

# UPREB: Universal Predictors of Regolith Behavior – Concept and Overview

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**To develop successful missions involving In-situ Resource Utilization (ISRU), such as extraction of oxygen or metals from regolith or use of regolith in lunar construction, fundamental knowledge gaps regarding the rheology of regolith on the Moon must be closed. The complex mechanical behavior of the irregularly shaped and sharp-edged regolith particles, which is particularly influenced by the extreme lunar conditions, is currently not well understood. To harness the full potential of lunar regolith, it is essential to understand how it behaves during handling, transportation, and processing on the Moon. In this paper, we report on a new methodology we have developed to understand and predict the flow behavior of regolith for lunar applications. Earth-based tests on regolith simulants and initial numerical models predicting its behavior in different settings represent the starting point, allowing us to identify flow-relevant characteristics of regolith in Earth's environment. In parallel, digital twins of lunar regolith particles will be generated from 3D tomograms, chemical composition data and observed physical interactions, with the intention to perform virtual materials testing on these digital twins. Furthermore, flow and material tests will be performed using regolith simulants in a parabolic flight campaign, where the harsh lunar conditions can be recreated with a dedicated testing facility, i.e., a vacuum and plasma chamber operating at appropriate temperatures and lunar gravity. Regolith rheology data collected in this setting will be used to calibrate, validate and improve numerical models and the digital twins. The validated numerical models and digital twins are key to generalizing the methodologies developed on the ground and in the parabolic flight to the behavior of lunar regolith on the Moon. Future lunar missions will provide more in-situ experimental data and allow further refinement and validation of the predictive models for lunar regolith flow behavior. This paper provides a system-level process description of the UPREB methodology, and is one of four papers. The other three papers focus on the key elements of UPREB, concerning the regolith image data acquisition and processing, digital twin development and numerical simulations of regolith rheology.**

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## Acronyms and Nomenclature

3D	=	Three-dimensional
AFM	=	Atomic Force Microscope
CAD	=	Computer Aided Design
CFD	=	Computational Fluid Dynamics
DEM	=	Discrete Element Method
DiRT	=	Digital Regolith Twin
FIB	=	Focused Ion Beam
ISRU	=	In-Situ Resource Utilization
LuRDAQ	=	Lunar in-situ Regolith Data Acquisition
LuSiFa	=	Lunar environment Simulation Facility
MLA	=	Mineral Liberation Analysis
MVTAT	=	Institute of Mechanical Process Engineering and Mineral Processing
PP	=	Particle - Particle
PPHT	=	Particle - Particle Interaction Hardware Tests
RE	=	Regolith - Equipment
ROXY	=	Regolith to Oxygen and Metals Extraction
SEM	=	Scanning Electron Microscopy
TUBAF	=	Technical University Bergakademie Freiberg
TUBS	=	Technical University of Braunschweig
UPREB	=	Universal Predictors of Regolith Behavior

### I. Lunar Regolith: A Hard-to-Handle Raw Material for ISRU

Space exploration activities are expected to grow significantly over the next decades, as evidenced by current trends and numerous roadmaps presented at national and global levels, beginning with the International Space Station and continuing to the lunar vicinity, the Moon, asteroids and Mars<sup>1-3</sup>.

This trend is fueled by advancements in technology, in particular, decreasing launch costs, with the space industry's market volume that is projected to reach \$1 trillion within the next 15-20 years<sup>4,5</sup>. Central to these ambitions is the concept of In-Situ Resource Utilization (ISRU), or "living off the land," which emphasizes the production of essential resources, such as oxygen and metals, locally, rather than supplying them from Earth. These resources are critical for life support, fuel production, construction, and other applications<sup>1,2,6,7</sup>. ISRU activities are anticipated to grow into a \$ 63 billion market by 2040, predominantly driven by oxygen production from local resources<sup>7</sup>.

ROXY (Regolith to Oxygen and Metals Conversion), a molten salt solid oxide membrane electrolysis process, developed by Airbus, meets the requirements for an economically viable ISRU process to extract oxygen and metals from regolith<sup>8-12</sup>. ROXY facilities are currently under development at different scales: A lunar demonstration mission with a miniaturized version of a ROXY reactor, called Mini-ROXY, is currently in preparation<sup>13,14</sup>. Furthermore, the viability of a scaled-up ROXY pilot plant, producing 1 ton of oxygen per year, has been investigated<sup>15</sup>.

