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LUXEMBOURG SPACE RESOURCES WEEK

Book of Abstracts

LUXEMBOURG SPACE AGENCY · esa · LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST · SPACE RESOURCES

MONDAY
APRIL 19TH

Session 1
New Discoveries

Chair: James Carpenter

16:00	Asteroid Sample Return Mission Hayabusa2
16:15	The OSIRIS-REx Touch-And-Go Sample Acquisition Event And Implications For The Nature Of The Returned Samples
16:30	The ESA Hera Mission: Relevance For Asteroid Resources
16:45	Now Making Oxyen on Mars: MOXIE and the Perseverance Mission
17:00	Deep Reduction of Energy Requirement for Lunar Ice Extraction
17:15	The ESA PROSPECT Payload for Luna 27: Status and Science Activities
17:30	The Volatiles Investigating Polar Exploration Rover (VIPER) Mission – Measurements and Constraints
17:45	Preparation Phase Outcome and Future Approach of ESAs ISRU demonstration mission (ISRU-DM)

Asteroid Sample Return Mission Hayabusa2

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Introduction

Hayabusa2 is the second asteroid sample return mission in the world following Hayabusa. The target asteroid is (162173) Ryugu, which is a C-type near Earth asteroid. Hayabusa2 was launched in December 3, 2014 from Tanegashima Space Center in Japan, arrived at Ryugu in June 27, 2018, and came back to the Earth in December 6, 2020. The sample return capsule landed on Woomera Prohibited Area in Australia. The main objective of the mission is to study the organic matters and water in the early stage of the solar system. Now we have the sample of Ryugu and the initial analysis of the samples will start soon.

Mission Results

Hayabusa2 stayed near Ryugu for about one year and five months. We got a lot of data of Ryugu (fig.1) by using four remote sensing instruments and four landing instruments. We also studied the physical nature of the surface of Ryugu by an impact experiment to create an artificial crater. Now we have understood a lot about Ryugu, which is a rubble pile object with low density, very dark surface, and hydrated minerals. We have executed touchdown twice to get the material of Ryugu. The second touchdown was done near the artificial crater to get the sub-surface materials.

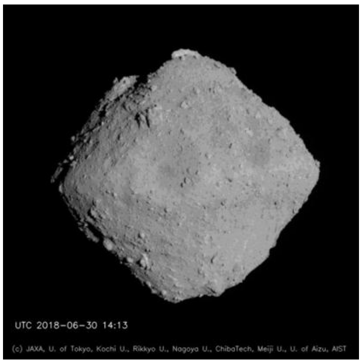

Figure 1: Asteroid Ryugu
(Credit : JAXA, Tokyo Univ. etc.)

Sample of Ryugu

The sample return capsule was quickly brought back to JAXA in Japan from Woomera. In the capsule there was a sample container, which had sample catcher with three chambers. We opened the sample container and then sample catcher in the clean chamber of the curation facility of JAXA. We found the materials of Ryugu in Chamber A for the first touchdown and in the Chamber C for the second touchdown (Fig.2). The total amount of the samples was about 5.4g. The target mass of the samples was 0.1g, so we were able to get more than enough samples. The curation works will continue until June 2021, and then the initial analysis by Hayabusa2 project members will begin. The samples of Ryugu will be distributed to the researchers in the world from June 2022 under the announcement of opportunity. Currently, we are very much looking forward to what the analysis results of the sample will be. We hope we will find some organic matters that will be the clues for the study of the origin of the life on the Earth. The minerals, the compositions, and the structures of the samples are also very interesting to know.

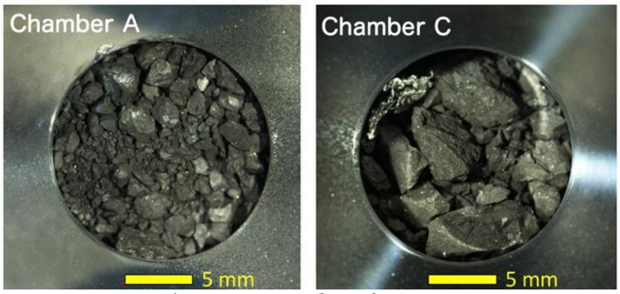

Figure 2: Samples of Ryugu
The left is the samples of the first touchdown, and right is the samples of the second touchdown. (Credit : JAXA)

The OSIRIS-REx Touch-And-Go Sample Acquisition Event And Implications For The Nature Of The Returned Samples.

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On October 20, 2020, NASA's Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft [1] contacted the surface of asteroid (101955) Bennu with the Touch-and-Go Sample Acquisition Mechanism (TAGSAM) and collected a regolith sample. This was the culmination of an extensive remote sensing campaign to characterize Bennu's surface and identify an optimum sample site. This site, dubbed Nightingale, is one of the rare locations that contains abundant small particles (<2 cm) ingestible by TAGSAM and is also relatively free of hazards (particles from 10 cm to 10s m).

The TAGSAM head contacted the surface with a downward velocity of 10 cm/s within 1 m of the targeted center of the Nightingale site. TAGSAM [2] acquired the bulk sample by releasing a jet of high-purity nitrogen gas that excites and "fluidizes" at least 60 g of regolith into the collection chamber. During the collection time, gas is injected into the surface and subsurface, mobilizing particles into the collection volume. The baseplate of the TAGSAM head contains 24 contact-pad samplers made of stainless-steel Velcro. These pads collect small grains up to 1 mm in diameter upon contact with the asteroid surface.

Surface contact was indicated by a signal from the spacecraft's accelerometer, which registered a small but measurable surface contact force. The surface responded like a compliant, viscous fluid, similar to discrete-element simulations of TAGSAM interacting with regolith with low intergranular cohesion. The spacecraft's downward velocity did not decrease substantially after contact. Post-contact, surface disturbance was visible in all directions around the TAGSAM head, indicating that the head was flush with the surface.

The predicted sample mass based on the sampleability assessment is 258–575 g, providing high confidence that >60 g of sample will return to Earth. Based on what we have learned from our science campaign during asteroid operations, the physical nature of the returned material is expected to be in a size range from sub-microns to several centimeters. We expect the sample to contain hydrated silicates [8], carbonates [9], magnetite [10], and organic components [11].

OSIRIS-REx is scheduled to depart Bennu in May 2021 and deliver the sample to Earth in September 2023. The capsule will land at the Utah Test and Training Range. The team will recover the capsule and transport it to the curation facility at NASA Johnson Space Center.

Acknowledgments: The material presented here is based upon work supported by NASA under Contract NNM10AA11C issued through the New Frontiers Program.

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The ESA Hera Mission: Relevance For Asteroid Resources

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Introduction

The Hera mission is in development in Phase C in the Space Safety Program of the European Space Agency for launch in 2024. It will rendezvous with the binary asteroid 65803 Didymos at the end of 2026 and will fully characterize its properties, including for the first time the internal ones, as well as the outcome of the impact performed by the NASA DART mission on its small moon called Dimorphos in order to deflect its trajectory around the asteroid primary. DART and Hera will thus perform the first asteroid deflection test using the kinetic impactor techniques.

Relevance for asteroid resources

While the requirements of the mission are focused on planetary defense, the measurements done by Hera do provide important data in preparation of asteroid mining. Hera is equipped with an asteroid framing camera, an hyperspectral imager, a lidar, a thermal infrared imager and two cubesats (Fig. 1), one called Milani mainly focused on the composition of the asteroid and dust detection, the other one called Juventas focused on its internal properties, gravity field, and surface mechanical properties. The size of Dimorphos being about 160 meters, Hera will for the first time investigate an asteroid < 200m in size. Those very small asteroids are expected to be the first targets of mining companies. The investigation of the physical properties and mechanical response of the surface layer (strength, roughness) as well as sub-surface properties (through observation of the interior of the DART crater) and internal ones provides important information for the choice of mining techniques.

