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RESEARCH

Outline case for a payload and mission scenario to perform in situ de-risking, validation and calibration of lunar granular materials handling

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Abstract

Granular materials handling will be one of the important processes for success of future lunar ISRU and related efforts. Although well matured for terrestrial applications, it is still uncertain how locally sourced lunar materials will behave while being handled in lunar environment conditions, especially the lunar exosphere and reduced gravity. Various experimental and numerical methods enable replication and simulation of these unique lunar environmental and material conditions on the Earth. However, there is concern about the validity of these results having not been validated and calibrated in lunar environment conditions with real lunar materials. The current work outlines a case for generating in situ lunar datasets of bulk material handling observations for de-risking, validation and calibration of lunar materials handling knowledge and associated Earth-based simulations. Proposed is a future lunar payload, incorporating a set of eight material handling sub-systems, to generate suitable datasets with both, local and Earth originated, material samples in the lunar environment. Also outlined is a mission design to deliver the payload to the lunar surface and operational plan focusing on use over multiple lunar days. The intention for this paper is to generate further discussion and debate among the community as to the validity of the arguments outlined and the value of, and approach to be taken, for implementing a payload concept to provide in situ validation.

Keywords Materials handling · Lunar granular materials · Bulk materials · Reduced gravity · Validation · Payload · Lunar lander · Mission

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Introduction and context

Plans to establish a persistent human presence on the Moon (NASA 2020; Lin et al. 2024; Krasilnikov et al. 2024) rely heavily on the success of In Situ Resource Utilization (ISRU) to source raw materials for construction and manufacturing (Zhang et al. 2023; Crawford 2015; Crawford et al. 2023; Bennett et al. 2020; Duke et al. 2006; Spudis 1996). A critical, yet often under-represented feature of ISRU is the effective handling of local granular materials (regolith) within the unique lunar environment, specifically under reduced gravity and vacuum conditions (Just et al. 2020; Shaw et al. 2022; Walton 2012).

While terrestrial bulk material handling is a mature field, this knowledge is not directly transferable to the lunar surface. The specific challenges posed by the lunar

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environment and the unique properties of regolith mean that current Earth-based simulations—such as drop towers, parabolic flights, and the use of simulants (Lomax et al. 2022; Pletser et al. 2010; Pratnekar et al. 2024)—lack necessary validation against actual lunar conditions. This gap creates a substantial risk of hardware failure or inefficiency for future lunar activities (In-Situ Resource Utilization Gap Assessment Report 2021). Consequently, there is a timely need to generate in situ datasets to validate and calibrate these simulations.

We propose that a dedicated lunar payload is important to perform this de-risking by observing material handling processes directly on the lunar surface. The feasibility of such a payload is increasingly supported by the development of commercial lunar lander platforms, such as NASA's CLPS (Schonfeld et al. 2023), ESA's Argonaut (ESA Argonaut Mission URL), and others international endeavours, which promise reduced access costs (Chang'e Mission URL, Chandrayaan Missions URL, SpaceX Starship URL).

The objectives of this paper are fourfold:

- To outline the case for generating in situ datasets for the validation of lunar materials handling knowledge.
- To propose a philosophy and architecture for a payload concept capable of obtaining this data.
- To present a mission scenario for delivering this payload to the lunar surface.
- To outline a baseline operations plan for multiple lunar days.

This work serves as a conceptual study intended to generate community discussion regarding the proposed approach for in situ validation. Such discussion is intended to be used in subsequent work to iterate and refine the current concept including performing detailed analysis and trade-off studies as part of the evolution of the payload design.

This document is the result of a collaborative effort within a wider activity titled "Materials Utilisation for a Lunar Economy" (MULE), involving primarily European researchers brought together via an ESA study activity and a group of masters-level students within an Astronautics and Space Engineering course at Cranfield University.

Outline case for in-situ datasets for validation of Earth-based simulations of lunar bulk materials handling

This section outlines the need for in-situ validation of Earth-based simulations of lunar bulk materials handling and discusses the potential impact of such an endeavour.

The lunar surface presents a harsh environment characterized by a hard vacuum exosphere, reduced gravity (one-sixth of Earth's gravity), extreme temperature variations, intense ionizing radiation exposure, charging effects due to solar wind and solar UV interactions, and constant micrometeoroid bombardment (Heiken et al. 1991; Harrel et al. 2021).

These conditions have shaped the unique properties of lunar regolith, compared to Earth geology. Consequently, the behaviour of lunar regolith during handling is expected to differ significantly from that of nominally similar materials on Earth. Therefore, terrestrial experience with granular material handling may not be directly applicable to lunar surface operations. Directly applying this experience could lead to non-optimal procedures and equipment designs. For example: the high angular nature of lunar regolith results in poor flowability (Walton et al. 2007, 2012), potentially causing issues with hopper or silo discharge (Reiss et al. 2014) and electrical charging of regolith particles by the solar wind (Horanyi et al. 1998; Abbas et al. 2007), coupled with a lack of charge dissipation, can cause levitation of smaller particles, leading to dust contamination problems (Zakharov et al. 2020; Cain 2010).

Current practices involve simulating lunar environmental conditions and regolith properties using terrestrial experiments (e.g., parabolic flight campaigns, drop tower experiments, regolith simulant testbeds, thermal vacuum chambers) and computer-generated Discrete Element Method (DEM) numerical simulations. However, except for basic sample collection activities during the Apollo era (Heiken et al. 1991; Longobardo 2021), there are no relevant datasets from the lunar surface analysing material handling procedures such as: emptying silos or hoppers, conveying, transporting and excavation.

These procedures will be crucial for future lunar ISRU technologies (Zacny 2012). Furthermore, presently available lunar regolith simulants were primarily developed for spectroscopic or chemical-process applications, neglecting material handling characteristics (Schrader et al. 2010; Sibille et al. 2006; Taylor et al. 2016). For example, there appears to be no attempt to incorporate standardized material handling characterization (e.g., material flow functions) into the databases of simulant properties.

