BENEFICIATION OF REGOLITH AND MOBILE EXCAVATION (TEAM BREMEN)

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Space exploration is advancing rapidly, and further steps such as the establishment of habitats on other planets and space missions from the Moon to Mars are expected. Limited resources are among the greatest challenges that must be overcome to enable extraterrestrial life. To promote scientific approaches in this direction, ESA has organized the second Space Resources Challenge. The challenge scenario is set for a future human mission to the lunar surface that would require oxygen for life support and other systems. The quantity is scaled down to a feasible field test scenario where a specific regolith size distribution is to be produced to support in-situ oxygen production activities. The teams are therefore required to excavate 15 kg of regolith and beneficiate it into different fractions of the desired particle size distributions. The primary feedstock expected is the fraction with a particle size range of 100 – 500 µm. Eight teams are participating in the challenge which involves the demonstration of the technology in a field test within the constraints of total system mass, energy consumption and operation time. Team Beneficiation of REgolith and Mobile ExcavatioN (BREMEN) is one of the participating teams with researchers from DFKI, DLR e.V, and University of Bremen. The proposed solution consists of two independent systems: a mobile excavation system and a stationary beneficiation system. The mobile excavation system is comprised of customized excavation and delivery mechanisms to collect and transfer the regolith to the stationary beneficiation system that shall process it into the desired particle fractions. The field test for validating the technologies shall take place at the lunar analog facility LUNA in Cologne, Germany. This paper presents the system architecture and subsystem designs for Team BREMEN's solution along with preliminary experimental validation for the selected designs and the next steps for continuing research to support the ESA Space Resources Strategy.

1. INTRODUCTION

The development of In-Situ Resource Utilization (ISRU) space technologies has a critical priority for long-term human space exploration missions. A resupply of resources from Earth to Moon, Mars or other planets is unsustainable for long term operations. The utilization of in-situ resources to satisfy these demands is clearly the feasible solution for a sustainable long-duration exploration campaign.

Prospecting, excavation and beneficiation technologies for lunar regolith are among the most relevant enabling technologies for downstream processes such as water extraction, oxygen production, metal extraction, solar sintering or additive manufacturing. While different technologies for oxygen production exist, a particularly interesting application is the oxygen production and metal extraction via molten salt electrolysis. The process involves immersing powdered lunar regolith in a molten salt bath, which acts as an electrolyte at high temperatures. Applying electricity, oxygen is extracted from the regolith oxides and migrates through the molten

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salt to the anode, where it is evolved as oxygen gas, while reduced metals remain at the cathode [1]. In this context, autonomous or semi-autonomous collaborative systems play a central role in the efficient exploration and extraction of resources and their beneficiation.

The Space Resources Challenge (SRC), initiated by European Space Agency (ESA) and European Space Resources Innovation Centre (ESRIC), is supporting the exploration and characterisation of resources found on the Moon (particularly water ice and regolith) and the acceleration of In-Situ Resource Utilisation (ISRU) technologies, in line with the objectives outlined in ESA's 2021–2027 Space Resources Strategy [2]. SRC's roadmap envisages the development and testing of technology for utilizing the space resources through competitions and supporting further technology developments of the proven solutions. The first Space Resources Challenge took place during 2021-2022[1] addressing prospecting of resources on the lunar surface.

The Second Challenge launched in 2024, aims to progress into collection and processing of the lunar regolith for further utilization[2]. Eight teams from Europe and Canada have been selected to participate in the field tests in October 2025 at the Moon analog facility LUNA[3]. The teams will demonstrate how their solution is capable of collecting the regolith and its beneficiation into fractions of the desired particle size distribution. Each team must, within 2 hours and 30 minutes, excavate 15 kg of regolith simulant and process it to obtain 5 kg of feedstock between 100 – 500 µm. The systems are evaluated under limits of time, weight ($\leq$ 60 kg), energy ($\leq$ 300 Wh), dust control, and overall reliability. The winning team will be awarded an ESA contract of 500,000 € for 12 months to do a feasibility study and further development of the technologies.

