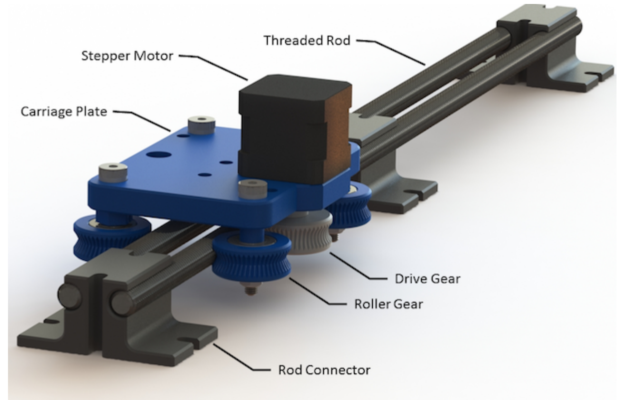

Fig. 7. Rail mechanism

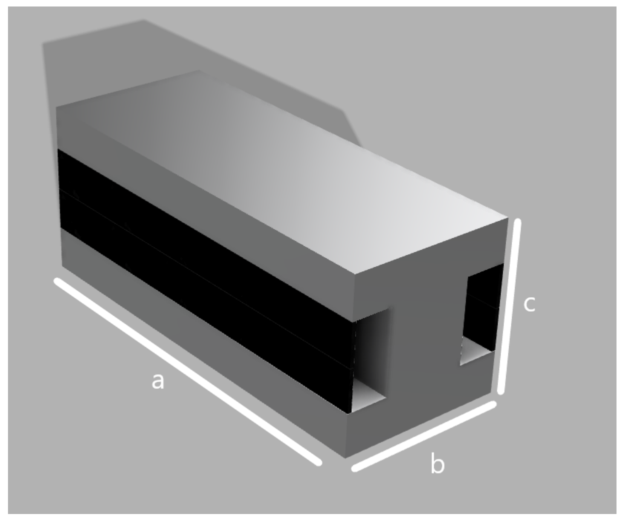

Fig. 8. Rails CAD

is approximately 20 % of the RASSOR 2.0 excavation rate.
With a different design the scoops loose their self-anchoring ability. So to ensure that the robot still have a sufficient contact to the asteroid surface the platform of the robot is mounted on a rail that is connected with the canopy as showed by Figure 1. The rail replaces the wheels which can be deconstructed and hence, the design from Figure 5 becomes the one presented in Figure 6. Also, the robots can lift themselves using their mining arms to reach the power station. As seen on Figure 1, the redundancy robots are fixed to the power station, using a locking mechanism. If however one of them is needed, the power station control unit would unlock it and bring the rail under itself so that the robot can fasten himself onto the rail.
The RASSOR 2.0 has a Technology Readiness Level (TRL) of 4 regarding the article by Mueller in 2016 [9]. It is assumed that the TRL in 2020 will be higher for the RASSOR 2.0 but considering the changes in collection and motion the TRL is taken to be equal.

D. *Rails*

In this subsection, the rails 3,4 and 5 from Figure 1 are presented. However the movement mechanism between the rail 3, 4 and the robot 1 and 2 plus between the robot's rail 3, 4 and the main rail 5 is not going to be detailed. Nonetheless, the mechanism can be assimilated with the one in Figure 7 with internal gear instead of external gear (N.B. Roller and Drive gear would be between the two threaded rod in the case of the system presented in this paper). The reason for that is to protect it from regolith particle that could block the gears like with the presence of a seal, visible in black on Figure 8. The dimensions a, b and c are dependent on the rail, see table I. Using this table and the fact that the

TABLE I
RAIL DIMENSIONS

Rail number	a (m)	b (m)	c (m)	Quantity
3 and 4	5	0.1	0.1	2
5	5	0.2	0.2	16

rails are made out of aluminium, the total mass of the rails is 3.1 t with a 20 % margin. The reason for the 5 m length in this mission is the volume of the cargo spacecraft, as transporting an 80 m rail in one piece is not feasible, it has been chosen to decompose it in 16 parts of 5 m, which is easier to handle. Hence some assembly operation will be needed on site, as described by sub part VI-B. Using the same anchoring process as for the canopy, one harpoon per main rail piece is going to be used. However for the robot's rail, a guiding mechanism will be installed on the face of the canopy as they need to translate over the surface mined. The TRL level of this system is between 7 and 8, as it is already used on earth but still need to be tested in space.