This lack of in-situ lunar validation presents a risk that technologies designed for lunar materials handling may fail or underperform when deployed. To mitigate this, a suitable dataset obtained directly from the lunar surface is urgently needed. This dataset would enable validation of Earth-generated data and assessment of regolith simulants, leading to more accurate simulations and reliable technology development.

Two options exist for generating such a dataset: (i) scientific approaches: measuring fundamental material and handling properties and (ii) pragmatic approaches: employing payload subsystems that closely replicate material handling processes relevant to future lunar operations (e.g., emptying and filling hoppers/silos, dynamic handling, excavating, sorting).

A pragmatic approach offers the added benefit of demonstrating and de-risking various mechanisms associated with future lunar ISRU technologies. The resulting dataset would comprise observations of granular materials being handled within these subsystems, from which fundamental parameters could be derived.

For the remainder of this paper, only the pragmatic approach will be considered. The authors believe that the additional knowledge generated about various material handling mechanisms warrants this focus. The scientific approach, whilst expected to measure basic materials properties relevant to materials handling, possibly with better accuracy, it would not generate the added pragmatic value of observing materials handling mechanisms in a lunar use case.

Top-level payload objectives and approach to payload design and mission concept

This section outlines a conceptual payload designed to generate in-situ datasets for validating Earth-based simulations of lunar bulk materials handling. A pragmatic approach was adopted, focusing on demonstrating practical materials handling techniques rather than pursuing a purely scientific measurement approach. This allows for a more direct assessment of operational challenges and technology readiness.

Payload philosophy and objectives

The payload development prioritizes demonstrating practical material handling techniques relevant to a future lunar surface economy. To ensure feasibility, the payload's volume, mass, and power allocation (outlined in "Payload configuration" section) were constrained to be compatible with anticipated commercial lunar lander capabilities (e.g., Peregrine, Blue Ghost, Nova-C and other).

While detailed requirements will be defined in later stages, the following top-level objectives guide the initial design:

(1) Lunar Relevance: Material handling processes relevant to a future lunar surface economy shall be tested on the lunar surface under realistic environmental conditions.
(2) Material Relevance: Bulk materials processed shall be relevant to the future lunar surface economy (e.g., lunar regolith, regolith mixed with water ice). Tests with Earth-based regolith simulants should also be conducted for calibration and validation purposes.
(3) Timely Development: Payload development and implementation shall be compatible with a timeline that enables data collection and community use within the early phase of lunar hardware development.
(4) Agile Approach: An agile or "fail-fast" approach shall be adopted for payload development to ensure compatibility with rapid development cycles and evolving lunar access capabilities.
(5) Commercial Compatibility: The payload shall be compatible with current or near-future commercial lunar lander/payload hosting opportunities.
(6) Data Collection: The payload shall include observation and data recording instrumentation to generate the required in-situ materials handling dataset.
(7) Ancillary Data: Where practical, the payload design shall incorporate features to enable the collection of data relevant to the lifetime and wear of mechanisms in the lunar environment, the effects of dust including dust generation and dust contamination (e.g. on optical surfaces) and contributing to early de-risking and Technology Readiness Levels (TRL) elevation of materials handling hardware.
(8) Budgetary Constraints: The total cost of the program shall be within defined budget limits (TBD).

Payload architecture

A pragmatic strategy was employed to assess the feasibility of incorporating various material handling processes into the payload, with the goal of enabling a sequential flow of material between different techniques. This includes:

- Regolith Acquisition: Excavation and conveyance of regolith from the lunar surface into the payload were considered integral to the material handling workflow (Just et al. 2020).
- Observation and Measurement: The payload incorporates essential observation and measurement systems to capture material behaviour during handling.
- Regolith Simulants: The inclusion of Earth-based regolith simulants within the payload was deemed valuable for strengthening the validation process.

Mission concept

To de-risk payload delivery and operation, potential near-future commercial opportunities were examined, including

NASA's CLPS missions and ESA's EL3/Argonaut. This assessment involved evaluating lander suitability and identifying potential lunar landing sites.

A simplified operations plan for a payload lifetime of one lunar day was developed to understand payload capabilities under a worst-case mission scenario.

This study employed a conceptual design approach to enhance overall comprehension of the payload and mission. This resulted in a high-level model that facilitates community consultation and feedback before further detailed development.

Detailed overview of the baseline payload design and comprising multiple regolith handling subsystems

Choice of material handling processes

The initial step in developing a payload concept was to consider and identify relevant materials handling processes that are anticipated to be required in future lunar surface economy activities.

A list of the main handling processes was developed by the authors who represented a broad range of terrestrial and lunar knowledge concerning materials handling. Through this approach following eight processes were identified. These processes were identified via an iterative process where we considered the major generic handling steps that would be required in lunar applications and how these could be implemented as subsystems in a compact payload and operated in a sequential or cascading sequence. At the current payload conceptual design stage, this was considered appropriate and in later design iterations more formal trade studies can be performed.

(i) *Excavation*.

A basic process to collect naturally occurring raw material e.g. regolith as well as accessing or collecting of processed materials stored in piles.

(ii) *Conveying*.

Conveying is a way of transporting solid granular materials such as grains or powders from the place of acquisition or between the processes.

(iii) *Sorting*.

Is a fundamental technique used to separate materials e.g. for the purpose of beneficiation. For the present study, it is assumed this will be based on mechanical particle size separation.

(iv) *Dynamic handling*.

Refers to the movement of the granular material through processes with the application of forces to induce the motion.

(v) *Static handling*.