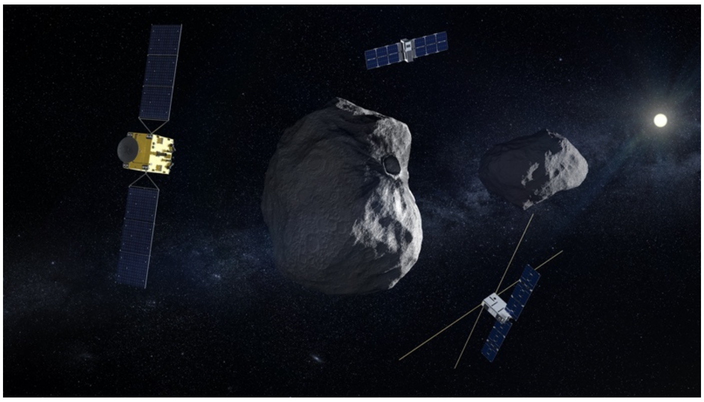

Figure 1: The Hera spacecraft and its two cubesats at Didymos

The consortium NEO-MAPP (Near-Earth Object Modelling And Payload for Protection) funded by the European Commission supports the development of Hera by developing new modelling tools, innovative approaches for data analysis, instrumentations and operations, which can also benefit to missions devoted to asteroid resources.

Acknowledgment: Financial supports from CNES and the European Union's Horizon 2020 research and innovation program under grant agreement No. 870377 (project NEO-MAPP) are acknowledged.

Now Making Oxygen on Mars: MOXIE and the Perseverance Mission

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Introduction

Currently on Mars aboard the Perseverance rover and anticipating its first opportunity to operate, the Mars Oxygen ISRU Experiment (MOXIE) will be the first live demonstrate of oxygen production on the surface of another planet (see Figure 1). MOXIE is a prototype of a system that will someday provide many tons of oxygen as the major component of the propellant for a Mars Ascent Vehicle that will return astronauts from the Red Planet.

How MOXIE works

Designed and integrated at NASA's Jet Propulsion Laboratory for MIT, MOXIE first collects, filters, and compresses the thin martian air, which consists of 95% CO_2 and small amounts of nitrogen and argon at a pressure of <10 mbar (Figure 2) using a custom scroll pump developed by Air Squared, Inc. It then pre-heats the gas to ~800˚C and injects it into a stack of 10 solid oxide electrolysis cells, developed by Ceramatec, Inc. (now OxEon Energy). The CO_2 is thermally and catalytically decomposed according to the reaction $CO_2 \rightarrow CO + O^{2-}$ at the cathode of the electrolysis cells, then the oxygen ions are selectively drawn through the yttrium-stabilized zirconia electrolyte where they recombine at the anode into O_2 molecules. The transfer of 4 electrons from anode to cathode completes the circuit and provides the motive force for the reaction. The pure oxygen product is characterized, then released through a precision aperture (labelled VFCD is Figure 2), while CO fuel and unused CO_2 are similarly characterized and discharged through an exhaust port.

Figure 1: MOXIE being lowered into the Perseverance Rover

MOXIE expects to produce 6-10 grams of 98% pure O_2 per hour, a factor of ~200 less than will eventually be needed on a full-scale system. Limited power availability on Perseverance is the primary constraint on production – a human mission is expected to be supported by a 25-30 kW power plant, while Perseverance generates 110W overall. The eventual full-scale system is expected to take up about a cubic meter and to weigh about 1 ton while generating in excess of 25 tons of O_2 for the ascent vehicle over the course of an Earth year.

MOXIE is expected to operate at least ten times during the primary Perseverance mission of one martian year, distributed across seasons and time of day.

References

[1] Hecht, M., Hoffman, J., Rapp, D. *et al.* Mars Oxygen ISRU Experiment (MOXIE) (2021), *Space Sci Rev* **217**, article 9. https://doi.org/10.1007/s11214-020-00782-8

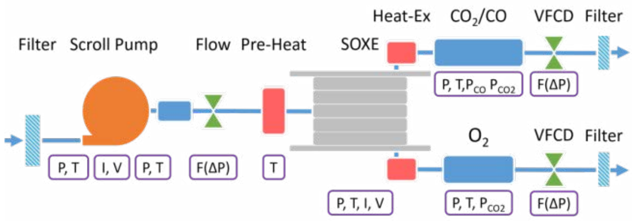

Figure 2: MOXIE first filters, compresses, and pre-heats martian air, then injects it into a Solid Oxide Electrolysis

Deep Reduction of Energy Requirement for Lunar Ice Extraction

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Introduction

Thermal extraction of ice from lunar regolith requires vast amounts of energy, so the infrastructure to generate or transport the energy into lunar Permanently Shadowed Regions (PSRs) is expensive to mature, deliver, and operate on the Moon. A recent study [1] estimated an ice mining and propellant manufacturing operation will require 2.8 MW of power. The mine would have 30,000 kg of surface assets costing €3.3B initial investment. A new (patent pending) [2] method to extract lunar ice from lunar soil has been studied via experiment and architectural analysis [3]. In this presentation we will provide the results.

Extraction Architecture

The goal is to create a Minimum Viable Product (MVP) ice mining and propellant service direct-to-customers with low initial investment that can scale-up incrementally, enabling a business case that grows smoothly as technologies are matured and risks are retired. The elements include excavators, a beneficiation system, a water cleanup and electrolysis system, power systems, and a space tug that travels directly from the Moon to Earth orbit to boost commercial spacecraft before returning to the Moon. Beneficiation uses several processes to remove rocks and gravel then lightly grind the fines to facilitate separation of ice and mineral fragments. It uses pneumatics, magnetics, and electrostatics (multiple embodiments under study) to separate the ~5 wt% ice from the ~95wt% tailings before transport. This minimizes the energy that must be used in the PSR. Most of the energy-intensive processes are kept in sunlight outside the PSR, vastly reducing infrastructure requirements.

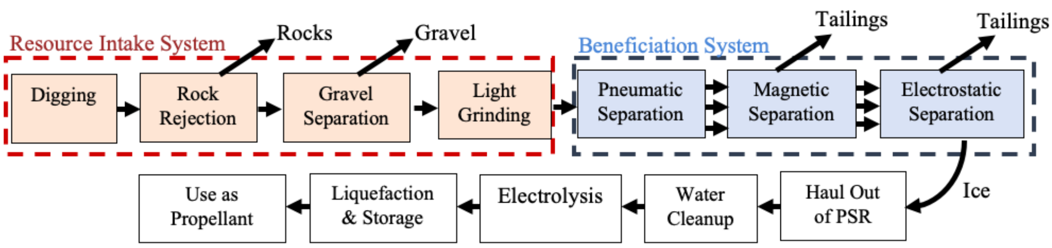

Figure 1: One embodiment of the extraction/beneficiation system

Experiments and Analysis

Ice beneficiation methods have been validated by experiment and analysis. Orbital dynamics and overall architectural analysis indicate a reasonable business case with 98% reduction of power compared to thermal extraction, a total of only 2,500 kg in assets required with a start-up cost of only €175M for the MVP to begin operations.

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[2] US Application No. 62/988,940 filed March 13, 2020.

[3] “Aqua Factorem: Ultra Low-Energy Lunar Water Extraction” NASA NIAC, https://www.nasa.gov/directorates/spacetech/niac/2020_Phase_I_Phase_II/

The ESA PROSPECT Payload for Luna 27: Status and Science Activities.

D. J. Heather[1], E. Sefton-Nash[1], R. Fisackerly[1], R. Trautner[1], S. J. Barber[2], P. Reiss[1], B. Houdou[1], the PROSPECT Science Team and Industrial Consortium. [1]ESTEC, ESA, Noordwijk, The Netherlands, [2]Open University, Milton Keynes, UK. (David.Heather@esa.int)

Introduction

The Package for Resource Observation and in-Situ Prospecting for Exploration, Commercial exploitation and Transportation (PROSPECT) is a payload in development by ESA for use at the lunar surface. Current development is for flight on the Russian-led Luna-Resource Lander (Luna 27) mission, which will target the south polar region of the Moon. PROSPECT will perform an assessment of the volatile inventory in the near surface regolith (down to ~ 1 m), and elemental and isotopic analyses to determine the abundance and origin of any volatiles discovered [1]. While lunar volatiles present compelling science at the poles, solar wind-implanted volatiles and oxygen in lunar minerals (extracted via ISRU techniques) constitute potential science return anywhere on the Moon. PROSPECT is comprised of the ProSEED drill module and the ProSPA analytical laboratory, plus the Solids Inlet System (SIS) (Fig. 1).

Phase C (detailed definition) began in December 2019. In parallel to the industrial activity, an associated plan of research has been formulated to guide ongoing development, build strategic scientific knowledge, and to prepare for payload operations.