E. Power station

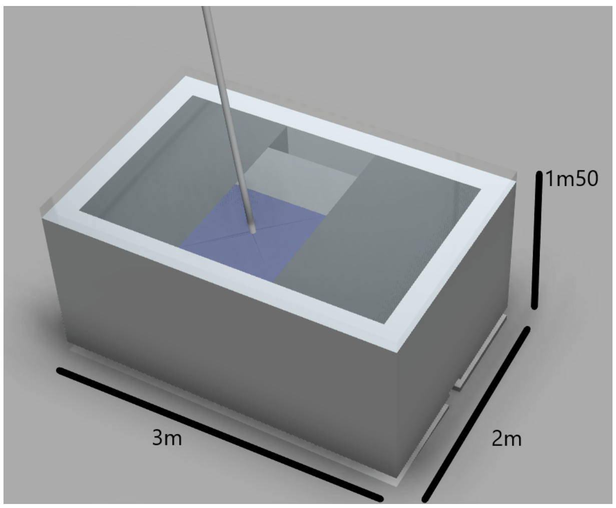

Fig. 9. Power station

The power station shown by Figure 9 is going to be the first part anchored to the ground by the astronaut using the harpoons. It contains the control unit (blue), the communication unit (grey, N.B. no communication antenna is present on the figures but it is still included in the mass and power budget), the emergency batteries (dark grey, see part V for more details), the charging system (not shown) for the robots and the locking mechanism for the redundancy robots (not shown). A lid is covering the whole system (transparent here for viewing purpose but made out of aluminum) so that no regolith particle can penetrate the modules. A wire linking the power station to the processing station is going to bring power from the solar panels to the robots while they are on charging mode and the various units on the surface of the asteroid. The mass of this whole unit is going to be $0.12\ t$ given its dimension and that it is made out of aluminum.

F. Anchoring system

In this subsection, the applied anchoring system is going to be described. The harpooning system, shown by Figure 10, is picked from the Rosetta mission [10].

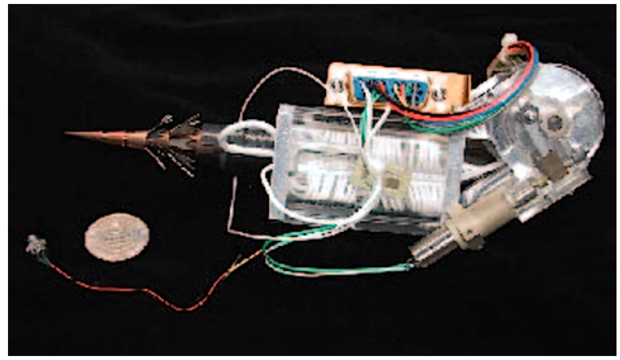

Fig. 10. Harpoon technology

The design process, as mentioned earlier, will not be covered in this paper. Nonetheless, 27 harpoons will be needed for the canopy, main rail and the power station. Its total mass is within the 20 % margin of every other system. Since this technology has already been used in space, its TRL is already really high with a level of 9.

G. Power and mass budget

With the quantities given in the previous sections, the overall mass and power budget for the mining equipment is compiled as seen in Table II. The values are used for the sizing of the power system that is needed for the whole mission. The total mass is given to the space vehicle group to choose a suitable spacecraft for the transportation of the equipment. Rails are not consuming any power in this calculation as the power consumption to move in a μG environment is considered negligible compared to the power consumption for mining. Also the mass and power in this table has already a 20 % margin applied to it.

TABLE II
POWER AND MASS BUDGET FOR MINING EQUIPMENT

Component	Quantity	Mass (t)	Power (kW)
Canopy	1	14.4	-
Robots	4	0.32	5.2
Rails	18	3.1	-
Power station	1	0.12	0.2
Harpoons	27	Within margin of other components	
Total	**-**	**17.94**	**5.4**

IV. PROCESSING SOLUTION

TO maximize the amount of rare metals that can be transported back to earth, the mined regolith will be processed on site, to refine it to up to 80% rare metals. A processing Station will be directly fixed to the top of the canopy, and it will process the raw mineral as explained in the following subsections. To keep the processing station as light as possible, a mass budget was determined, and the table below shows the mass of its different components:

TABLE III
MASS OF THE SUBSYSTEMS

Mass of subsystem (t)	
Mirrors	6
Centrifuge	1
Spectrometer and cutting laser	0.4
Packaging and transportation equipment	0.6
Total	**8**