Team BREMEN proposes a modular mobile robot equipped with an excavation and collector unit to extract and deliver excavated material; and a stationary beneficiation unit to process the collected regolith into the desired particle size distribution. The separated system concept enables efficient workload distribution and straightforward integration at the field test.

2. STATE OF THE ART

Addressing the challenge entails the integration of several key subsystems, primarily the excavation system, the beneficiation system and the rover mobility platform, supported by auxiliary components including the regolith storage unit, the transport mechanisms linking excavation, storage, and beneficiation. Valuable references for these subsystems have been developed in competitive frameworks such as NASA's Lunabotics Challenge. Similar to ESA ESRIC SRC, NASA's Lunabotics Mining Competition is a US-dominated activity started in 2010 to support ISRU technologies[3]. Within the scope of this annual event, university-level participating teams develop solutions for tasks such as collecting and storing lunar regolith simulant using portable and autonomously controllable robotic systems[4]. These prior developments provide a technological foundation for the ESA ESRIC SRC 2025.

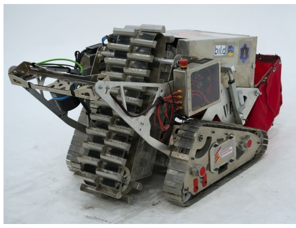
2.1. Excavation Concepts

The key task in excavation for the SRC lies in identifying an optimal solution under multiple performance constraints: sufficient excavation rate, low energy consumption, minimal system weight, reduced dust generation, and robustness against failures.

Several excavation concepts have been implemented in the context of NASA's Lunabotics Challenge (see Fig. 1). One concept is the bucket-based front loader 1a, where a shovel-like bucket is mounted at the front of the rover and actuated by a linear actuator to lift regolith into a storage container. Another concept is the belt-driven continuous excavation system 1b, in which small buckets mounted on a conveyor belt enable continuous excavation and vertical transport. Similar is the chain-driven excavation system 1c, where multiple buckets are attached to chains. NASA has developed the In-Situ Resource Utilization (ISRU) Pilot Excavator (IPEx) 1d as a prototype to investigate efficient regolith excavation methods for lunar operations [5]. The system employs a counter-rotating bucket drum mechanism, where two cylindrical drums with buckets mounted on their surfaces rotate in opposite directions. This configuration balances the reaction forces generated during excavation, thereby reducing the mechanical load on the rover mobility platform. In addition to surface penetration, the rotating drums simultaneously collect regolith and transport it toward the center simplifying subsequent handling.

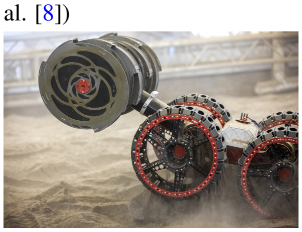
[1] First SRC Challenge: https://src.esa.int/the-challenge-2021-2022/
[2] Second SRC Challenge: https://src.esa.int/the-challenge-2021-2022/
[3] ESA-DLR LUNA Facility: https://luna-analog-facility.de/en/

(a) Artemis Grand Prize rover. (Image credit: University of Utah [6])



(b) KVHV rover prototype. (Image credit: Iowa State University News [7])

(c) Bucket-ladder excavator of 2013 Lunabotics competition. (Image credit: Lichtenheld et al. [8])



(d) Flat sieves schematic inside LES^3 robotic arm [9].

Figure 1: The state of the art excavation and transport solutions for ISRU regarding research works.

The above mentioned concepts each have specific advantages and limitations. The front loader concept features a simple structure and generates less dust; however, its excavation speed is limited. Additionally its long lever arm shifts the center of gravity forward and consequently reduces the overall system's stability. The belt and roller chain concepts enable high-speed and continuous excavation; however, accompanied by considerable dust generation. Belt-driven transmission faces considerable challenges in lunar environments due to the vacuum, abrasive regolith, and extreme thermal cycles. Roller chain or gear-based transmissions offer greater robustness and are considered more suitable for space. The Pilot Excavator–type drum system enables a large excavation area per rotation, but is restricted by shallow excavation depth, higher weight, and greater integration complexity.

2.2. Beneficiation Concepts

Many downstream ISRU processes rely on well-controlled feedstocks with tailored size distributions to optimize flow, reactivity, or structural performance. Therefore, particle size separation mechanisms are among the critical beneficiation technologies to be developed.