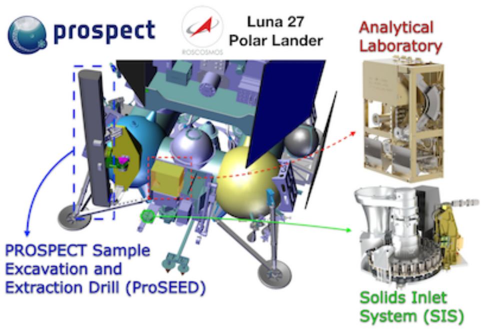

Figure 1: Renderings of PROSPECT onboard Luna 27, including the ProSEED drill (left), and ProSPA (right). ProSPA comprises 1) the Solids Inlet System (lower right), with a camera assembly [2] and a carousel of ovens used for volatile extraction, and 2) the analytical laboratory (upper right) containing a gas processing system, and magnetic sector plus ion-trap mass spectrometers

ProSPA Bench Development Model (BDM). The BDM of the ProSPA analytical lab at the Open University has been tested to demonstrate science performance against measurement requirements. Dedicated efforts recently focused on verification of evolved gas analysis (EGA) and demonstration of ISRU capabilities [3, 4], improving our understanding of our sensitivity to volatile abundance and possible contamination [5].

Volatile Preservation: Particular efforts have recently focused on understanding the capability of PROSPECT to sufficiently preserve the volatile content in regolith throughout the sampling-analysis chain for the range of expected volatile contents, e.g. [6]. Detailed modelling and experimental work is ongoing to better understand water sublimation rates in realistic operational environments [7] and to better constrain the potential effect on measured D/H of sublimation of lunar water ice [8]. Results from this will help ensure that PROSPECT will meet its science objectives even in a 'hot operational case'.

Sample analysis: In 2020, PROSPECT Science Team members successfully requested two samples of lunar regolith (2 g each) from the Apollo collections. Proposed experiments will investigate loss of water ice through sublimation and the effects that the bulk properties and ice-regolith coupling have on the sublimation process.

References

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The Volatiles Investigating Polar Exploration Rover (VIPER) Mission – Measurements and Constraints

A. Colaprete[1], R. C. Elphic[1], M. Shirley[1], K. Ennico-Smith[1], D. S. S. Lim[1], K. Zacny[2], J. Captain[3] [1]NASA Ames Research Center, Moffett Field, CA, [2]Honeybee Robotics, Pasadena, CA, [3]NASA Kenedy Space Center, FL.

Introduction The Volatiles Investigation Polar Exploration Rover (VIPER) mission is a lunar polar volatiles prospecting mission developed through NASA's Planetary Science Division with flight in late 2023 [1]. The mission includes a rover-borne payload that (1) can locate surface and near-subsurface volatiles, (2) excavate and analyze samples of the volatile-bearing regolith, and (3) demonstrate the form, extractability, and usefulness of the materials. The primary mission goal for VIPER is to characterize the distribution of water and volatiles across a range of thermal environments. This characterization will assist in understanding the origin of lunar polar volatiles and help evaluate the In-Situ Resource Utilization (ISRU) potential of the lunar poles. VIPER will be optimized for lunar regions that receive prolonged periods of sunlight (short lunar nights); prospectively, the mission duration will be more than 90 Earth days, and result in a traverse distance of up to 20 km.

Measurement Goals and Payload A critical goal to both science and exploration is to understand the form and location of lunar polar volatiles. The lateral and vertical distributions of these volatiles inform us of the processes that control the emplacement and retention of these volatiles, thereby helping to formulate ISRU architectures. While significant progress has been made from orbital observations [2-6], measurements at a range of scales from centimetres to kilometres across the lunar surface are needed to validate "volatile mineral models" for use in evaluating the resource potential of volatiles at the Moon. To this end, the primary mission goals for VIPER are to (1) provide ground truth for models and orbital data sets, including temperatures at small scales, subsurface temperatures and regolith densities, surface hydration and hazards (rocks and slopes), (2) correlate surface environments and volatiles with orbital data sets to allow for better prediction of resource potential using orbital data sets, and (3) address key hypotheses regarding polar volatile sources and sinks, retention and distribution, key to developing economic models and identifying excavation sites.

The VIPER payload consists of three "prospecting" instruments which operate continuously while roving, including the Neutron Spectrometer System (NSS), the Near InfraRed Volatiles Spectrometer System (NIRVSS) and the Mass Spectrometer observing lunar operations (MSolo). A 1-meter auguring/percussive drill called the The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT) is used to bring subsurface cuttings to the surface in 10 cm increments where they are interrogated by NIRVSS and MSolo. TRIDENT also includes a temperature sensor at the bit and a heater/temperature sensor combo 20 cm above the bit. As such, TRIDENT would be able to provide downhole temperature and thermal conductivity.

Multi-Lunar Day Mission Traverses Several detailed traverse plans for VIPER have been developed to further help with rover development and to develop mission operational concepts (see Figure 1). The mission planning is organized into two phases, including an "early" phase during which rover traversing and observations follow as much of a pre-planned schedule as possible (with pre-planned anomaly mitigation plans) and "late" phase, during which more real-time decision making is implemented and reactions to "early phase" findings are enabled. Both phases take advantage of the near real-time communications with the rover and real-time geostatistical analysis methods to maximize observation effectiveness.

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Preparation Phase Outcome and Future Approach of ESAs ISRU demonstration mission (ISRU-DM)

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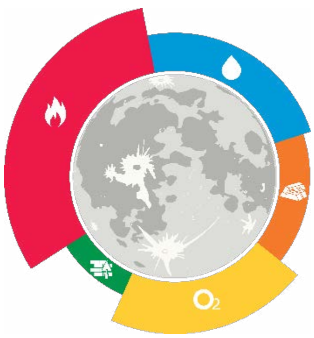
Abstract

The ISRU-DM mission has recently completed its preparation phase. This has concluded Phase A where a number of payload demonstrator concepts have been defined by industry. ESA with its industry has primarily investigated the hydrogen reduction of ilmenite, carbo-thermal reduction with methane and FFC Metalysis processes. This was to answer a number of key questions. How will the payload be flown? What are the flight terms and conditions? What should the process for resource extraction be? What is a relevant demonstration? What are the critical risks?

The preparatory contracts ran from 2018 to 2020 in four parallel contracts covering landers and payloads. Within this time two full review processes were undertaken to assess the design and establish the next steps.

The advantages and disadvantages of the flight opportunities were established, noting that there are some significant constraints which have an impact on the demonstration scope. These areas of constraints, particularly for commercial landers, show hard limits on thermal and power. Each process was found to have its merits. But a more requirements driven, rather than process driven, approach was considered more convenient than choosing the process outright.



Beyond Phase A, the programme of work and approach to the next preliminary definition phase has been established, which will be a challenge to decide a winner to implement Phase B1. The structure of the procurement process, requirements and timescale will be reported. The lessons from Phase A are taken into account, constraining demonstrator scope based on a perceived future ISRU user need, but leaving the process and demonstrator concept somewhat open. The focus of requirements for the demonstrator are to prove a process and create an operational heritage for a scalable, reliable system. It is believed that a worthwhile demonstrator can be achieved under 100 kg, and even then that it shall be further optimised.

WEDNESDAY
APRIL 21TH

Session 2
R&D needs and gaps

Chair & Moderator: Aidan Cowley

16:00	Beneficiation of Lunar Regolith: Progress and Challenges
16:15	Continuous Microfluidic Solvent Extraction of Cobalt from Mimicked and Real Asteroid Leaching Solutions
16:30	Identified Research Needs For Additive Manufacturing With Molten Lunar Regolith
16:45	Mobile Selective Laser Melting of Lunar Regolith
17:00	Oxygen extraction through regolith thermal reduction
17:15	Progress understanding lunar oxygen extraction with the FFC process
17:30	Towards the prospection of water ice on the Moon and beyond: on the need for a better understanding of water ice sublimation rate and related O and H isotope fractionation
17:45	Wet-processing and synthetic H2O weathering of unrefined regolith towards high strength 'sandcastles'

Beneficiation of Lunar Regolith: Progress and Challenges

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A range of processes to extract oxygen and water from lunar regolith have been proposed such as hydrogen reduction and molten salt electrolysis. At the proof-of-concept stage, the nature of the material fed into the reactor does not need to be controlled or optimised. For larger scale and continuous operation, reliable production requires there to be control over the reactor feedstock characteristics. Controlling the size range of regolith, for example removing coarse and fine particles, and/or concentrating specific minerals or particle types, has the potential to improve the operation of any reactor handling naturally variable materials. This step, beneficiation, is often overlooked in the ISRU flowsheet, in part due to a lack of understanding of the effects of feedstock variability on downstream operations. The challenges of handling and manipulating lunar regolith in situ are numerous – on Earth, separating mineral particles by size at 50 μm without water is difficult. On the Moon, the environmental conditions and particle characteristics increase the complexity significantly.