A. Packaging by mining robots

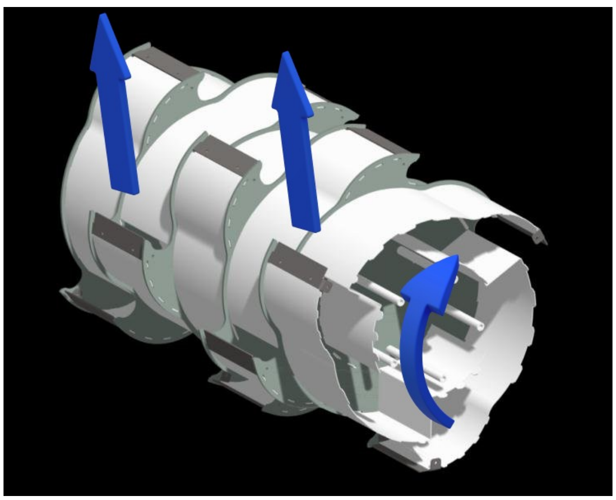

Fig. 11. Bucket of the RASSOR robot projecting regolith to the canopy

As explained in the mining process, the robots will mine the regolith and throw it upwards to the top of the canopy. The mined regolith travels up to the canopy and accumulates at the entry of the processing station. It is then packaged into cylinders of about 40 kg of regolith and inserted into ceramic containers, which will contain the raw mineral when it is melted.

B. Melting of raw material

THE packaged regolith in ceramic containers will then be melted to continue the processing. Parabolic mirrors are pointed towards the ceramic containers to heat the raw mineral. Those mirrors are anchored to the asteroid and are about 100 m from its surface to maximize sun exposure. To melt the mineral, a temperature of about 1550 $^{\circ}C$ is needed, which means an average power of 10 kW will melt 1 t of regolith per day. To achieve this, there will be 16 parabolic mirrors of 1 m^2, for redundancy, which will have a peak power of 20 kW and melt one ceramic container in 30 min, to allow time for the following steps of the processing.

C. Separation in centrifuges

Once the regolith is melted, the ceramic containers are inserted into a centrifuge to separate the rare metal from the other components. Because of the very high difference between the density of the different minerals in regolith, as shown in the table below, rare metals with a higher density will accumulate at the bottom of the ceramic containers because of the centrifugal force. To reduce stress and wear on the canopy, there will be 2 counter-rotating centrifuges.

TABLE IV
DENSITY OF THE ASTEROID COMPONENT

Density of the asteroid component	
Magnesium silicate	2 g/cm^3
Iron	7.8 g/cm^3
Palladium	12 g/cm^3
Platinum	20 g/cm^3

The centrifuge will generate a centrifugal force, which acts as gravity, and rare metals will sink at the bottom of the container while lighter materials like silicate and magnesium will be at the top. An example is illustrated in the figure below, where the red particle is the rare metals, still in solid state at 1550 $^{\circ}C$, in the melted regolith, in blue. The separated sample will then cool down and solidify before the last step of the processing.

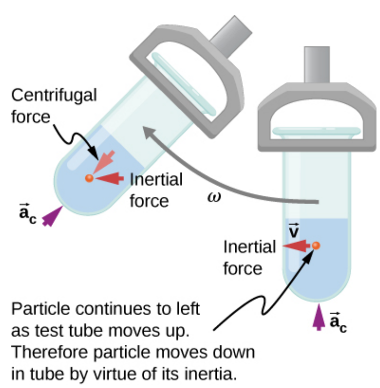

Fig. 12. Separation of rare metals in centrifuge

D. Detection and cutting laser

The solidified sample is then passed through a spectrometer, which detects where the rare metals begin, as to not miss any of them. It then sends the information to a laser which cuts the sample at the right position to keep only the rare metals.

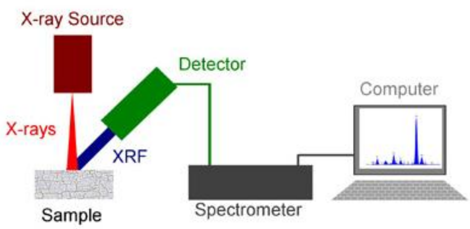

Fig. 13. Spectrometer

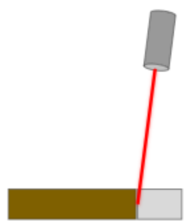

Fig. 14. Laser cutting

The processed metals, in a cylinder shape, are then transported to the docked cargo to be stored until departure.

V. Power system

A. Power budget

RASSOR robots have a nominal power consumption of 4 W/kg of mined regolith. This means, with two robots working full time, a power of 5.3 kW is needed. For telecommunications the estimated power consumption is 200 W and for the processing station 300 W. Subsystems and electrical actuators need an overall power of 200 W.
Adding a 20 % margin to the aggregate for security and the degradation of the system over time, it results in a total power consumption of 7.2 kW.