Indicates the storage of granular materials without significant movement or flow. Materials are typical at rest within storage bins, silos or hoppers. Dynamic aspects are relevant in the filling/loading and emptying/discharge of storage vessels.

(vi) *Electrostatic separation*.

Relates to electric charging (and discharging) of granular materials due to solar radiations and triboelectric processes and used in some contexts to perform particle separation and sorting, i.e. beneficiation, and in others to cause detrimental effects including movement of particles to unintended locations and resultant dust and particle adhesion problems for mechanical parts and surface coatings.

(vii) *Pile forming*.

Pile formation is a common, simple and efficient way to store large quantities of bulk materials. Additionally, regolith pile formation around and over lunar structures such as habitats for protection is frequently proposed.

(viii) *Compaction and compression*.

Compacting and compression of granular materials—e.g. via controlled application of linear compaction stress—will be a common procedure for a wide range of applications. One future use of such a process could be lunar brick formation.

Overview of a proposed payload architecture

The architecture of the proposed payload has four core features that will be described in this section.

A key initial design decision is whether material handling processes should operate independently or sequentially (cascaded). While a design maximizing the number of incorporated processes within lander payload volume and mass constraints was sought, the trade-offs between these approaches were carefully considered. Operating processes independently would substantially increase the mass and

volume of the single structure, including individual mechanisms for dosing granular materials into each process. Managing the output regolith from each independent process would pose an additional challenge, further limiting the number of processes within the payload's mass and volume limits. Conversely, a sequential (cascaded) arrangement allows the output of one process to serve as the input for the next. This significantly reduces the mass and mechanisms required for dosing granular materials, enabling more processes to be incorporated within the given payload constraints. However, this cascading approach introduces a potential increase in the risk of single-point failures or the cascading consequences of a given failure compared to a parallel approach. Despite this increased risk, to maximize the number of processes within the payload design limitations, a sequential (cascaded) design approach will be adopted.

Following the rationale for minimizing mass and dosing mechanisms, the design also addresses sample acquisition. A dedicated, independent sample acquisition system would represent a significant, and unnecessary, increase in payload mass and volume. Therefore, leveraging the core process demonstrations of excavation and conveying for this purpose offers an efficient solution. Since excavation and conveying are primary processes to be tested, these same processes will be implemented for acquiring samples from the lunar environment and transporting them into the payload core. This dual-role approach not only avoids redundant systems but also directly supports the primary payload objectives. Given the advantages of the cascading architecture, the sequence if the handling processes is intended to be that given in the list in "Choice of material handling processes" section and described in Fig. 2.

To enable observation and data acquisition for the material handling processes, a non-contact, remote sensing approach, primarily using optical imaging, is planned. This single approach offers a rich set of observations, providing valuable data on process performance and enabling flexibility in responding to non-nominal situations. Optical imaging also facilitates the development and early de-risking of video imaging and analysis techniques, crucial for robust process control in future full-scale lunar material handling systems. This streamlined approach significantly simplifies payload development compared to complex, distributed sensor networks with extensive wiring harnesses, while simultaneously establishing a strong foundation for future monitoring and control.

Observing existing terrestrial lunar regolith simulant(s) within the lunar environment will be a crucial capability. This will directly validate their suitability for use in Earth-based simulations by comparing their material handling performance in representative lunar conditions with the behaviour of actual lunar materials. Since substantial quantities of real lunar regolith are unlikely to be available for terrestrial testing in the foreseeable future, the fidelity of these simulations is essential. Therefore, the payload architecture will include a storage and dispensing (or dosing) subsystem specifically designed to handle and release one or more existing terrestrial lunar regolith simulants within the payload.

Process implementation

The following section outlines individual identified material handling processes in terms of potential hardware and their sequence according to the proposed cascading design format of the payload.

Excavation

Two primary types of lunar regolith excavation systems exist: discrete and continuous (Just et al. 2020). Discrete excavators, such as front-end loaders and backhoes, offer versatility for various tasks and terrains. Continuous excavators, like bucket wheels and trenchers, provide a consistent flow of excavated material, ideal for large-scale operations.

The selection criteria for the excavation system prioritized continuous operation, anticipating its importance in future full-scale lunar applications (Just et al. 2020; Hoeber et al. 2021).

Continuous excavators offer a steady material supply for downstream processes, simplifying system integration and control. Additionally, for this payload's limited volume and mass capacity, a discrete excavator's complexity would be challenging to implement effectively.

Therefore, a continuous excavator in the form of a bucket wheel was chosen. Bucket wheels appear well-suited for lunar regolith, offering efficient excavation and predictable scaling properties (Diaz Lankenau et al. 2012). This approach aligns with the anticipated needs of future large-scale lunar excavation operations.

The selected bucket wheel design will be integrated with a dump bed—a feature to hold excavated material and allow transfer to a conveyer system. This assembly will be mounted on a deployable arm with multiple degrees of freedom, enabling regolith collection from an arc-like area adjacent to the lander (Fig. 2a, b).

Conveying

Conveying systems can be broadly categorized into long-range and short-range solutions. While long-range systems like belt conveyors and rail systems are suitable for large-scale lunar surface operations, this payload focuses

on short-range conveying within confined systems of few metres in size. Options such as screw conveyors, tubular disc-drag conveyors, and vibratory conveyors were considered (Walton 2012).

The choice of conveying system was guided by several factors: mechanical and design simplicity, lack of sensitivity to gravity and bulk materials properties, and adaptability to the payload's constraints. Screw conveyors offer a simple design with a single tube and motor, though their efficiency can be affected by gravity and material properties. Tubular disc-drag conveyors are generally independent of gravity and material variations but are more complex to implement. Vibratory conveyors were deemed unsuitable due to the significant gradients within the payload.

A screw conveyor was selected for its overall simplicity and robust performance. This choice balances efficiency and ease of implementation within the payload's spatial limitations.