At Imperial College London, we are addressing the challenges of the beneficiation of lunar regolith by combining our terrestrial mineral processing expertise with the specific needs of ISRU. There is a focus on the classification of regolith by size and type, exploiting electrostatic properties of particles in the lunar atmosphere. In this talk, we will give an update on our ongoing projects. At a fundamental level, we are investigating the saturation charge of particles under ideal (terrestrial) conditions. The data will provide a valuable input into the design of effective contact, or tribo-, chargers for use in electrostatic separators. The charge acquired on particles in a tribocharger has been modelled using Discrete Element Method (DEM). Subsequent simulations allow for the testing of conceptual tribocharger designs, in order to provide clear design guidelines for effective electrostatic separation. We will also present preliminary results from a novel vibratory size classification system and on the transport of particles in an electric field.

The research presented in this talk will showcase the progress being made in the beneficiation of lunar regolith in our group, however it will also highlight the gaps in knowledge that must be addressed in order to constrain further this often overlooked stage of the ISRU value chain.

Continuous Microfluidic Solvent Extraction of Cobalt from Mimicked and Real Asteroid Leaching Solutions

Volker Hessel[a,b], Marly Wouters[a,c], Shamaun Rahman[a], Hideaki Miyamoto[d], Nam Nghiep Tran[a,e]

[a] School of Chemical Engineering and Advanced Materials & Andy Thomas Centre for Space Resources, University of Adelaide, Australia.

[b] School of Engineering, University of Warwick, United Kingdom.

[c] Eindhoven University of Technology, the Netherlands.

[d] Department of Systems Innovation, The University of Tokyo, Japan

[e] Department of Chemical Engineering, Can Tho University, Vietnam.

Abstract

Over 600 space missions have been launched since 1959. 17 are currently underway for space resource exploitation. Two will land on asteroids to return samples: NASA OSIRIS-Rex on near-Earth Bennu and JAXA's Hayabusa-2 on 1999 JU3. Those and other missions produce hundreds of publicly accessible observation documents.

This research proposes a pathway for the last step of the asteroid mining process: the purification of the adjacent metals, cobalt and nickel (Zhang et al., 2017), in the frame of in-situ resource utilization (ISRU) in space. Major technological and economic challenges will need to be overcome, and one main issue to be tackled is the reduction of water usage in this process. Therefore, the leached metal solutions are expected to contain ultra-high metal concentrations, up to 10 mol/l (Hessel et al., 2021). These solutions will have challenging thermodynamic properties (increased density, viscosity and interfacial tension). As a result, an analysis of dimensionless numbers for fluidics and mass transport was made, showing that some of these are favourable under the constraints of accessible microfluidic operations. Experiments were performed with advanced microfluidic reactors (a coiled-flow inverter (CFI) and an industrial re-entrance flow reactor from Corning®) at high metal concentrations and high nickel to cobalt ratios (3:0.3 mol/l Ni:Co). Using Cyanex 272 as a selective extractant for cobalt, extraction efficiencies of 60% with high separation factors (>1000) were reached in just one extraction stage (Wouters et al., 2021). The CFI showed high extraction efficiency for low fluid velocities and a residence time of 60 s. For the Corning® reactor, high fluid velocities or the use of many modules (>3) are needed to obtain an emulsion, resulting in high extraction efficiencies at a very short residence time of 13 s. The comparison between the CFI and the Corning® reactor shows that they share the best operation point (at 120 ml/h), but the Corning® reactor performs better at higher flow rates and thus can leverage higher productivity. However, the CFI is easier to operate and has a much lower pressure drop, resulting in low energy input. Finally, an iron meteorite sample was leached and efficiently extracted in both microfluidic reactors. The meteorite Campo del Cielo, the third-largest one which ever hit Earth, was leached and extracted at maximal 87% efficiency.

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Identified Research Needs For Additive Manufacturing With Molten Lunar Regolith

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Introduction

The use of local resources on the Moon offers great technical and economic potential. In particular, for the construction of large structures on the Moon, regolith is a promising raw material due to its thermal insulating properties and wide availability. The treatment and handling of regolith is currently being investigated in numerous research projects, while some of them rely on heating up the Regolith to high temperatures. In the presented approach, additive manufacturing with molten lunar regolith and the research needs are described.

Concept

The concept involves melting the lunar regolith simulant TUBS-M [1] under vacuum conditions, layering it up and then solidifying it by passive cooling to produce solid structures. In this process, the regolith is to be heated in a melting chamber by radiative heating above the liquidus temperature (around 1350 °C [2]) and then discharged by gravity through a nozzle [3]. This approach enables the manufacturing of large robust structures without additives. Since the process takes place in a vacuum, numerous new properties of molten lunar regolith will be derived from the experiments, which are of importance for further processes of In-Situ Resource Utilization.

Research needs

Numerous unknowns have arisen in the design of this process that need further investigation for handling molten lunar regolith. For example, most process parameters, such as viscosity and wettability, are strongly dependent on the temperature and the chemical composition of the regolith. In addition, suitable materials must be selected to withstand the high temperatures and corrosive properties of the lunar regolith. Furthermore, the heating and cooling rate of the melt decisively determines the glass and crystalline content and thus the material properties. The identified research needs, which will be covered within the scope of this concept, are to be presented. [3]

Acknowledgement:
This work is supported (support code 50WM2057) by the Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Bundestag.

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

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Mobile Selective Laser Melting of Lunar Regolith

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Abstract

In-Situ Resource Utilization (ISRU) technologies pave the way for a sustainable colony on the Moon. Above all, the construction of structures using only the available resources is an important factor in reducing costs and logistical effort. The MOONRISE project aims to melt lunar regolith using lasers on mobile platforms for the Additive Manufacturing of structures [1]. This process, working in a non-contact mode, is called Mobile Selective Laser Melting (M-SLM) and has the advantage that only electrical energy and a moving system are required.

A payload mainly consisting of a printed circuit board (PCB) for system communication, a fiber coupled diode laser, an electrical diode driver, a beam focusing optics, and an LED illumination was designed. For baseline operation, a laser beam of typically 70 W (up to 140 W) is directed for 6 s to a fixed spot on the lunar surface at a distance of about 25 cm. These parameters were chosen according to previously conducted laboratory experiments with regolith simulant. LED illumination is available for visualization of the molten regolith by external cameras. The payload can be accommodated on a rover or a robotic arm to ensure mobility for the melting experiments. Following that, an Engineering Model (EM) has been built and tested for functionality and under varying environmental conditions.

Tests were continued with the EM under vacuum and lunar gravity conditions in the large-scale research device Einstein-Elevator [2] allowing for experiment durations of about 4 seconds. The interior of the samples with a diameter of about 3 mm mainly consists of glass, i.e. amorphous solidified melt of regolith simulant, containing spherical voids of various sizes as analysed by X-ray tomography. In terms of mass and volume, all samples show comparable values.

Figure 1: 2D structure

Further, we accommodated the EM on a robotic arm to ensure mobility and produce flat rectangular specimens. Solid 2D structures of 20 mm x 20 mm x 4 mm in size were reproducibly generated despite the inhomogeneous simulant material (Fig. 1). So, it can be assumed that also larger samples can be manufactured with the process.

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Oxygen extraction through regolith thermal reduction

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Introduction

Space exploration is going to play a relevant role within the just started decade, with the Moon at its centre.

Many activities are on going to enhance science of\on and from the Moon and to develop the fundamental technology to accomplish the challenging objectives the foreseen missions to our satellite need.

Among those the capability to detect, extract and manipulate the in situ resources is central for humans back on the surface and more.

Politecnico di Milano, in consortium with OHB-I and OHB-S, under an ESA financed study, is running tests on a ground demonstrator for the specific thermal reduction processes for oxygen extraction from oxides in the lunar minerals. To accurately understand the process, Politecnico di Milano run a numerical modelling of the whole process steps and a comprehensive characterisation of the feedstock simulant. This allowed understanding the process in deep.

The paper will go through the simulant characterisation approach and results, the process description and modelling, the lab plant description and the experimental test campaign results, obtained with the implemented plant, addressing future steps towards an in situ testing on Moon surface.