As ISRU and lunar exploration efforts progress, the handling and processing of lunar regolith will play a pivotal role. Lunar regolith is the broken-up rock that covers most of the lunar surface up to several meters, which was produced over billions of years due to countless impacts and micrometeorite bombardments<sup>16,17</sup>.

The handling and transportation of regolith in facilities, like ROXY, is a central and often underestimated process. Such facilities will rely on the transfer of excavated regolith to the facility and subsequent handling between various elements of the facility. This includes passing regolith through funnels, pipes or similar devices. The transportation behavior in these devices is mainly influenced by the surface topography of the single particle, the friction between particles, the cohesion, the electrostatic charge and other physical parameters of the regolith. These issues arise from the unique and complex behavior of regolith under lunar conditions, where extreme temperature variations, reduced gravity and electrostatic interactions influence its rheological and mechanical properties. Faulty dimensioning of regolith handling devices may lead to clogging or sticking which could jeopardize the feasibility of such facilities.

This leads to three fundamental questions which must be answered to evaluate the viability of a ROXY facility on the Moon, and, by extension, to almost any lunar equipment that will interact with lunar regolith:

- How does regolith behave when being handled, processed and transported on the lunar surface and in a lunar facility, in partial gravity and subject to the lunar environment?
- How does this affect its use for oxygen and metals extraction, or other applications?

- How can the behavior of regolith in a lunar environment be predicted to facilitate the production of the reliable regolith handling elements that are needed as part of a lunar facility?

Any attempt to understand, characterize and predict the behavior, handling, and transport of regolith on the Moon must consider the driving factors that determine those properties. Lunar regolith consists of powdered lunar rock with a broad particle size distribution. The particles are sharp-edged, electrostatically charged due to the Moon's lack of atmosphere and interspersed with fragments of glass<sup>16</sup>. Key driving factors of flow characteristics are the irregular and complex shape of the regolith particles, the reduced gravity on the Moon, and electrostatic charging of particles. The main factors influencing the sticking and clogging of lunar regolith on the Moon are a combination of its physical nature and the environmental conditions on the Moon.

Gravity influences the transportation properties of regolith particles, such as clogging of funnels and gravity-driven flow. These processes are furthermore affected by electrostatic cohesion of particles and adhesion between particles and surfaces. Dust particles adhere particularly strongly to surfaces due to the electrostatic charge, mainly caused by solar ultraviolet radiation. During the day, ultraviolet radiation knocks electrons out of the lunar soil (photoemission), positively charging the dust particles. This charge is so strong that dust particles can be raised from the soil by electrostatic repulsion, creating a temporary dust atmosphere. Due to the reduced gravity on the Moon, this dust persists for a long time and represents a challenge for people and equipment, as it settles into cracks and mechanisms, causing blockages. Since the Moon does not have a protective atmosphere or a magnetic field, high-energy protons and electrons of the solar wind hit its surface directly, leading to further electrostatic charging of the lunar surface and dust, and accumulated charge cannot be drained again. In shaded areas, the dust is negatively charged, while in sunlit areas it remains positively charged. This effect is due to the variation in the photoelectron current between lit and shaded areas. These charge differences create a complex electric field that causes motion within the dust clouds. In addition, the influence of Earth's magnetic tail reinforces the charge opposites between the dust grains and the lunar surface, which can lead to even greater charging and levitation of the particles<sup>18,19</sup>.

Our current understanding of lunar regolith properties comes from samples brought back from the Apollo missions, some in-situ measurements and remote sensing data. However, substantial knowledge gaps remain in understanding the rheology of lunar regolith. Large-scale experimental investigations of mechanical properties of regolith are currently unfeasible on the Moon, since these are associated with high costs and long development periods, which are often incompatible with development timelines of lunar equipment. Also, reproducing lunar conditions on Earth requires elaborate experimental setups, e.g., parabolic flights or drop towers with an appropriate lunar environment simulation facility. Additionally, no large quantities of lunar regolith are available for mechanical experiments and regolith simulants may not yield the same results.