To optimize space utilization, a two-stage screw conveyor design with a transfer box was implemented, enabling efficient material transport from the excavation point to the processing units while accommodating the payload's spatial constraints and deployment requirements (see Fig. 2b).

Sorting

The need for beneficiation of materials within future lunar systems is to be expected. One obvious example of this is the need to size separate granular and powder materials, for example to aid in mineral separation or to minimise particle size variation to optimise various process (Suhaizan et al. 2023; Radl et al. 2023). In lunar use cases the need to avoid implementations that require consumables such as fluids and gases due to supply chain issues means mechanical sieving or screening is an obvious solution. Since basic sieving approaches rely upon gravity, operation in a lunar gravity environment would be expected to influence performance and detailed design.

For the payload, a vibratory sieve separator was chosen. This system utilizes multiple mesh sieves arranged in a carousel-like configuration, including an empty mesh position for redundancy in case of blockage or to bypass the sorting process if needed. A similar design that could be used in the payload is shown in Fig. 2c.

Dynamic handling

Dynamic handling techniques, utilizing rotating drums, are important for processing granular materials like lunar regolith. These techniques involve rotating cylindrical vessels to induce particle motion, facilitating processes such as mixing, blending, and heating (Chou et al. 2012). However, the effectiveness of dynamic handling in rotating drums can be influenced by the lunar environment, particularly the reduced gravity.

Furthermore, compact rotating drums with transparent end windows are emerging as tools for research and characterization. By incorporating video recording and analysis, these drums enable observation of material behaviour under different conditions (Walton et al. 2007; Kleinhans et al. 2011).

For this payload, a rotating drum with adjustable speed settings will be employed. This capability allows for the investigation of various flow regimes within the drum. The transparent end wall permits video recording of material behaviour during experiments, facilitating analysis. Additionally, an automatic slit opening integrated into the drum's cylindrical wall enables automated filling and emptying of the drum before and after experimental runs.

To explore further the rotating drum design space and how such a system could be implemented in the payload, a simple breadboard version has been constructed and is shown in simple Computer Aided Design (CAD) form in Fig. 2d and as a photo of experimental breadboard in Fig. 1b.

Static handling

Multiple future lunar activities will involve filling, storing and emptying granular/ bulk materials from storage vessels – this is termed static handling. Common implementations for storage vessels are various forms of storage hoppers which includes silos, bins and tanks. Such hoppers are often discharged via gravity feed. Variables for hopper designs includes shape, wall inclinations, discharge outlet. The lunar environment and nature of lunar materials is expected to significantly influence hopper design and performance.

For the payload a classic wedge hopper is chosen but with adjustable wall inclination angles and variable width rectangular discharge outlet. The adjustability enables in-situ exploration of how wall angles and outlet dimensions influence discharge performance of regolith flow behaviour in lunar conditions. The fixed (non-adjustable) vertical hopper walls will be transparent enabling video recording of filling and discharge behaviour.

To explore further the hopper design space and how such a variable wall hopper could be implemented in the payload, a simple breadboard version has been constructed and is shown in simple CAD (Fig. 2e) and as a photo of experimental breadboard (Fig. 1a).

Electrostatic separation

Lunar regolith acquires significant electrostatic charge when exposed to UV radiation, solar wind, ionising radiation

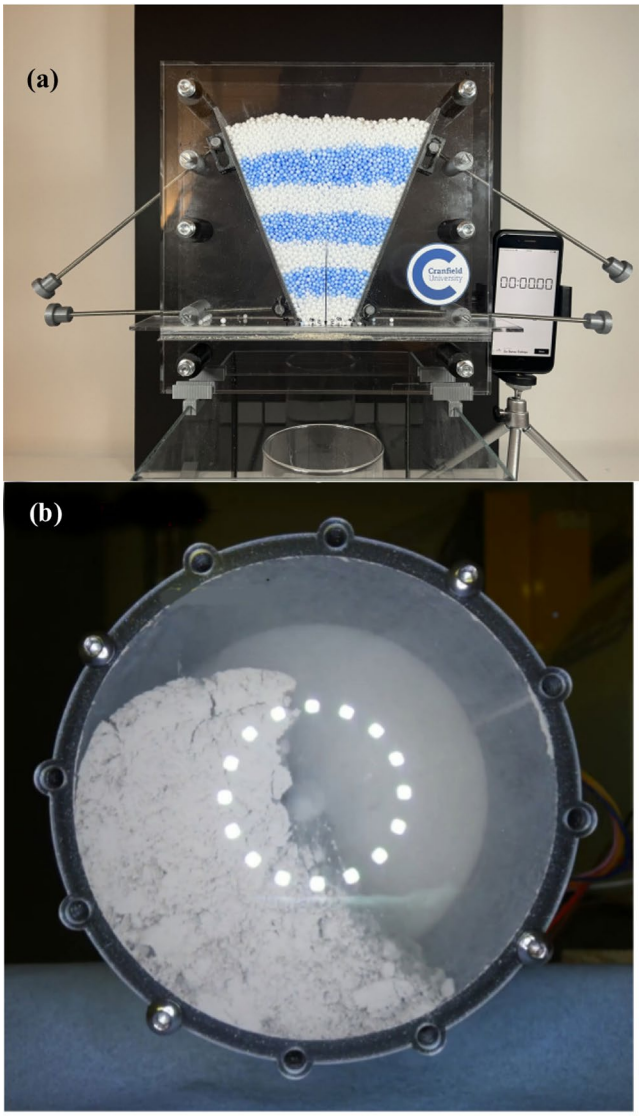


Fig. 1 **a** A simple laboratory breadboard version of wedge hopper with a manual adjustable inclined walls and discharge outlet. This example is filled with white and blue expanded polystyrene beads. The beads are 2 mm in diameter and hopper is 250 × 250 × 40 mm in dimension. Video frame **b** Rotating drum with 80 mm external diameter and 30 mm of depth, with adjustable rotating speeds, for test filled with NU-LHT-2 M lunar regolith simulant (Zanotti et al. 2024). Transparent vertical walls allow video recording of the granular material behaviour