Progress understanding lunar oxygen extraction with the FFC process

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Introduction

Developing technology for the efficient generation and utilisation of resources in space is an important enabling step for sustainable long duration exploration missions. Oxygen is a critical resource for both propellant and life-support and, looking forward, metals and alloys will be required for off-Earth manufacturing and construction. Lunar regolith is ubiquitous on the lunar surface and is a suitable feedstock for both resources. The Fray-Farthing-Chen (FFC) molten salt electrolysis process offers a high-yielding alternative to other oxygen extraction processes [1]. Additionally, the flexibility of the FFC process in the terrestrial metallurgy industry demonstrates its future promise for off-Earth metal production [2].

Conceptually, the FFC process is relatively simple. Applying a current to solid regolith submerged in molten salt reduces the oxides to form metals and liberates oxygen anions (O^{2-}) that migrate through the electrolyte to the positively charged inert anode, where they combine to generate gaseous oxygen. Proof-of-concept work carried out has demonstrated the efficacy of the FFC process for full reduction of powdered regolith to generate powdered metal [3]. In practice, there are significant challenges and knowledge gaps that need to be addressed with ground-based research before the promising applications for this technology in exploration can be realised.

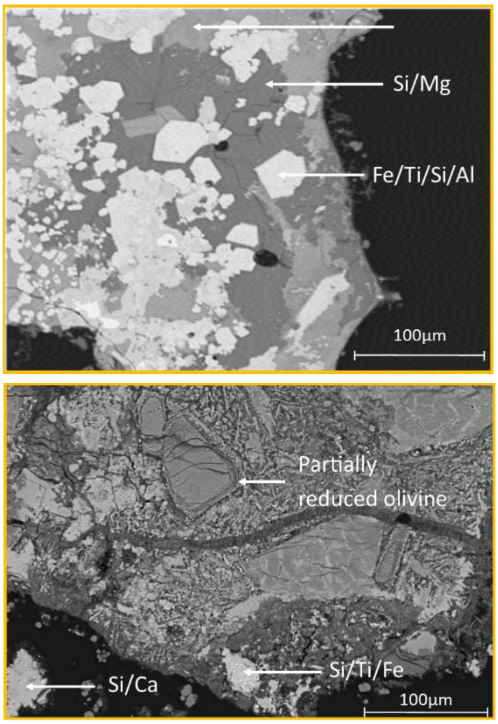

Figure 1: A comparison of the reduction product in high temperature $CaCl_2$ (top) and low temperature $CaCl_2/LiCl$ eutectic (bottom).

Like most other oxygen extraction processes, the need for high processing temperatures is a key drawback for the FFC process. When assessing the long-term feasibility and input requirements, it is important to understand the trade-off between temperature and efficiency, for example Figure 1 shows the limited reduction progress at a lower temperature in the same time. In this presentation we provide an update on the ongoing research into the FFC process at the European Space Research and Technology Centre (ESTEC).

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Towards the prospection of water ice on the Moon and beyond: on the need for a better understanding of water ice sublimation rate and related O and H isotope fractionation

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Pressures on (non-renewable) natural resources has steadily increased over the past 50 years. Recently, the exploration and utilization of space resources has been identified as a potential new avenue for opening our economy to external resources of energy and raw materials. In-Situ Resource Utilization (ISRU) intends to reduce the costs and complexity of bringing supplies from the Earth's deep gravity well into space. Water extraction and processing are highly relevant for ISRU and for space missions, since it may serve for producing propellant for spacecrafts and satellites, energy, radiation shielding, thermal management and life-support consumables. The Moon stands as a resource-rich accessible planetary body for ISRU. Prospecting lunar water deposits is a prerequisite for classifying them as resources and for designing and implementing water extraction and processing systems. This will pave the way a space mining business plan and assessment of its long-term economic feasibility. Over the last decades, several missions relaying on remote sensing techniques have attempted to explore water abundance, distribution, composition and physical form at the lunar poles. It was suggested the presence of relatively pure water ice in multiple permanently shadowed regions (PSR), water ice sublimating from lunar regolith grains, in form of frost, filling pore spaces, adsorbed layers, hydrated minerals, and recently molecular water in sunlit regions.

Among the international efforts for *in-situ* lunar polar exploration – targeting pressing scientific and industrial knowledge gaps – stands the joint Roscosmos/ESA Luna 27 mission scheduled to launch in 2025 [1], with the "Package for Resource Observation and in-Situ Prospecting for Exploration, Commercial exploitation and Transportation (PROSPECT)" on board. In order to interpret the results derived from those missions it is critical to understand the extent and nature of any potential changes that water ice may undergo during the sampling chain. However, the sublimation rate of water ice and the related isotope fractionation remain poorly understood in extra-terrestrial and lunar conditions. Thus, the calculation of water ice's abundance and isotope signature remains highly uncertain, hindering the assessment of potential lunar water resources and the interpretation of scientific planetary data. This knowledge gap is largely inherent to the still prevailing instrumental limitations. In order to overcome these limitations, we have designed a prototype geared towards carrying out sublimation under high vacuum and low temperatures and measuring the related isotope fractionation. Our system shall reach a base pressure in the range of 10^{-8} mbar (-170°C) and carry out sublimation at 10^{-6} mbar (~ -110°C) at a stable and homogeneous temperature. The system shall allow the water collection at high recovery yields and without isotope added instrumental isotope fractionation. The results obtained from this prototype shall provide urgently needed data for improving existing theoretical models for the simulation of the physical process occurring during water ice sublimation under lunar environmental conditions and for improving and validating the theoretical isotope fractionation model for low pressure systems at cryogenic temperatures that we are developing.

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Wet-processing and synthetic H_2O weathering of unrefined regolith towards high strength 'sandcastles'.

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Introduction

Due to the harsh climate, atmosphere and radiation conditions, human missions with long residence times on the Moon and Mars would require early ISRU approaches for habitat and infrastructure building. Especially in terms of building materials, various past ISRU works focused on concrete-like materials or the sintering of extraterrestrial regolith into (often dry-pressed) ceramic bricks. However, dry-processing of space weathered regolith materials (with their sharp morphologies and unique surface properties) can be expected to faces various challenges. In this respect, wet-processing, which is the most used approach for the shaping of oxidic materials on Earth, has significant advantages (e.g., higher particle packing, dust reduction) and what is essential after 'fusion drying' wet-processing leads to hard powder agglomerate structures due to the interaction of minerals with water.

Wet-processing of Lunar regolith simulants

Weathering lunar regolith through dispersion in water will lead to the release of ions into the liquid – if such dispersions are dried, the ions will be precipitated at interparticle contact points resulting in hard powder compacts/agglomerates. This mechanism could either be used to build infrastructure or complement other ISRU efforts on the Moon. Furthermore, the dissolution/precipitation of individual Lunar minerals and glasses might be employed to produce synthetic phyllosilicates. In recent work [1], we have used the wet-processing of simple Lunar regolith simulants from two feldspar powders for dry powder compacts (similar to dry sandcastles). In a first step, feldspar powders were dispersed in deionized water and a pH buffer to study mineral dissolution. Dispersions were aging to increase ion concentrations and subsequently, water content was reduced. The resulting pastes were molded into cylindrical shapes and dried. Dried powder compacts yielded compressive strength of ~ 0.23 MPa from deionized water and 0.52 – 0.7 MPa for powders dispersed in buffer solution. Longer and more specialized leaching experiments with high fidelity simulants can be expected to result in powder compacts with higher compressive strength, especially relevant for real Lunar regolith, which is highly reactive to H_2O.

Wet-processing of Martian clay regolith simulants

Fusion drying of clays has been (and still is) an essential construction technology for all major civilizations on Earth. In recent work [2], we have introduced wet-processing of phyllosilicates for ISRU, using Mars global simulants (MGS-1C). We could develop a universal clay-based material system for unfired clay structures (adobe) on Mars that can be formed using all common shaping processes. Fusion dried adobe from clay slurries/pastes had a compressive strength of 5 – 30 MPa, which is similar to common terrestrial concretes.