In the past, the analysis of lunar regolith has focused on its chemical and mineralogical composition and properties<sup>20,21</sup>. To mimic lunar regolith in that regard, various types of regolith simulants<sup>22</sup> have been developed. Additionally, mechanical properties of regolith simulants have been investigated<sup>23</sup>. However, it remains unclear whether regolith simulants are representative for lunar regolith with respect to their mechanical properties, as these are not only influenced by mineralogical properties, but also by the shape of regolith particles and the lunar environment. While these relationships are well understood for many granular materials and mechanical processes on Earth<sup>24</sup>, the shape of lunar regolith particles have only been analyzed for single<sup>25</sup> or a small number of particles in the past<sup>26,27</sup>. In addition to the 2D characterization of statistically relevant quantities<sup>28</sup>, 3D micro- and nano-CT measurements of large numbers of particles from two samples of lunar regolith from the Apollo 11 and Apollo 14 missions have only recently been performed<sup>29</sup> and analyzed<sup>30</sup>, and could be used for verification purposes.

An alternative approach is therefore necessary, that will allow to predict the behavior of lunar regolith, ideally based on a combination of tests on Earth with regolith simulant and varying environmental conditions, numerical modelling and simulations. Such a method does not yet exist, since research on lunar regolith has so far often focused on specific applications, such as making building materials or extracting resources, rather than a general predictive model for its behavior in different settings.

This paper is one of four papers that report on the development of the UPREB (Universal Predictors of REgolith rheology and Behavior) methodology, which is intended to close this gap by providing a general predictive model for regolith behavior in static and dynamic situations. UPREB has been developed in collaboration between four entities: TU Bergakademie Freiberg, Ulm University, Technical University of Braunschweig, and Airbus Defence and Space. This paper provides a system-level process description of the UPREB methodology. The other three papers will focus on the key elements of UPREB regarding acquisition and

processing of tomographic image data<sup>31</sup>, development of a digital twin for regolith and numerical simulations of regolith rheology<sup>32</sup>.

## II. UPREB Objectives and Development Logic

It is the objective of UPREB to provide a general predictive model for regolith behavior in static and dynamic situations, that will allow to answer the following questions:

- What is the structure of individual regolith particles and how do structural descriptors correlate to each other?
- How does the chemical composition correlate to the structural descriptors?
- What are the particle-particle interactions and what are the flow properties of bulk regolith?
- How do the structure and the composition of individual regolith particles influence the particle-particle interactions?
- How does regolith interact with equipment and how can its bulk motion through equipment be described?
- How do the particle-discrete descriptors influence and correlate with the bulk motion and interaction with equipment?
- How does regolith behave in static situations when in contact with equipment?

Currently, such a methodology does not exist. However, there are approaches from related scientific fields that can be used as elements of UPREB. These approaches are:

- 3D Characterization of individual particles with high spatial resolution in the  $\mu\text{m}$  range, incl. imaging and measurement of physical properties (around  $10^4$  particles)
- Stochastic modelling and generation of structural models and digital twins of the particles from the high-resolution data, as part of virtual materials testing (an approach to optimize materials, thereby saving test runs with many material variants and replacing them with virtual tests)
- Physical modelling of the interaction of a large number of particles using methods such as DEM and Machine-Learning Technologies, with the possibility for verification through representative hardware experiments
- Rheological and static experiments using regolith simulant and in-situ lunar regolith experiments for calibration and validation of models and simulations.

These approaches are commonly used to optimize materials for specific applications, but for UPREB, instead of trying to optimize a material, lunar regolith is considered as a given material. Different manifestations of regolith under different environmental conditions are used as a starting point for the creation of a comprehensive model to predict the behavior of the material in new, previously unobserved conditions. An essential point here is that the models must be validated by tests with different characteristics and environmental conditions (e.g. reduced gravity, ambient atmosphere / pressure, electrostatic charge, etc.)<sup>33-40</sup>.

As part of this work, the above four approaches were adapted, recombined and consolidated to achieve the objective. The result is a completely new process and scientific methodology, that allows to predict the behavior of lunar regolith under lunar conditions, which is of great interest not only for the conception of ROXY facilities, but for many applications that deal with the interaction of equipment on the moon with lunar regolith. A patent application of the UPREB methodology is in preparation.