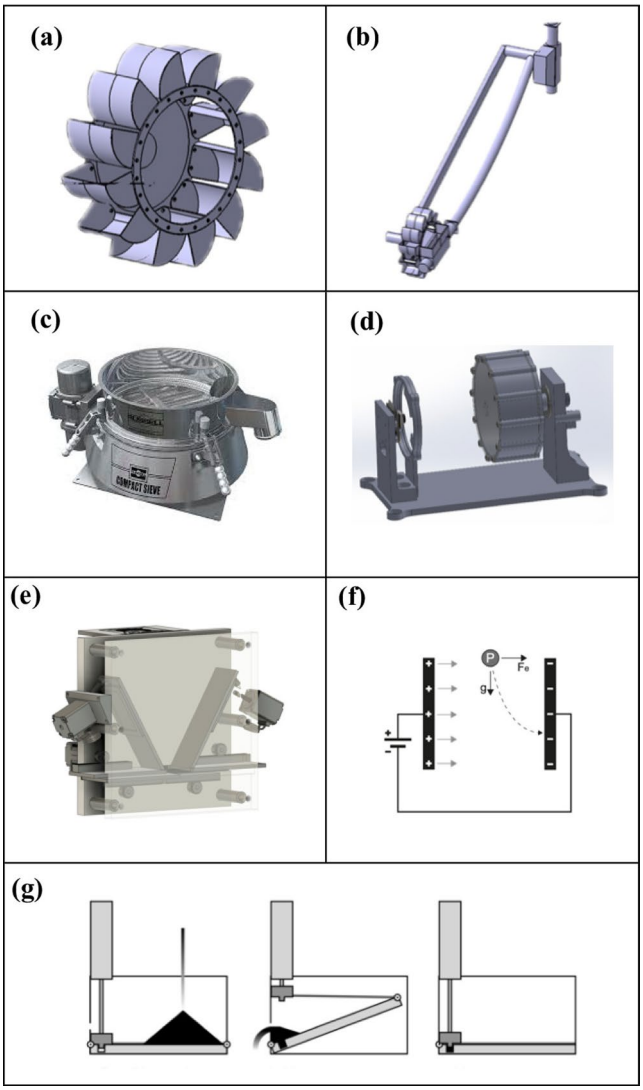


Fig. 2 Schematic presentation of subsystems to be installed in baseline payload: **a** Excavation—Bucket Wheel, **b** Conveying—screw conveyer, **c** sorting—sieve (credit: Russell Finex Ltd.), **d** dynamic handling—rotating drum, **e** static handling—wedge hopper, **f** electrostatic separation, **g** container for pile forming, and linear actuator for compressing

and triboelectric effects from handling and exacerbated by hindered charge dissipation due to the lack of a significant atmosphere and regolith low electrical conductivity. This contributes to a general lunar dust problem and in particular via transport/levitation and adhesion (Stubbs et al. 2006; Gaier 2005, 2011; Murphy et al. 2010; Wagner 2006) but also could enable exploitation in some applications such as materials beneficiation.

The proposed payload offers a simple opportunity to investigate the interaction of charged lunar regolith with electric fields (Freeman 2025), Fig. 2f. By utilizing the free-fall of a regolith stream between the hopper discharge outlet and the pile formation feature, the payload configuration enables the placement of planar electrodes on either side of the stream. Applying a potential difference across these electrodes generates an electric field, which can influence the trajectory of the falling regolith particles. High-resolution video imaging within the payload allows for direct observation of this interaction.

Such observations and hardware implementation would contribute to understanding the properties and behaviour of charged lunar regolith and the use of electric fields to control dust (both attract and repel) and possible use in materials

beneficiation (Kawamoto et al. 2018; Afshar-Mohajer et al. 2011).

Pile forming

Pile formation is anticipated to be a common feature of future lunar systems, with the lunar environment and regolith properties significantly influencing the specifics of pile formation dynamics (Slyuta 2014; Fritz 2009).

The payload offers an opportunity to observe pile formation, albeit at a small scale, by utilizing the free-falling discharge from the static handling hopper. The incorporation of high-resolution video imaging within the payload allows for direct observation of the pile formation process.

To facilitate this, a flat surface will be positioned below the discharge opening of the hopper, enabling the formation of a regolith pile. The video system will capture the dynamics of pile formation, allowing for the analysis of key characteristics such as pile stability, avalanching behaviour, and angle of repose (Al-Hashemi 2018).

Compaction and compression

On the lunar surface, compaction of regolith through the application of linear/compressive stress will be important for various activities, including the handling and performance of regolith in construction and geotechnical applications. This includes tasks such as forming bricks for lunar structures and compacting foundations for landing pads and habitats (Farries 2020; Gupta et al. 2024).

The payload's ability to form a regolith pile presents an opportunity to integrate compression testing. To achieve this, the pile will be enclosed within a system of vertical barriers, three fixed and one movable via a linear actuator. This setup allows for the application of controlled compressive stress to the regolith, simulating compaction processes relevant to lunar surface operations. A horizontal cover will also be included to restrict vertical displacement during compression, and force transducers will measure the applied forces. The design will incorporate mechanisms for efficient regolith removal and system reset, enabling subsequent testing with new piles. This can be achieved, for example, by retracting one of the barriers and using the linear actuator to push the processed regolith towards a waste chute.

The system will provide basic knowledge about the compressive stress-strain response of regolith and insight into possible mechanisms, hardware and operations for final use applications including construction and geotechnics.