The key task in the processing of the regolith as part of the challenge is to beneficiate the excavated regolith (15 kg minimum) and produce minimum 5 kg of feedstock with a particle size distribution of 100 - 500 µm. The particle fraction of $>$ 500 µm and $<$ 100 µm shall be collected in separate bins.

Flat sieves are traditional tools used for particle size separation in soil analysis. Their simple design consists of a flat, perforated plate with uniform mesh openings, typically made of stainless steel, mounted within a frame. The soil sample is poured onto the sieve and manual or mechanical agitation allows particles smaller than the mesh size to fall through while larger particles remain on top. Just et al. (2022) investigated a lunar excavation and size separation system (LES^3) and demonstrated the use of flat sieves inside a movable robotic arm to produce distinct size fractions from lunar regolith simulants [9].

The rotary sieve, as described for example by Chepil (1962), operates by rotating a cylindrical drum containing multiple sieves with decreasing mesh sizes assembled concentrically. Gravitational forces in combination with shear flow and vibrational movement initiate interaction between particles and sieving surface [10]. While coarse particles are collected inside the inner sieves, finer particles are collected inside outer sieves.

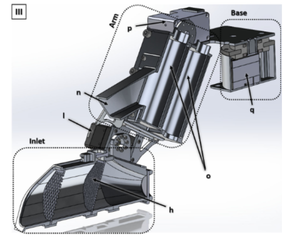
The centrifugal sieve applies a similar working principle but includes a rapid rotational movement of the cylindrical or conical screens to generate centrifugal forces and push particles outside towards the sieving surface more efficiently [11]. This method is particularly advantageous in low-gravity environments, such as the Moon, where traditional sieving methods may be less effective, however it comes at a cost of higher loads on the overall structure and the need for high power motors to produce the necessary centrifugal forces. Besides a variety of advantages, a major issue arising from the use of sieving mechanisms in general is the risk of sieve blinding. Alternative concepts such as the rotating cone separator and the slotted ramp separator try to eliminate these issues.

The rotating cone separator uses the friction differences that occur, when particles of different sizes and different surface area to mass ratios travel over a surface with an engineered roughness. Regolith is fed near the center of rotation and flows down the cone surface. Based on the resistance the particles face due to the surface texture, particles of different sizes end up in different trajectories and can be collected separately. While finer particles are slowed in inner sections, coarser particles continue flowing to outside sections. The Lunar Soil Particle Separator (LSPS) demonstrated this technology in practice [12]. It uses aluminum cones with a diameter of 15 to 43 cm, a 30° cone angle to horizontal and a 10° inclined axis of rotation to vertical in a two-stage process to separate coarse, medium and fine fractions. It rotates at a rotational speed of 80 to 140 rpm and uses feed rate of up to 20 kg per hour.

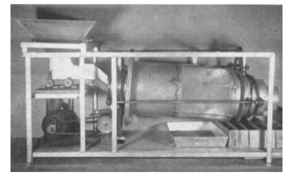
The system was successfully tested in ambient as well as vacuum environment and profits from lightweight material, a low-power variable speed motor and the elimination of blinded or clogged sieving-surfaces.

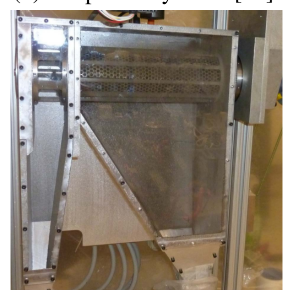
The slotted ramp separator functions based on similar operating principle. Instead of a rotational movement, the regolith particles travel in a translational manner over an angled ramp with engineered surface roughness. The ramp is equipped with a series of slots of defined and increasing width, enabling to sequentially collect regolith particles according to their size. While finer particles are slowed in the top section due to surface friction, coarser particles continue flowing to bottom sections. Using the slotted ramp, high-quality separation can be realized into a wide range of particle sizes with minimal cross contamination while slot width, ramp length, angle and surface roughness can be used to alter separation efficiency. This concept was also analysed and tested within the LSPS development process [12]