In the next sections, the key building blocks of the UPREB methodology are explained.

### A. Particle Discrete Data Acquisition

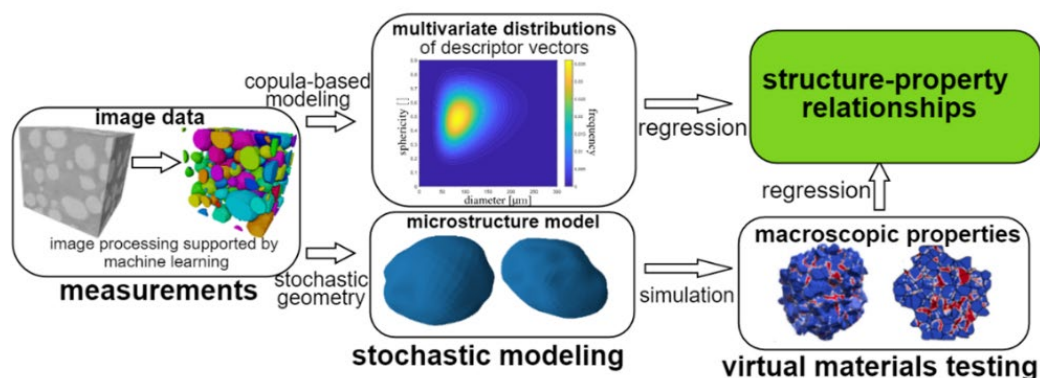
The microstructure of regolith particles, including descriptors of size, shape and roughness, can be determined via particle-discrete 3D X-ray Tomography. This method can achieve a spatial resolution of below 1  $\mu\text{m}$  and is established at the Institute of Mechanical Process Engineering and Mineral Processing (MVTAT) at the Technical University Bergakademie Freiberg (TUBAF). An example of the generated image data can be seen in Figure 1. Samples are prepared for analysis, whereby everything is done to support particle segmentation to enable particle-discrete image capturing. The sample is exposed to an X-ray source from different angles. The attenuated signal is then transferred to visual light via a scintillator and magnified to a detector screen using a microscopic optic. The stack of projection images of the particles undergoes tomographic reconstruction and image processing techniques, leading to the final 3D particle-discrete tomogram. Considering the size of regolith constituents, the resolution achieved with this method suffices to resolve individual regolith particles in size and shape. Also, using this method it is possible to image clusters of particles, that could have merged together. Furthermore, spatially resolved internal properties, such as chemical composition, can be acquired using correlative measurement methods, such as laser ablation, focused ion beam (FIB) and scanning electron microscopy (SEM). In combination with AFM measurements, the surface topography of a subset of particles can be captured, leading to a complete description of individual regolith particles.<sup>41</sup>



**Figure 1. Regolith particle generated by 3D X-ray Tomography at TUBAF. The length of the particle is 240  $\mu\text{m}$ .**

### B. Statistical Analysis of Structural Descriptors and Virtual Materials Testing

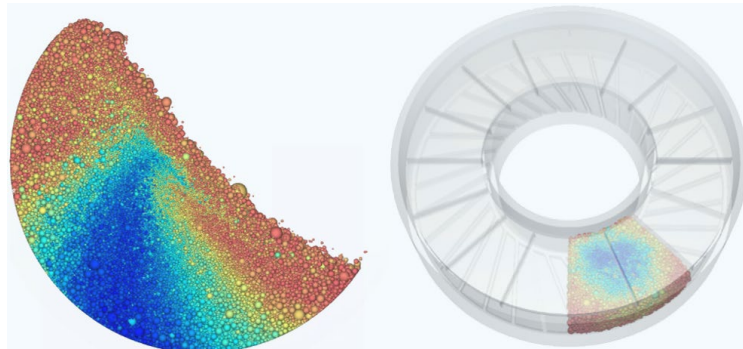
3D image data is used as an input for a statistical analysis of the geometry and texture of the regolith particles and clusters, which is performed by the Institute of Stochastics at Ulm University. Morphological descriptors of regolith particles, such as volume, surface area, sphericity, and aspect ratio are measured and statistically analyzed. This also applies to the computation of descriptors for the surface texture of the particles observed in the 3D image data, which correlates with the chemical and mineralogical composition, which are measured in a previous step, or known from the manufacturer of the regolith simulant. By this microstructure analysis of particles, followed by modelling of multivariate descriptor distributions, correlations between the particle descriptors can be investigated. Moreover, these multivariate distributions of particle descriptors can be used to calibrate a stochastic 3D model for generating digital particle structures. The thereby generated digital particles can then be used as inputs for numerical simulations to determine macroscopic properties. This is the concept of virtual materials testing and is especially suited to regolith due to the scarcity of lunar regolith on Earth. The schematic of the concept is shown in Figure 2.