Design solution for pile forming and compressing of the test material can be seen in Fig. 2g.

Video and lighting for observation and data collection

As previously stated, non-contact locally-remote sensing is preferred for monitoring granular material behaviour in the eight processes. An optical imaging system for video data capture is the assumed method. This system must provide sufficient spatial and temporal resolution for appropriate-quality data capture. However, further exploration of resolution requirements is not prioritized at this design stage. While the proposed primary monitoring system utilizes optical video, the integration of a hyperspectral camera would provide valuable spectral data, enabling chemical and mineralogical observation. This additionally presents an opportunity for early, in-situ de-risking of hyperspectral technology, which is anticipated for routine process control use in future full-scale lunar economy material handling.

To ensure consistent data acquisition with the optical video system, controlled illumination is essential. Therefore, the payload's video and lighting subsystem should include an integrated lighting system. This will provide uniform illumination across all material handling process subsystems, minimizing the impact of varying ambient light and optimizing video capture.

To capture video data from the eight material handling subsystems, two primary configuration approaches can be considered. The first involves deploying multiple fixed cameras, each dedicated to one of the eight processes, along with the option of a single fixed hyperspectral camera on one of the eight processes – the latter as a single only camera due to expected mass and volume constraints. The second utilizes a single movable camera mounted on a robotic arm, in addition to the fixed hyperspectral camera. The robotic arm-mounted single camera offers the potential to replicate the coverage of eight fixed cameras. Additionally, it allows for enhanced data acquisition beyond the primary viewpoints of fixed cameras, as the robotic arm enables data capture from numerous additional angles. Furthermore, a movable camera facilitates data collection for understanding mechanical wear, dust generation, transport, and mitigation, as well as supporting payload inspection, troubleshooting, fault diagnosis, and recovery.

Other subsystems

In addition to the implementation of the eight material handling processes, several supplementary subsystems have been considered and are outlined further in this section.

Robotic arm

If a payload robotic arm is included for video image capture, the arm can be utilized to assist in payload fault recovery, specifically addressing material flow blockages and clogging. Inspired by terrestrial bulk material handling practices, where mechanical impacts (e.g., using hammers) are employed to clear blockages, the robotic arm could be designed to apply similar localized mechanical forces to facilitate blockage removal and system restoration.

Housing and use of regolith simulants from Earth

As previously stated, the payload could include the transport of a number of terrestrial lunar regolith simulants to the lunar surface and dispense them into a subset of the eight processes. This will enable validation of their material handling properties in lunar conditions and thereby support their terrestrial use as lunar regolith simulants in derisking future lunar technologies.

The hardware implementation is assumed to utilize a carousel-type arrangement housing discrete regolith simulant samples, which can be dispensed into the payload at appropriate points and times within the handling process sequence. Given the need for a carousel dispenser, it is anticipated to be placed after the regolith acquisition system (excavation and conveying subsystems) and before the sorting subsystem. Each discrete sample is envisaged to have a mass in the order of a few hundred grams, with a total of approximately five samples. Notably, a carousel containing terrestrial granular materials offers a redundancy advantage: if the regolith acquisition system fails, material handling data can still be obtained using the carousel's samples.

Dust, wear and technology readiness level

The earlier decision to choose a payload based on material handling processes anticipated for future full-scale lunar implementations offers several advantages compared to a purely scientific approach. Specifically, it has the potential to yield timely knowledge in three key areas: (i) dust generation, its consequences, and mitigation strategies. (ii) wear and tear of mechanisms in the context of lunar material handling and (iii) increased Technology Readiness Level (TRL) for various material handling hardware implementations.

It is expected that at number of the materials handling subsystems within the payload are going to generate suspended dust. It is well known within the community that dust will be a major negative issue that will need to be addressed, when implementing full scale processes involving granular material handling in lunar environments (Abel et al. 2021). Therefore, the materials handling payload is an opportunity to gain practical knowledge about dust generation as well as its fate. To achieve this with minimal additional hardware elements, the existing video, lighting and robotic arm subsystems could be used to visualise and document the generation of dust as well as its fate. For the latter the deposition of dust on surfaces could be visualised and the installed robotic arm used to clean surfaces to aid in the subsequent visualisation of dust build up. One of the consequences of dust deposition and contamination would be the build-up of dust on the optics of the video elements and would consequently demand the inclusion of features to mitigate this, i.e. wipers, electrostatic "rappelers" and coatings. Given that video systems are likely to be used for process control in full scale future materials handling implementations, this gives an early opportunity to understand and derisk various dust mitigation approaches.

The environment for future full scale lunar materials handling operations will be harsh compared to most Earth scenarios. This comprises abrasive and cohesive materials, extreme thermal conditions and most importantly a maintenance environment that is severely restricted compared to Earth situations. Therefore, early and timely knowledge to be gained concerning wear within hardware and subsystems for materials handling will be extremely valuable. The payload offers a contribution to this. An approach that would have a minimal impact on payload mass and complexity could be the use of simple wear indicators on relevant hardware parts and the use of the video system to document the subsequent wear. Other approaches could include appropriate monitoring of electrical power demands and, of interest to the current authors, the use of vibroacoustic monitors.

As has already been indicated in this section, both, the use of specific materials handling subsystems and ancillary subsystems such as video observation and dust mitigation applications, will provide an early opportunity on the lunar surface to raise the TRL of many of these components and procedures. This will be of great value for the community.

Payload configuration

The overall payload design including the subsystems, has already been described in early parts of this section. Here, the configuration of the payload will be outlined. Later in the document the accommodation of the payload within a hosting lunar delivery system and a possible operations plan will be presented.