B. Solar arrays

The solar arrays are attached to the processing station on top of the canopy. This solution is taken to have a full time sunlight on the panels.
AZUR SPACE Advanced Quadruple Junction GaAs Solar Cells are the cells chosen for the arrays. They are 30.18 cm^2 cells with a nominal efficiency of 32 %, this means a 1.3 W production per cell (Equation 3, $irr = 1.37\ kW/m^2$ is the solar irradiance, with eff as cell efficiency and ca as the cell area).

TABLE V
POWER CONSUMPTION OF EACH SYSTEM

System	Power Consumption (W)
RASSOR	5300
Communications	200
Processing Station	300
Subsystems	200
Security Margin	20 %
Total	**7200**

$$cpp = irr \cdot eff \cdot ca \tag{3}$$

To get the 7.2 kW needed a total of 6570 cells are used . This number includes a 20 % margin for extra security and array degradation.
The resulting system is two 10 m^2 arrays (5 m x 2 m) with a total mass of 40 kg with structure and harness.

C. Batteries

Since solar arrays are constantly operative, there is no need for an energy storage system. However an emergency battery has been implemented to keep the system safe from off nominal power deficiencies. It is charged with the solar arrays power surplus and intervene in eventual anomalous cases where the needed power is higher than the power supplied by solar arrays.
A next generation lithium-sulfur dioxide battery has been chosen, with its extremely high specific energy of 500 Wh/kg, a cell of 50 kg is mounted with an energy capacity of 25 kWh.

D. System Overview

For the processing unit, common spacecraft wires are used to transfer the power from the arrays. To connect the solar power system to the surface facility a 10 m long cable goes from the processing unit to the surface of the asteroid, into the power station. Here it powers the communication unit and, through a system of wires passing inside of the rails, brings power to the robots and electrical actuators.
The total estimated weight of this system is 150 kg.

TABLE VI
WEIGHT OF SOLAR ARRAYS AND WIRES

Part	Mass (kg)
Solar Arrays	40
Emergency Battery	50
Harness	60
Total	**150**

VI. SYSTEM SETUP

IN this section the mission phases of the asteroid mining mission are explained including the set-up of the mining and processing systems and the further plans for the transport of the refined material. Additionally the task done by the human mission are presented.

A. Mission phases

The first launch is the cargo vehicle that will transport the mining equipment and the refinery station to the asteroid. It will travel for ten month and will arrive in 2032 at the asteroid. It will follow the trajectory of the asteroid in a safe distance until the human mission will arrive around one year later in 2033. After setting up the system for 18 days the human space vehicle will begin its journey back to earth and the mining process starts. One year later the cargo vehicle that once transported the mining and refining equipment will transport the first refined material back to earth. A second cargo vehicle is scheduled to arrive before the first cargo vehicle leaves to directly start storing the next mining outcome.

B. Human schedule on asteroid

The human mission will set up the canopy including the robots and the power station on the asteroid. The fist step is to install movement aids for the astronauts to move on the surface (see Table VI-B). Then the power station is anchored to the asteroid. From that point the rail can be connected to the power station along the length of the mining area. Next step is the fixation of the canopy and anchoring of it with the harpoons. The rails carrying the robots are then installed between the canopy and the main rail. The processing station does not require any further work from the astronauts. The last step is the installation of the canopy. Here the canopy is lifted to the station above and connected to the collection point of the processing station.
A schedule of the astronauts work on the asteroid can be seen in the table below.

TABLE VII
OPERATION SCHEDULE FOR HUMAN MISSION

Days	Operation
1-3	Installation of movement aids (poles and ropes)
4-5	Installation of the power station
6-9	Installation of the main rail
10-12	Fixation of the base of the canopy
12-13	Installation of RASSOR rails
14-16	Lifting and connecting the canopy to the processing unit
17-18	Testing and troubleshhoting

VII. MINING OUTPUT

A. Valuable materials

With the size of the canopy and the depth of the regolith of 1 m the volume of regolith under the canopy is 1575 m^3. This correspond to a mass of 8800 t. It is planned to send one cargo ship per year with a mass of 50 t refined materials. Assuming that the 15 % of rare materials are separated from the centrifuge, an amount of 350 t of regolith is needed to gain this output. considering that the centrifuge and the laser cutter are unable to separate the PGMs completely from the iron and magnesium-silicate, the proportion of PGMs will be approximately 80% after the refining process.