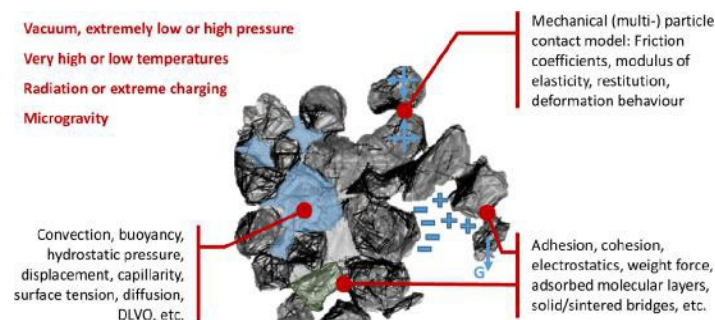
**Figure 2. Schematic of the procedure to establish structure - property relationships using virtual materials testing and stochastic modelling of 3D image data<sup>42</sup>.**

### C. Particle - Particle Interactions and Behavioral Simulations

The Discrete Element Method (DEM) together with other simulation techniques, like Computational Fluid Dynamics (CFD), are applied to simulate the processing of lunar regolith under extreme conditions. Specifically, CFD-DEM coupling is used to simulate the plume-surface interaction of a rocket on the lunar surface by the Institute for Particle Technology at the Technical University of Braunschweig (TUBS)<sup>43-45</sup>. The principle can however also be applied to other situations, such as the flow of regolith through a funnel or other mechanical device. Such an application can be seen in Figure 3a. Furthermore, properties associated with the interactions between the particles, such as cohesion between the particles, are evaluated. Simulations of particle-particle interactions using a rotating cylinder or a shear cell, shown in Figure 3b, are developed to mitigate the need for performing the tests using hardware, which are costly and time-consuming. However, some hardware tests using different manifestations of regolith in different environmental conditions are required for calibration, but as soon as the simulation has been validated, it can be used as a replacement.



**Figure 3a. Simulation of the particles' movement in a rotating cylinder for the measurement of the dynamic angle of response and simulation of a ring shear cell to measure the cohesion for a given material.**



**Figure 3b. Cluster of virtual particles shown, with physical interactions and particle properties added to the cluster. These are determined in experimental set-ups and the whole construction of structural digital twin and physical properties used as input to particle simulations, such as plume-surface interactions, shear cells, or flow behaviour experiments<sup>46</sup>.**

### D. Regolith Interaction with Equipment

To understand and simulate the behavior of regolith in situations involving the interaction with equipment and to calibrate the models, regolith tests with hardware have to be performed in the lab with regolith simulants under different environmental conditions. These could involve analyzing the dynamic properties of regolith flowing through funnels of different shapes, sizes, materials and surface textures, or through pipes of different diameters and surface textures. Furthermore, the static behavior, such as settling density on equipment or density and behavior in fluids like water or molten salt, can be measured. Ideally, correlations between the properties of the equipment and the behavior of the regolith can be drawn, with the ultimate aim to tailor the design of subsystems of the equipment responsible for regolith handling to fulfil its correct purpose. Ideally, the hardware tests are performed in settings and facilities that closely replicate the lunar environmental conditions, i.e. in reduced gravity (in a lunar parabolic flight or drop tower), under high vacuum, in a plasma atmosphere, and at representative temperatures, or are performed with samples of lunar regolith.

These tests are vital, since they will allow to determine the influence of the harsh lunar environmental conditions on the test results. Therefore, the results from these lab tests can be used to calibrate, validate and improve the models and simulations of interactions of regolith with equipment, which are developed in parallel to the hardware experiments. The verification of the simulations and models will first be performed using regolith simulants, due to its relative abundance on Earth and ease of hardware experiments compared to lunar regolith data. As soon as lunar regolith data is available and in-situ hardware experiments have been performed, the models and simulations will be able to improve their predictive nature for lunar regolith applications.