The design philosophy for a payload, as mentioned earlier, is to arrange eight materials handling subsystems as a linear sequence with one subsystem feeding a material into the following subsystem. This is to minimize the overall payload mass and volume budgets. The following are the arguments that lead to the preferred ordering of the

subsystems: given the need to acquire lunar regolith and assuming that a hosting spacecraft/ lander will not possess an independent sample acquisition and distribution system, a combination of the payload excavation and conveying system will be used to acquire samples. Thus, the excavation system will be the first subsystem in the linear sequence, followed by conveying subsystem as the second. Conveying subsystem will perform transport of lunar regolith from the excavation subsystem to the top of the gravity fed stack of all other subsystems see Fig. 3a. The top of the gravity fed stack must also be able to accept material from the alternative source, specifically the carousel subsystem containing granular materials transported from Earth. Therefore, the carousel should be positioned such, that it can discharge material samples directly into the top of the stack.

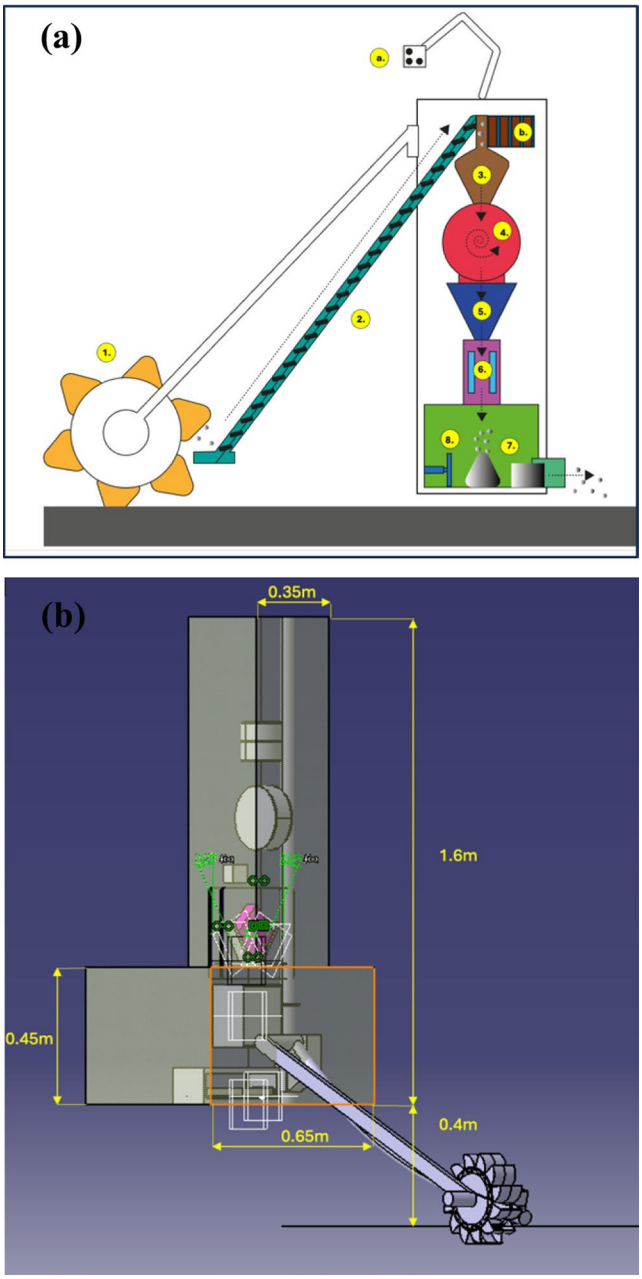


Fig. 3 **a** Simple schematic presentation of the material handling experimental payload with subsystems presented with different colours: (1.) bucket wheel, (2.) screw conveyer, (3.) sieve, (4.) rotating drum, (5.) wedge hopper, (6.) electrostatic plates, (7./8.) container with linear actuator, (a.) robotic arm, (b.) carousel dosing device for Earth samples. **b** is an indicative computer aided design (CAD) representation of packaging the developed version of the payload within payload accommodation volumes of Blue Ghost lander

The third materials handling subsystem, the first in the vertical gravity fed stack will be the sorting subsystem. The reasoning for this is to allow two possibilities of sample preprocessing for subsequent materials handling subsystems. One option is to configure the sieving subsystem to allow material to be passed without any size segregation. The second option is to configure sieving subsystem such that size fractionation occurs and only a subset of particles passes to subsequent subsystems. The second option also allows the core aspects of the sieving process to be observed and studied.

The next four material handling subsystems will be implemented in the following order: dynamic handling subsystem (rotating drum), static handling subsystem (discharge hopper), electrostatic separation subsystem, and container for pile formation and compression. This order is determined by the dependencies between subsystems. Pile formation requires a well-defined, gravity-fed regolith flow, which is best provided by the discharge hopper. Similarly, the electrostatic separation subsystem needs a controlled regolith flow and is therefore positioned after the discharge hopper. This arrangement allows for easy activation or deactivation of the electrostatic subsystem by simply applying or removing the potential difference between the electrodes. The dynamic handling subsystem, with its less predictable regolith flow, is placed before the discharge hopper.

The last subsystem in the sequence will be the compacting and compression subsystem, which will take the regolith of the pile forming subsystem and perform compaction as well as sample removal from the payload.

Other systems considerations

While a detailed payload design is not yet finalized, order-of-magnitude budgets have been estimated for key systems engineering parameters, including mass, volume, dimensions, power, and data requirements. This preliminary assessment evaluates the superficial feasibility of the proposed payload concept.

To determine payload mass and volume, assumptions were made regarding the requirement to handle sample masses on the order of a few hundred grams per sample and compatibility with upcoming lunar payload delivery

and hosting systems. Simplified designs were developed for each subsystem, enabling the estimation of mass and dimensions. This resulted in a vertically oriented payload configuration with a total mass of 79 kg and a maximum dimension of 1.6 m (see Fig. 3b).