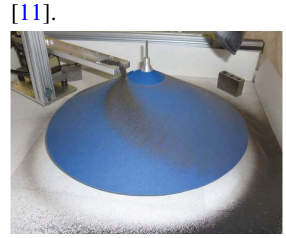
In addition to mechanical systems of separation, electrical methods have also been investigated for particle size separation. Adachi et al. present an electrostatic traveling-wave system that sorts lunar regolith by balancing electrostatic and gravitational forces, demonstrating dry, mechanical-free separation of particles and experimentally collecting < 20 µm particles in a 1.5×10^{-2} Pa vacuum [13]. Model experiments and distinct-element-method simulations demonstrate that small particles acquire a higher charge and reach greater heights in vacuum. The authors predict successful extraction of $\sim$10 µm particles on the Moon with appropriately placed collection boxes.



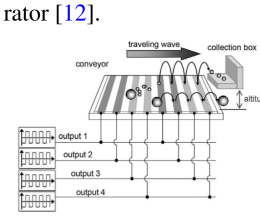
(a) Flat sieves schematic inside LES^3 robotic arm [9].


(b) Chepil rotary sieve [10].


(c) Dreyer centrifugal sieve [11].


(d) LSPS rotary cone separator [12].


(e) LSPS slotted ramp separator [12].



(f) Adachi electrostatic size sorting system [13].

Figure 2: State of the art beneficiation for ISRU.

3. TEAM BREMEN'S PROPOSED MISSION ARCHITECTURE FOR THE FIELD TEST

The solution developed for the ESA Space Resources Challenge is the result of a collaboration between DLR e.V. Bremen and the Robotics Innovations Center (RIC) of the DFKI supported by the robotics group of the University of Bremen. DLR is responsible for the beneficiation subsystem, while the DFKI develops the excavation and transport subsystem. This division results in two independent complementary systems: a modular mobile robot equipped with an excavation and collector unit to gain and deliver excavated material and a stationary beneficiation unit to extract the correct sized regolith. The separated design enables energy efficient workload distribution and straightforward integration at the test site.

The team BREMEN's envisaged concept of operations for the demonstration of regolith excavation and beneficiation technologies and achieving the objectives as a part of the field test at the LUNA analog facility in Cologne for the Space Resources Challenge is shown in Fig. 3. The system consists of a stationary regolith processing payload and a mobile excavation system. The regolith excavation and transport system consists of the COYOTE III [14] rover equipped with an excavation mechanism able to collect surface regolith samples and deposit them into the inlet of the regolith processing system. The stationary regolith processing system has two subsystems: the regolith dosing system (RDS) and the regolith beneficiation system (RBS). The RDS consists of a conveyor mechanism that transfers the collected regolith into the regolith beneficiation system with a controlled feed rate. The RBS consists of a rotary sieve system that processes the bulk regolith into the desired particle size fractions and the beneficiation feedstock is collected in the three collection bins.

3.1. Regolith Excavation and Transport System

The entire system adopts a modular design, which improves flexibility, simplifies maintenance, and makes it easier to integrate or replace subsystems according to different tasks. This approach also supports testing and development by allowing individual modules to be modified without affecting the whole system. The system is divided into the following parts: ① Coyote III Rover: The mobile excavation and transport system is based on the existing Coyote III rover, a modular micro-rover developed by DFKI. Coyote III is designed for high mobility in unstructured terrain, with a compact size of about 994 × 584 × 380 mm and a base mass of around 12.5 kg, leaving a payload capacity of 10–15 kg. It is powered by a LiPo battery (44.4 V, 7 Ah) and has onboard sensors such as RGB and ToF cameras, lidar, IMU, and wheel encoders for autonomous navigation. The rover uses helical wheels with inclined lugs that make steering easier; the hollow design lowers steering resistance and gives better mobility on soft soil. Its modular design with a standard electro-mechanical interface (EMI) makes it easy to add other subsystems. ② The connection interface, adapted to the EMI, integrates three main subsystems. The weighing system is implemented by four load cells in combination with HX711 amplifier. The power supply system consists of two batteries and multiple DC modules. The control system is based on a Raspberry Pi 5, which communicates with peripheral drivers including two FOC speed controllers for BLDC motors, an LED driver, two cameras, and other sensors. The interface establishes downward linkage to the rover, upward linkage to the screw conveyor system, and lateral linkage to the excavation system. ③ The excavation system is driven by a BLDC motor with two roller chains. Multiple small buckets are mounted on the chain to perform the excavation. Two linear actuators provide the lifting and lowering motion. A camera and LED illumination are used to support task supervision. ④ The screw conveyor system consists of an inlet hopper, a screw feeding tube, and an outlet hopper. Its speed is controlled by a BLDC motor. The system is mounted on four load cells at the bottom and is mechanically separated from the other subsystems, which allows continuous measurement of the regolith weight.