The models and simulations will remain open to continuous improvements to increase the validity and predictions using inputs from updated experiments performed in different and potentially new conditions. These could involve additional experiments performed in a lunar parabolic flight or drop tower, and, ideally, on the Moon itself. Like this, the quality of the predictions from the model will be improved over time, to achieve the goal of predicting the behavior of lunar regolith interacting with lunar equipment on the Moon subject to the lunar environment.

### III. UPREB System-Level Process Description

The major elements that make up the UPREB methodology have been introduced in the previous chapter. This chapter provides a system-level process description, detailing how the individual elements are combined into one coherent system.

The elements are split into two categories: one category focuses on properties of individual regolith particles, and the other focuses on the properties of regolith particles in bulk. In general, both categories are dependent on environmental conditions. It is assumed that all properties should be measured as a function of different environmental conditions, such as temperature, pressure, electrostatic charge, and reduced gravity. It is known that the harsh lunar environment is the cause of the complexity of the lunar regolith particles, so to understand how the environment also affects the handling of regolith is crucial to developing equipment that can overcome the technical challenges.

Especially when considering lunar regolith, it is important to understand how the harsh lunar environment influences the behavior of regolith. This could be achieved, for instance, by conducting experiments in a Lunar Environment Simulation Facility (LuSiFa) in a lunar parabolic flight or in a drop tower. Despite the short amount of time at lunar gravity, these experiments are crucial to mimicking the lunar environment and understanding the influence it has on the behavior of regolith, prior to lunar in-situ experiments.

Due to the unavailability of lunar regolith for experimental purposes on Earth, the UPREB methodology is based on and will be initially validated with the use of regolith simulant. Initial predictions for lunar regolith can still be extrapolated from the simulations, with the limited amount of lunar regolith data available now, however the accuracy of the predictions will be limited due to uncertainties in the representativeness of regolith simulant and facility-generated lunar environment. To increase the accuracy of the predictive nature for lunar regolith, lunar data from in-situ experiments will be needed to calibrate and verify the predictions.

#### A. Individual Regolith Particle Descriptors

The first general category (properties of individual particles) is separated into two subcategories:

- The first is the structural descriptors of individual particles (relating to the shape, size, surface texture, etc.) and can be identified using high resolution 3D images (Particle Discrete 3D Image Data), which are acquired in the Discrete Particle Image Acquisition. Once the Particle Discrete 3D Image Data is available, they are used as input to the Regolith Particle Descriptors Analysis, where the structural descriptors are measured and analyzed.
- The second are the so-called internal descriptors, such as chemical composition, that have to be measured using other methods, such as MLA (Mineral Liberation Analysis). This data also provides input for the Regolith Particle Descriptors Analysis.

The analysis of the discrete particle data consists of a stochastic analysis, where the univariate distributions of each particle descriptor, as well as their multivariate distributions are determined. A stochastic model for the 3D structure of regolith particles is developed and calibrated to the measured multivariate distributions of particle descriptors. This model serves as a validated digital twin for regolith, from which digital particles can be generated, which statistically resemble measured particles with respect to key properties.

This approach has been applied to other materials and can reliably reproduce digital twins of the material at a high level<sup>47</sup>. As such, the method has been verified and can be applied to a wide range of powders and materials, such as regolith simulants or lunar regolith.

Regolith simulants are readily available commercially, whereas the availability of lunar regolith is very limited. However, this part of the analysis does not need the physical lunar regolith material, but only the image data of it, which is available from the Apollo missions.