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THURSDAY
APRIL 22ND

Session 3
Capability Showcase

Chair: Patrick Michel and Advenit Makaya

13:30	Introduction
13:35	Highway to the Moon with Ariane 6
13:42	Low-Thrust Round-Trip Trajectory Optimization To Thousands Of Neas
13:54	The Progress Of Asteroid Mining Plans At Origin Space
14:06	Space Situational Awareness As An Enabling Capability For Asteroids Mining
14:18	Honeybee Robotics Space Resource Exploration And Excavation Capabilities
14:30	Puli Lunar Water Snooper - An In-Situ Water Mapping Payload For Lunar Surface Missions
14:42	STAARK Luximpulse Robotic Arm For Lunar Resources Utilisation
14:54	Microwave Heating Demonstrator (MHD) Payload For Fabricating Construction Components And Extracting Resources
15:06	Research Progress on In-Situ Exploration and Utilization of Extraterrestrial Resources
15:18	Deep space communication and navigation services: how microsatellites can boost the exploration and commercial exploitation of the solar system

Highway to the Moon with Ariane 6

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Introduction

During the IAC held in Washington DC in Oct. 2019, Arianespace announced "The Moon Multi-Launch Service" opportunity with Ariane 6 to address the growing lunar market. An Ariane 6 will be launched from the European Guyana Space Center to a Lunar Transfer Orbit (LTO) in 2024. Up to more than 7,000 kg of lunar landers and/or orbiters will be aggregated on an Ariane 6 "Multi-Launch Service" Carrying System, currently in development, in a full Rideshare configuration, thanks to the high volume and high lift capability of the Launch Vehicle [1]. This 100% rideshare approach will allow to bypass pairing constraints specific to lunar missions (constraints on launch date/time/window) and give passengers full agility to achieve their goals while reducing launch costs.

Figures and Tables

Figure 1: Arianespace's Moon Multi-Launch Service

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Low-thrust round-trip trajectory optimization to thousands of NEAs

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Introduction

In recent years asteroids have become increasingly interesting due to a heightened awareness of their scientific, commercial, and hazardous properties. Scientifically, they continue to unveil precious details about the Solar System's origin and ongoing evolution due to 1) technological advances that have improved their discovery and characterization rates by orders of magnitude and 2) the many fly-by and rendezvous spacecraft missions that have visited a growing list of these diverse objects. They are commercially valued at trillions of dollars once the technology has evolved to the point where mining is economically viable. Finally, the danger of asteroid impacts on Earth has become fully appreciated only in the past half century and dedicated efforts to identify the most dangerous km-scale asteroids have already reduced the risk of an unknown impact by more than 90%. Even so, the residual risk remains significant and justifies continued investment in identifying smaller, but still hazardous, objects.

Therefore, irrespective of whether the motivation is scientific investigation, deflection for planetary defense, or the profit margin of an asteroid mining company, there is a growing need for rapid cost evaluation of asteroid mission scenarios that requires novel optimization tools and techniques. The identification of the most interesting or profitable targets may require screening trajectories for thousands of objects over long time scales of up to a hundred years to identify optimal candidates. Potentially millions of trajectories may need to be calculated to provide a consistent comparison, especially for round-trip sample return or mining missions. The problem's complexity is reduced with the use of high-thrust, pseudo-impulsive chemical propulsion but explodes in the case of more realistic continuous, low-thrust missions that e.g. use less fuel and are therefore more profitable.

In this work we describe our method to solve this problem based on combining a fast but low fidelity optimizer with a high-fidelity trajectory design to provide quick and robust trajectories. We applied our algorithm to optimize round-trip low-thrust missions to a catalogue of more than 4,000 synthetic but realistic ultra-low Δv near Earth objects over the course of the next 100 years. In this case, the customer, TransAstra Corporation, plans to extract water from the asteroids, use some of the extracted water as fuel for the return trip to the Earth-Moon system, and then sell the remaining water to customers in high Earth orbit or e.g. at NASA's Lunar Gateway. Our tools allow the company to maximize their profit margin by minimizing the use of fuel/water over multiple launches, rendezvous time spans, and return opportunities to each target over the course of the century.

The Progress of Asteroid Mining Plans at Origin Space

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Introduction

Origin Space is a Chinese commercial company dedicated to exploring and utilizing space resources. The near-term mining target is near-Earth asteroids. The company's road map for mining asteroids is to find-prospect-land-collect-return, and all stages can be developed in parallel.

To achieve the goal, the company has launched several test satellites and payloads in 2019 and 2020, including UV and X-ray telescopes. It will launch two other satellites in 2021: NEO-1, the space mining bot; and YANGWANG-1, an optical and UV telescope. The NEO-1 will verify and demonstrate multiple functions such as spacecraft orbital maneuver, simulated small celestial body capture, intelligent spacecraft identification and control, etc. The YANGWANG-1 will try to find new near-Earth asteroids and use its UV telescope to observe the characteristics in the ultraviolet band [1].

Figures and Tables

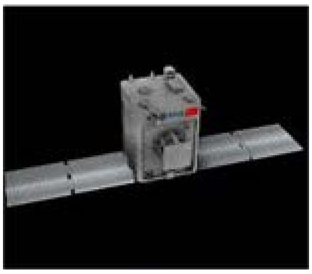

Figure 1: Schematic diagram of NEO-1 space craft, Origin Space's first space mining bot.

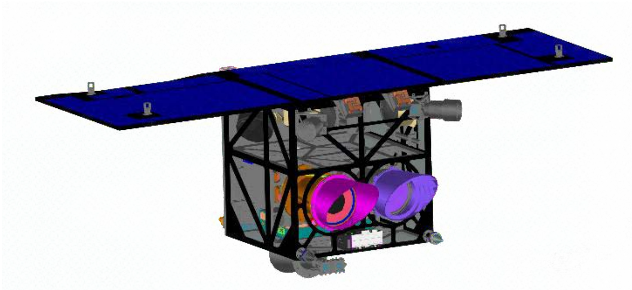

Figure 2: Schematic diagram of YANGWANG-1, Origin Space's optical and UV space telescope

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Space Situational Awareness as an enabling capability for asteroid mining

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Introduction

Space exploration and colonization missions are rapidly becoming more and more real, as technology advances and associated costs decrease. Future large scale commercial activities in space will require key resources and raw materials, such as oxygen, water or fuel. In order to preserve economic viability of missions, such resources shall be obtained from in-space sources rather than from Earth, to overcome the high cost of Earth launch. They may be found on the moon or even more so on asteroids that are approaching our planet, such as NEO (Near Earth Objects). Approximately 10% of NEOs are more accessible than the Moon, and maybe 50% of these are likely to be potential orebodies[1]. A similar challenge is posed by the fact that some resources on earth are increasingly scarce, some of them are even coming to an end, while the volume of those same ones present on the Moon or asteroids is extremely attractive, opening the opportunity for potential commercialization and making Space Mining a potential business opportunity to transport valuable materials back to Earth. As a result, there is a prospective demand for Space Mining, as well as In-Situ Resource Utilization (ISRU), and several government and private ventures are already targeting such activities.

In order to support Space Mining activities, Space Situational Awareness (SSA) is required to make a leap ahead in terms of reliability and insight capability, especially as far as prospecting new mining opportunity is concerned. SSA capabilities would then be the equivalent of the Exploration process in the Oil & Gas industry. Currently SSA is only looking at NEO for monitoring and alerting purposes[2], with several NEO centres created by the most prominent Space Agencies. They propose a stepwise process that moves from observation to orbit propagation and alerting, if a certain threshold is reached. A similar standardized process can be derived to research the best candidates for possible Space Mining missions, analysing convenient orbits to minimize Delta-v, expected chemical composition and projected perturbation of nominal orbit *in lieu* of collision probability. Such processing chain should work as a command and control structure, being fed by multiple sensors and having the capability to task new acquisition in order to refine the preliminary analysis. In this scenario, the capability to fuse together different sources is also a clear advantage. Similarly to what is done in the O&G industry, if the candidate is considered mature, also a probe flyby can be considered, in order to get the final confirmation and then launch the Space Mining mission.

Although the typical dynamics of NEO with respect to earth do not require real time monitoring and extreme object custody, the availability of a constellation of LEO space based sensors can definitely improve the detection and characterization capability of the system and possibly increase the performances in terms of ISRU mission design. Finally, an enhanced SSA capability can provides additional benefits to the exploration segment as a whole. A better Space Traffic Management will help protecting mining spacecrafts during launch and re-entry phase and a deeper knowledge about NEOs trajectory would also allow safer interplanetary transport voyages.