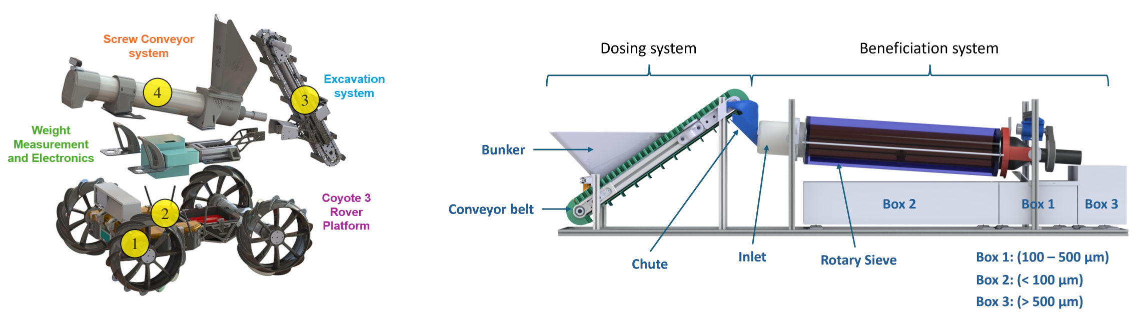


Figure 4: Team BREMEN solution: (left) Excavation and transport add-ons on the modular planetary exploration rover platform Coyote III; (right) Regolith beneficiation system specifications.

3.2. Regolith handling and Beneficiation system solution

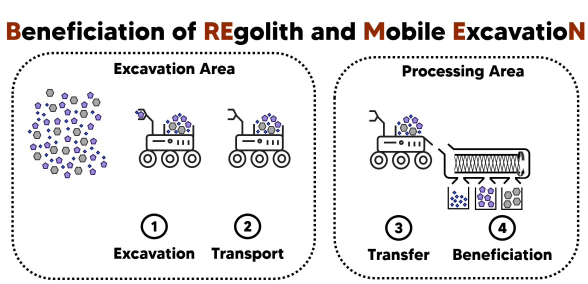


Figure 3: System ConOps of Team BREMEN for ESA ERSIC Space Resource Challenge.

The stationary regolith handling and beneficiation system consists of two subsystems: the regolith dosing system (RDS) and the regolith beneficiation system (RBS). The RDS ensures that the feed rate of the regolith going into the beneficiation system is constant and limited to achieve optimal performance while allowing for a buffer volume enabling continuous regolith processing of the RBS while the rover gathers more material. The next sections describe in detail the subsystem specifications

Regolith Dosing System (RDS)
The primary objective for the RDS is to offer buffer volume for receiving the regolith from the excavation and then conveyance of this material at a fixed feed rate into the regolith beneficiation system (RBS). Material gets deposited into the dosing mechanism after each excavation run of the rover, in batches of approximately 5 kg. During the next excavation run of the rover, this batch is slowly fed to the RBS. The dosing system comprises of a bunker that is made out of aluminium sheet metal and can hold approximately 6.5 kg of regolith (at a bulk density of 1.45 g/cm^3 [15]) and a conveyor belt beneath the bunker to move the deposited regolith further into the RBS. The walls of the bunker are inclined at an 50° angle to avoid regolith bridging. The conveyor belt features corrugated side walls to form a barrier to the sides of the belt, as well as cleats, which