## **B. Regolith Bulk Properties**

The second general category is split into two subcategories again, i.e. Particle - Particle (PP) Interactions, and Regolith - Equipment (RE) Interactions:

- Particle - Particle (PP) Interactions: The first considers the interactions of particles, which are determined using test equipment, such as shear cells, rotating cylinders or flat planes. Physical or flow properties of regolith, such as the static and dynamic angle of repose or cohesion, are the results from these PP Interaction Hardware Tests (PPHT). These results are used as input to a Digital Regolith Twin Generator, which attaches the physical properties to the generated digital particles from the Digital Regolith Structure Model Generator, leading to a Digital Regolith Twin (DiRT) in structure and physical behavior. Furthermore, these results can also be used to calibrate simulations of these PPHTs, which can, after sufficient calibration and validation, be used as a replacement to the hardware tests. The DiRT can be used as the medium for these simulations and can be used to generate a significant amount of data. As above, this method can also be applied to lunar regolith, whereby in-situ hardware tests from lunar data acquisition, if available, are used to calibrate the DiRT Generator to generate lunar regolith twins, as well as calibrate the simulation tests to lunar regolith.
- Regolith - Equipment (RE) Interactions: The second refers to the behavior of regolith in bulk in dynamic or static situations involving interactions with equipment. Using equipment, such as funnels, pipes or other mechanical devices, motion properties of the regolith flowing through the equipment are determined. It is also analyzed how the shape, material and surface texture of the equipment influences the motion of regolith. As well as dynamic test, experiments to determine the static properties of regolith when in contact with equipment, such as radiators or flat surfaces, are performed. These measurements are used to calibrate simulations of the dynamic and static experiments (RE Simulations with Digital Regolith Twin), which simulate the motion of the DiRT through CAD designs of equipment or the static behavior of DiRT on the equipment. For simulations of lunar DiRT, RE Hardware Tests with lunar regolith from lunar data acquisition can be used to improve the simulations to accept the lunar DiRT as the input medium. Once the rheological, dynamical and static interaction properties of regolith in lunar equipment are known and the simulations thereof are validated based on a subset of hardware experiments, the simulations can be extended to simulate the behavior of lunar regolith in CAD models of equipment, that have not yet been manufactured. Like this, different designs of the equipment can be tested virtually to evaluate the feasibility and optimization potential of the design for the intended purpose. These RE simulations, being able to accept DiRT or lunar DiRT as the medium and performing motion or static virtual experiments using CAD models of equipment, can be applied to any equipment for future lunar missions, highlighting the universality and potential of the UPREB methodology.

The simulations and correlation information can then be used to amend the design of the equipment to improve its functionality and improve the probability for overall mission success. As a first use-case and demonstration of the UPREB methodology, the funnel used in the Mini-ROXY demonstration mission<sup>13,14</sup> could be optimized to facilitate an unimpeded flow of lunar regolith into the cartridges.

## **C. Universality of UPREB**

UPREB provides a general predictive model for regolith behavior in static and dynamic situations in different environmental conditions. It presents a universally applicable methodology in two ways.

First, the intention is that the resulting models and simulations can be applied to any lunar equipment or infrastructure, if designs, i.e., CAD models, thereof, are available. A first feasibility demonstration of the methodology can be achieved with the Mini-ROXY funnel and can then be extended to other designs of lunar infrastructure. This represents the first interpretation of the universality of UPREB.

Second, due to its original connection to the development of ROXY facilities, UPREB was primarily developed for lunar regolith. However, because the individual constituents of the methodology have been established for powders and granular materials other than regolith, the methodology could in fact be applied to any granular material, as long as the structure of individual particles can be analyzed as needed, e.g. in terms of spatial resolution. This could be applied to regolith on other planets and astronomical bodies, but also for Earth applications, such as volcanic material for instance.

## IV. Discussion and Outlook

The reliable handling of regolith is a necessary condition for the operation of many lunar devices and facilities. A new methodology (UPREB), which serves to conceive and design equipment that works as intended in interaction with lunar regolith, was developed within the scope of this work. Validation of UPREB will be performed by the team as a next step. In addition to model development, a series of test campaigns with regolith in different environmental conditions are essential components of the validation:

- In the laboratory: A Regolith Flow breadboard was built. Tests are planned for 2025.
- Parabolic flight: A concept for parabolic flight system, LuSiFa, has been created, and a design campaign thereof will commence in May 2025, with the intention of applying for the next available ESA lunar parabolic flight opportunity.

UPREB is an open methodology in the sense that the quality of its models and predictions will benefit from additional input data. Therefore, collaborations with additional partners who can provide complementary data e.g. from drop tower experiments, early lunar missions, etc., are highly appreciated.

## V. Acknowledgments

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