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Honeybee Robotics Space Resource Exploration and Excavation Capabilities

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Since 1983, Honeybee has completed hundreds of projects developing innovative robotics and mechanisms for NASA, the US Department of Defense, and commercial customers. Honeybee specializes in developing technology to search for life and utilize the rich resources of the solar system. Over the last decade, Honeybee has developed a number of technologies for space resource ore body exploration and extraction, including TRIDENT, GasDrill, and PlanetVac, to name a few.

Figure 1: TRIDENT Drill.

TRIDENT (The Regolith and Ice Drill for Exploration of New Terrain) is a rotary percussive drill designed to be deployed from either a rover or a lander. Trident was designed to drill in both dry and icy regolith, and features dust tolerant components and abrasion resistant designs for long term use in extreme lunar environments. TRIDENT (Figure 1) has an internal temperature sensor to measure subsurface temperature and a heater for mobilizing volatiles. In-drill fiber optics instruments, spectrometers, and other sensors are possible additions. Because TRIDENT was designed from the ground up for space resources applications, it is highly dust tolerant and temperature agnostic. TRIDENT will be flying on the PRIME and VIPER missions in 2022 and 2023.

GasDrill (Figure 2) is a pneumatic drilling system capable of rapidly digging into compacted regolith with a drastically lower power requirement than traditional drills. The GasDrill system was developed for LISTER (Lunar Instrumentation for Subsurface Thermal Exploration with Rapidity), flying on the TO1D CLPS mission in 2022. Because traditional drills require either removing the regolith from underneath (e.g. using an auger drill as on Apollo) or crushing it and recompacting it into a side wall (using a hammer mole as on InSight), they have power requirements up to 450W. GasDrill requires only 60W with a solenoid and a single motor to drive its spooling tube. GasDrill is highly efficient at moving regolith, with up to 1 kilogram of regolith moved for every gram of gas. For space resources applications, GasDrill can determine the outer edges of a high ice content ore body and can be combined with a sampling system such as PlanetVac for rapid subsurface sample acquisition.

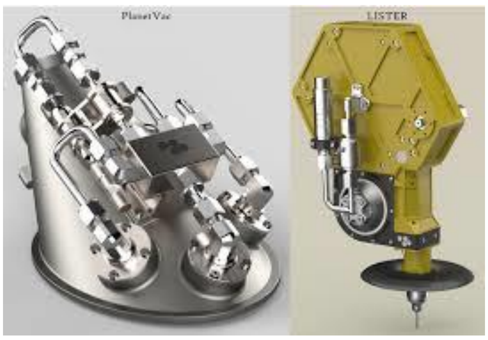

Figure 2: PlanetVac and LISTER.

PlanetVac (Figure 2) is a pneumatic sampling system, using compressed gas to excavate and transport regolith, small rocks, and even volatile material to an instrument suite or sample return container. It has been tested at component and system levels in a simulated lunar environment as well as in a live lander test and will also fly the on TO1D CLPS mission. Sample acquisition and delivery is one of the most difficult aspects of space resource exploration. Reduced gravity flights have shown lunar regolith, because of its high cohesion, will bridge and in turn will not reach an instrument cup or sample return container. PlanetVac alleviates these issues and excels in the most difficult aspects of sample delivery and acquisition. The PlanetVac system has been adapted for use on Phobos, Earth's Moon, and Europa.

Puli Lunar Water Snooper – An in-situ water mapping payload for lunar surface missions

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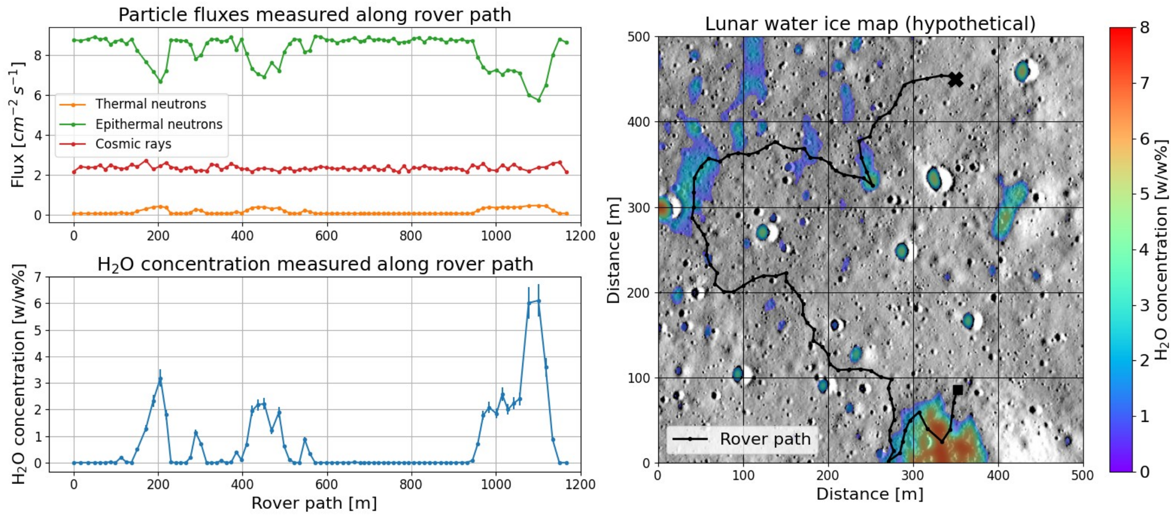
The Puli Lunar Water Snooper (PLWS) instrument is being developed by Puli Space Technologies to in-situ identify and measure the subsurface hydrogen (including water ice) content of the lunar regolith, addressing an essential need of the ISRU community and scientific goals of the NASA Artemis program [1].

The PLWS detects low energy albedo neutrons emerging from the regolith due to cosmic rays, using commercial off-the-shelf CMOS image sensors as particle detectors. Based on the measured particle fluxes, PLWS can also measure the water-equivalent hydrogen concentration of the surrounding lunar soil.

It is designed to be mounted on small lunar rovers with its extremely light mass (<400g) and small dimensions (10x10x3cm). On a rover, it will be capable of collecting invaluable scientific data and producing very high resolution hydrogen resource maps on the lunar surface (see in figure), even finding micro cold ice traps [2].

After winning two NASA challenges with the concept [3], the development of PLWS is funded and supported by NASA for a year. Flight models will be ready in January 2022, and the first PLWS might be delivered to the Moon in a NASA mission within the next 3 years.



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STAARK robotic arm for lunar resources utilisation

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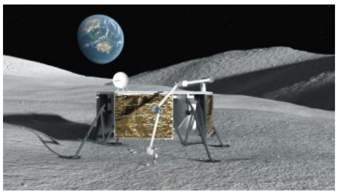
Introduction

Nearly 50 years after the Apollo program, the ARTEMIS program aims at returning mankind to the Moon, and prepare it for the next giant leap: the exploration of Mars. ARTEMIS plans an initial human landing by 2024 and sustainable exploration of the Moon by the late 2020s. These ambitious steps are meant to pave the way for future human missions to Mars. However, both sustainable presence of humans on the surface of the Moon and future exploration of Mars are not possible without a strong robotic infrastructure that will provide scouting, preparation, and support to human presence.

In the preparation of ARTEMIS, NASA has identified the following core mission elements for ARTEMIS: launch system, crew vehicle, ground system, deep space network, commercial payload services, volatiles polar exploration rover, power and propulsion element, habitation and logistics outpost, deep space logistics, extravehicular activity system, landing system, lunar vehicle, lunar ground station, lunanet, mobility platform, habitat, surface power, and lunar surface innovation initiative [1].

Luxembourg put in place the SpaceResources.lu initiative in 2016 aiming at positioning the country as a pioneer in the exploration and in situ resources utilisation (ISRU), pushing for strong incentives for increasingly seeking involvement of the private sector in all aspects of space. In 2020 Luxembourg became a founding member of the Artemis Accords. In this context, Luxembourg-based Made In Space Europe, a Redwire company, set the goal to develop inexpensive robotic arms to address the focus areas of ARTEMIS program, namely providing capabilities to the core mission elements.

Indeed robotic arms are key and critical enabler for ISRU as they increase the range of operations of the lunar surface missions by providing capabilities such as:



- deploying payloads to the surface (e.g. spectrometers),
- relocating payloads on the lander to increase instruments Field of View (e.g. telescopes),
- inspecting lander after the landing (e.g propulsion nozzles),
- manipulating sampling instruments (e.g. driller/scoop) to collect samples from different places around the lander and bring them to the canister located on the lander for further analysis,
- manipulating volatiles extraction instruments,
- pointing contactless instruments to analyse composition of regolith (e.g. lasers),
- pointing cameras to check mission operation progress.