drag the loose regolith upwards. The belt is angled at 35°, since the angle of repose of lunar regolith simulant is typically higher [16]. Figure 4 illustrates the system along with the components mentioned. In practice, some residual regolith still slides down the belt between the cleats and side walls, which is then caught by the bunker walls and eventually reaches the top, where it gets deposited into the RBS via a chute attached just below the top roller of the conveyor belt, to guide the regolith into the inlet of the beneficiation system. The belt is driven by a geared DC motor via a drive roller at the lower end of the belt and tensioned via this drive roller assembly. The motor has a 336.11:1 gearbox, resulting in a speed of 11.5 rpm at 24 V at maximum torque with a current draw of 340 mA.

Regolith Beneficiation System (RBS)
The RBS utilizes rotary sieves for processing of the bulk regolith. It consists of two concentric sieves with different mesh sizes. The inner sieve has a mesh opening of 500 µm and the outer sieve has a mesh opening of 100 µm. The innermost output is therefore the coarse particle fraction > 500 µm. The output between both the sieves contains the particle fraction between 500 – 100 µm and the finest fraction that passes through the finest outer sieve is collected right beneath the rotating sieve, as shown in Fig. 4. The rotary sieve mechanism was selected given its high accuracy potential for particle sizing in combination with the cleaning mechanism that mitigates the risk of sieve blinding with continuous operations. Also, the sieve is inclined to improve the flow of regolith through the sieve. In lunar conditions, the angle of the sieve and the rotational speeds can be varied to maintain sieve performance in the space environment.

4. EXPERIMENTAL RESULTS

4.1. Key Performance Indicators (KPIs)

To evaluate the BREMEN team's solution in terms of excavation, transport of regolith, and beneficiation, the KPIs in Table 1 were selected during the preparation phase to define the relevant objective and make it measurable, quantifiable, and comparable. In addition to these objectives, minimizing the dust raised during the different operations is also pursued.

Table 1: Defined KPIs to measure the success of the proposed solution of Team BREMEN.

KPI	Category	Definition	Measurement method	Unit	Target
Active operational time	Time	Duration of active operations in the field test	Logs of timer	h	$= 2.5$
Energy budget	System	Energy available to be consumed per hour	Logs of energy sensor	Wh	≤ 120
System mass budget	System	Total mass of the system	Weighing scale	Kg	≤ 60
Average excavated simulant per hour	Mass	Mass of excavated regolith simulant per hour	Weighing scale	Kg	≥ 6
Beneficiated simulant (500 - 100 µm) per hour	Mass	Mass of regolith simulant to be collected per hour	Logs of weighing scale	Kg	≥ 2

4.2. Preliminary test results

Excavation test
Excavation tests were carried out with two different types of materials. The type A (Fig. 5 right side, light-colored sand) was sand from the Baltic Sea with a grain size of 0–1 mm, as described in [17]. The regolith simulant (type B) used for the tests was LMS-1 lunar mare regolith simulant produced by *Space Resources Technologies* [18] (Fig. 5 left side, dark-colored regolith).

The experiments showed that the roller chain concept excavated both material types at speed of 1–2 kg/min with about 10–12 W power consumption, and that excavation efficiency was positively correlated with the downward penetration speed ensuring sufficient bucket–soil contact. Material A exhibited better flowability with lower dust generation, whereas Material B, due to its finer and more adhesive particles, adhered to the bucket and released additional dust upon vibration. After excavation, the regolith did not refill the pit quickly due to cohesion. Vertical excavation alone was less efficient. A more effective method was to dig vertically to a certain depth and then move the rover slowly forward to perform additional horizontal excavation.