B. Storage

A storage tank is connected to the processing station. Inside of the storage area is a shelf installed which is designed to fit the cylindrical shape from the centrifuge operation. Each tube can carry several samples in a row. Transportation is done by a robotic arm form the laser cutter directly to the storage area. It pushes the samples inside of the tubes. When the cargo vehicle arrives it docks at the storage area. The material is then pushed inside the vehicle for the transport. The materials that will not be transported back to earth will be ejected from the processing station into an orbit that will not collide with the asteroid or the cargo spaceships visiting the processing station.

VIII. WHAT IF CASE: IMMOBILIZED ROBOT

AS the robots are working in deep regolith, the chances for a robot to get stuck during the mining are high. In this case a backup system will help to free the robot out of the regolith. Therefore the second robot is able to move with its rail from its side to the other side of the middle rail towards the stuck robot. it is then moving close to the robot and start digging around it to help remove the regolith. If the operation requires to dig from both sides of the immobilized robot the helping robot needs to change the side of the rail again to pass the rail of the immobilized robot and then return to the same side.

IX. Conclusion

To conclude, this report presented the logistics of the human spaceflight mission given during this course. The asteroid was assumed to contain rare metals such as platinum and other platinum group metals (PGMs), and the mission was designed based on those assumptions. First, a mining solution was designed to mine the precious metals in the space environment. Second, a processing solution was designed to refine platinum and other PGMs on site. Third, an off-nominal case was investigated to prove the robustness of the mission and its back up features. Finally, an overall logistics analysis, such as mass budget, power, operations and waste disposal was discussed.

The resulting mass and power of the final mining solution are summed up in Table VIII. The operation produces 50 t of refined materials in a year with a percentage of 80 % PGM. The mission is planned to last as long as it is profitable to mine the asteroid. The mass of regolith would enable a duration of 26 years, but it is assumed that parts of the system like the robot will not last that long and a future human mission could be expected for maintenance and replacement of critical component that are subject to wear.

TABLE VIII
Mission's power and mass budget for logistic

Component	Mass (t)	Power (kW)
Mining System	14.4	5.4
Processing system	8	0.3
Power system	0.15	-
Total (with 20% margin)	**27.06**	**7.2**

Further research is necessary to the concept as it has not been tested in micro-gravity before. Also the design of the canopy, the robots and the rails have to be tested and their TRL has to be increased in the future to make them suitable for this mission.

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Appendix A
Design of the mining and processing station

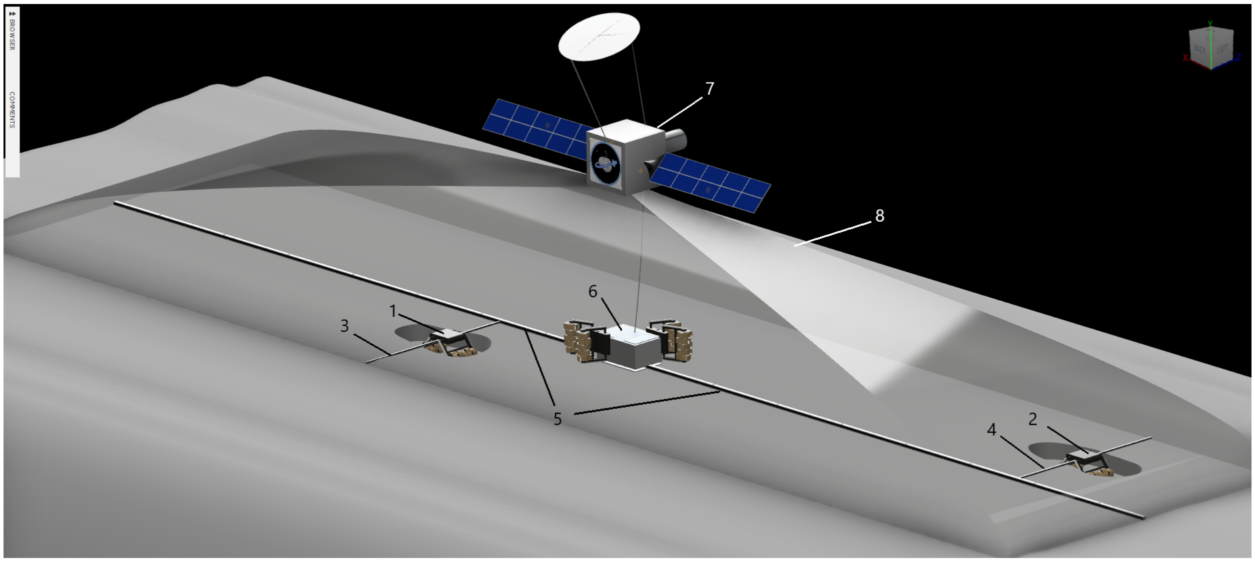

Fig. 15. Assembled design