This paper addresses the innovation and use cases of the STAARK robotic arm for lunar surface activities.

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Microwave Heating Demonstrator (MHD) payload – for fabricating construction components and extracting resources

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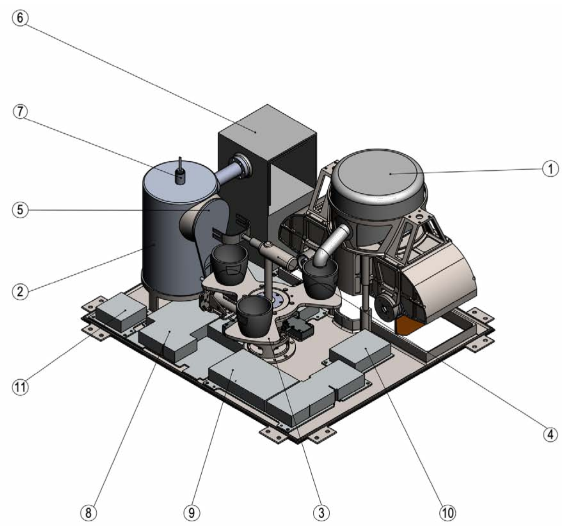
Introduction

Lunar regolith could be thermally treated to extract resources and build an outer habitat shell using additive manufacturing techniques (a.k.a. 3D printing) by robots [1]. Proof of concept experiments has demonstrated that microwaves couple efficiently with lunar regolith and sinter/melt it to build 3D structures and enable resource extraction [2]. However, there are still several questions that can only be answered through experiments on the Moon surface. Thus, the Open University (OU) initiated a collaborative project MARVEL (**M**icrowave heating **A**pparatus for **R**egolith **V**ariant **E**xperiments for **L**unar ISRU), with Added Value Solutions UK Ltd. and VIPER RF. The team aims to prepare the groundwork for the UK to lead the development of a Microwave Heating Demonstrator (**MHD**) payload on future missions to the Moon with the flight hardware being developed and built in the UK. The initial concept development of the MHD payload was completed with support from UKSA's NSTP GEI funding (Figure 1 [3]).

In this presentation, we will report the current progress of the MHD development conducted through the NSTP Pathfinder grant, focusing on the challenges with cavity design and the concept of a 1 kW solid-state microwave generator that could be used for future lunar missions.



ITEM NO.	DENOMINATION	QTY.
1	Lunar Regolith Sampler	1
2	Microwave Cavity	1
3	Crucible Transport Wheel	1
4	Crucible Transport Arm	1
5	Microwave Cavity Door	1
6	Mass Spectrometer	1
7	Pyrometer	1
8	Solid-State Microwave PSU	1
9	General Purpose PSU	1
10	On-board Computer and Data Logger	1
11	Pyrometer Control Unit	1

Figure 1: 3D CAD model of the MHD payload (dimensions 400 x 400 x 250 mm) [3]

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Research Progress on In-Situ Exploration and Utilization of Extraterrestrial Resources

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Introduction

With the development of human's deep-space exploration, space missions, such as building a lunar research station and landing on Mars, have put on the agenda. Due to the limitations of carrying capacity and cost, traditional means of rocket delivery cannot effectively support the development of future space missions. It is necessary to reduce or even remove the dependence on the matter and energy replenishment from the earth. Thus, in-situ exploration and utilization technologies to obtain sustainable water, oxygen, energy and other supply for human living and long-term extraterrestrial survival have been intensely required. Here, we will present our work in developing in-situ exploration and utilization technologies of extraterrestrial resources, including in-situ water/ice resources extraction and utilization from extraterrestrial soils, extraterrestrial artificial photosynthesis, in-situ energy storage and conversion, and 3D printing and manufacturing of lunar regolith (Figure 1). The key technologies have been designed to realize high-quality water acquisition, the conversion of CO_2 and H_2O into O2 and other fuels, power generation, respectively. Meanwhile, an extraterrestrial survival system with producing continuous water, electricity, oxygen and other supply has been exploiting through the integration and coupling of the key technologies.

Figures and Tables

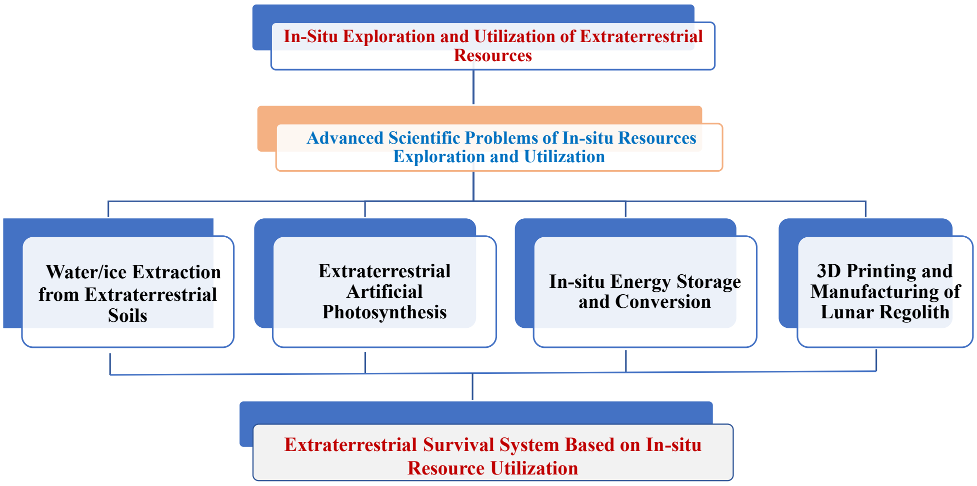

Figure 1: Schematic illustration for in-situ Exploration and Utilization of Extraterrestrial Resources.

Deep space communication and navigation services: how microsatellites can boost the exploration and commercial exploitation of the solar system.

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One of the biggest challenges for the exploration and exploitation of the solar system is to establish a communication link with the space assets and to precisely locate them. Currently most of the deep space missions rely on big and expensive ground infrastructures operated by the space agencies, but this approach will be not sustainable in the next years, as the number of missions is expected to steeply increase because of the investments of the private sector.

Argotec has been working on deep space communication and navigation solutions based on microsatellites with the goal of providing a cheap and reliable service to commercial and institutional missions. The vision is to exploit the flexibility of microsatellites and growing interest in applications beyond LEO for such platforms to create infrastructures for the exploration of the solar system, in particular the Moon and Mars.

ANDROMEDA is a lunar communication and navigation service based on a constellation of microsatellites that will provide 24/7 connectivity to users located in strategic areas such as the south pole and complete coverage of the lunar surface. The service is provided by satellites with a mass lower than 60 kg that will allow the establishment of communication relay infrastructure providing speeds of tens of Mbps between the lunar users and the Earth. The satellites are based on the Hawk platform that Argotec has developed and qualified for deep space missions and are equipped with highly reliable avionic systems that provide a long lifetime even in the lunar environment. The first phases of the service are planned to start as soon as 2024.

To boost the capability of the service and, in general, to improve the deep space communication, Argotec is also developing a user terminal for deep space that works in S and K band that enables seamless communication with the ANDROMEDA relay constellation and the Earth. The user terminal is compatible with small spacecraft and it is designed to be modular and easily customizable according to the missions' needs. It will reach TRL 7 in 2022.

The Mars Comms/Nav (MCN) is a multi-satellite constellation that Argotec is studying in the frame of an ESA activity that shall prototype key technologies for establishing a communication and navigation infrastructure at Mars, thereby enabling multifarious new missions without the burden of carrying their own expensive systems to establish Earth link. Utilising S and K bands for user link and Ka band for the backbone link, the MCN will provide a high average data relay volume, up to hundreds of GB per day, from Mars assets to Earth. In addition, the service provides positioning accuracy in the order of few metres to users on Mars surface.

Development of navigation techniques for autonomous orbit determination for deep space constellations based on the measurement of range and doppler effect using inter-satellite link signals is also being pursued at Argotec. One satellite is used as master node which performs the measurements to reconstruct the position of the other nodes. In this way the need of performing ranging and tracking from Earth is strongly reduced, and it is possible to have a good navigation service wherever a GNSS-like approach is not feasible. Additionally, this shall immensely reduce the operational costs of satellites in deep-space.

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