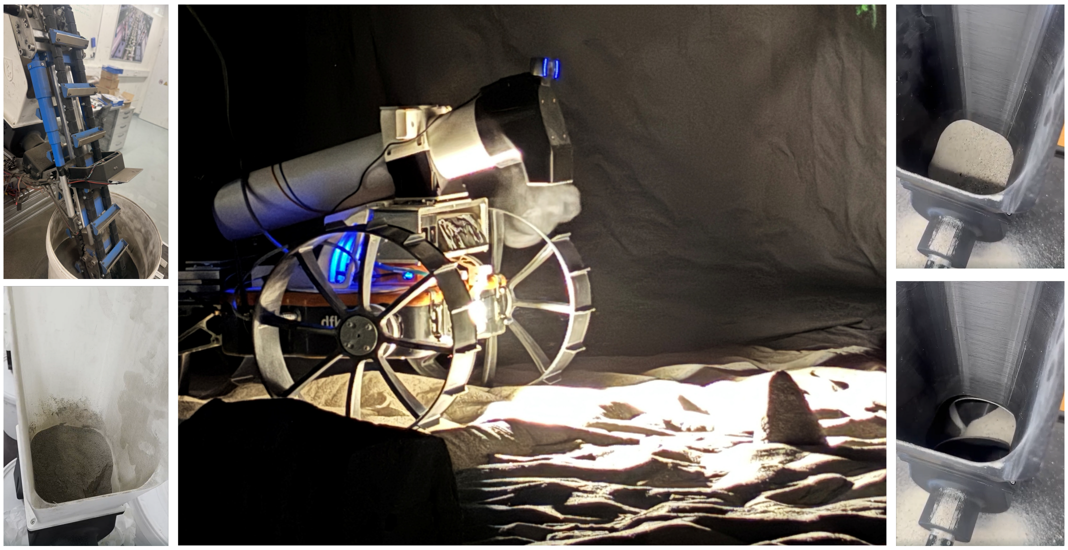


Figure 5: Excavation and transport tests with the proposed sub-/system (*left:* Material B; *right:* Material A).

Regolith transport test

Regolith transport is two staged: inside the rover, a screw conveyor transfers material from the excavation inlet to the storage container, and afterwards the rover delivers it to the beneficiation station. Tests showed that the screw conveyor could transport both regolith types at 3–4 kg/min with 12–14 W power consumption. The results align with the granular fluidization theory [19], where high starting torque is needed to initiate motion, but once the regolith becomes fluidized. Material B is more compact and cohesive than material A, leading to higher torque during conveying. Proper distribution in the container is important for achieving a favorable center of mass (COM) reducing the risk of motor overload. In addition, the outlet velocity of regolith was found to be positively correlated with dust generation.

Regolith Beneficiation tests

The preliminary experiments for the RBS were conducted to test the different feed rates for the dosing mechanism and to understand the overall system functionality. Given the challenge constraints, the energy consumption was considered as one of the critical performance parameters to be observed during the experiments. These experiments were conducted with type B regolith simulant. The preliminary experiments for the RDS were carried out to evaluate material handling performance under varying motor speeds. Tests focused on key operational parameters including current draw, deposition time, belt slippage, and effective energy consumption. The mass of deposited material was measured to determine throughput, while checks for material loss were also performed. Results showed that higher motor speeds generally reduced deposition time but increased current draw and belt slippage likelihood, elevating energy consumption. Conversely, lower motor speeds improved deposition accuracy and minimized material loss, at the cost of longer operation times. The balance between speed, energy efficiency, and material handling reliability was identified as a critical factor for optimizing the dosing system. The experiments were also performed with the RBS using 500 g batches of the same regolith simulant to assess performance at varying operational parameters such as the input feed rate, inclination of the rotary sieve and the rotational speed of the sieve. The tests recorded energy consumption, processing time, and assessed component wear, while the beneficiated feedstock was evaluated through test sieving. Results indicated that feed rate played a decisive role in efficiency, with the highest feed rate producing notably better throughput and separation quality compared to slower inputs. Faster operation also reduced processing time without significantly increasing wear or energy costs. These findings suggest that higher feed rates may optimize beneficiation performance, balancing energy efficiency with effective material separation.

5. CONCLUSION

The development and integration of excavation and beneficiation subsystems demonstrate a feasible approach towards meeting the requirements of the ESA SRC. First experimental results confirm the functionality of the proposed solution and indicate promising performance under expected challenge conditions. Ongoing work shall focus on further optimization, extended testing, including human operators and system-level validation to improve reliability and robustness for the continuous operations. A post-field test review shall be conducted to gain insights into system operations and pave the way for future developments of the enabling technologies.

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