Electrical power budgets were estimated by considering the core electromechanical components and standard electrical subsystems. Electrical heating or cooling requirements were assumed to be unnecessary. The estimated maximum power requirement is 95 W for a single experimental cycle.

Video data is expected to dominate the data budget. A maximum of eight cameras may be utilized during the operation, potentially with individual cameras assigned to each subsystem. This could generate approximately 655,000 Mbit of data, compressible to less than 108,000 Mbit. Consequently, a minimum data transmission rate below 10 Mbps over 3 h would be needed to download all data to Earth.

Mission

Having outlined the case for, and top-level details of a payload to acquire in-situ material handling data, this section will consider the possible mission contexts for delivering such a payload to the lunar surface.

The ability to deliver and operate payloads on the lunar surface is being revolutionised by new commercial operators. The NASA Commercial Lunar Payload Services (CLPS) program is an exemplar of this (NASA CLPS URL). Assuming the payload will be delivered by a program of this nature, the feasibility of a payload can be further explored by utilizing one of the landers associated with the CLPS program as a case study. For this purpose, the Blue Ghost Lander from Firefly Aerospace was chosen. Blue Ghost was selected providing proper payload mass capacity of 150 kg, good nominal power supply per kg of payload and possibility of combining different payload bays on the lander to accommodate specific payload design (see Fig. 4). Price

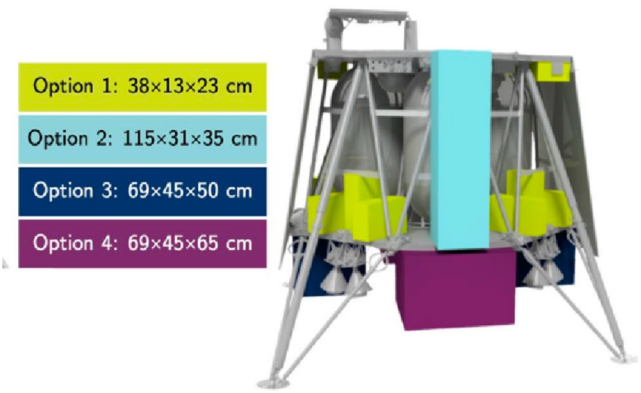


Fig. 4 Blue Ghost lander with available payload bay options highlighted (credit: Firefly Aerospace)

was estimated at 1 M$ per kilogram of payload delivered to the Lunar surface (Firefly Aerospace URL).

For the payload accommodation study the payload Option 2 and Option 4 were chosen, given two requirements: first the need for a significant height of payload for the gravity fed stack of subsystems (hence Option 2) and secondly the need to access the lunar surface with the excavator and conveying subsystems (hence Option 4). A simple configuration of a various payload subsystems is shown in Fig. 3a, demonstrating that accommodation within Blue Ghost appears possible. Figure 3b shows the excavator–conveyer subsystems in a deployed configuration accessioning the lunar surface and lunar regolith. Not shown is a stowed configuration that will be used for the flight.

It is anticipated that future access to the lunar surface will become more affordable and frequent. This increased accessibility will enable the deployment of multiple implementations of the proposed payload. Initial consideration of the location for a first deployment of the payload involves the following logic. There is a major community interest in the lunar south pole as the location for future human activities including those relevant to granular materials handling (Flahaut et al. 2020). Hence, the baseline location for a first implementation could be the lunar south pole region. Presently, this would mean that there would be no prior local "ground truth" data concerning regolith material properties. Therefore, an alternative first deployment location could be a place that has been visited previously and already has some local "ground truth" data available and would consequently enable direct comparison with field measurements and further derisk certain aspects of a first mission. Considering the interest in studying the behaviour of different lunar materials, the landing location needs to consider the availability of materials relevant to future full-scale use cases. For example, for various types of ISRU, including non-volatile and volatile rich materials and for various aspects of geotechnical engineering.

For any given potential landing location there is a need to consider local variability in the distribution of a different geology/mineralogy. The spatial variation may be on scales from submeter to a few kilometres (Jaumann et al. 2012; Carrier et al. 1991; Crawford et al. 2023). This has an impact on mission design in that there will be a relationship between (i) prior knowledge of geology/ mineralogy distribution, (ii) precision of landing, (iii) for a static lander with fixed payload the reach and (iv) the presence of local mobility, e.g. a fetch rover or payload mounted on a rover. It is assumed for a first implementation of a payload on the lunar surface, there would be a static payload that accesses the lunar surface with only a deployable arm, comprising the excavator and conveying subsystems, which would result in a limited ability to acquire a diverse range of samples.

Table 1 Framework for a multiple lunar day payload operational plan with indicative time values; time in: T+hh: mm

DAY 1		DAY 2–5		DAY 6	
T+00:00	Landing Delay	T+00:00	Lander Recommissioning	T+00:00	Lander Recommissioning
T+48:00	Lander Descent	T+06:00	Payload Commissioning for LD-X	T+06:00	Payload Commissioning LD-6
T+49:00	Lander Decommissioning	T+30:00	Core Payload Operations LD-X	T+30:00	Core Payload Operations LD-6
T+55:00	Lander Commissioning for Payload Support	T+318:00	Payload Decommissioning for Lunar Nights	T+222:00	Payload Decommissioning for EOL
T+61:00	Payload Initial Commissioning	T+342:00	Lander Decommissioning for Lunar Night	T+246:00	Lander Decommissioning for EOL
T+85:00	Core Payload Operations LD-1	T+345:00	Lunar Night - X		
T+277:00	Payload Decommissioning for Lunar Nights				
T+301:00	Lander Decommissioning for Lunar night				
T+304:00	Lunar Night − 1				

LD lunar day, *X* lunar day 2–5, *EOL* end of life

To expand the range of samples acquired, future versions could incorporate sample fetch rovers or payload mounted on a mobile platform. This would allow the collection of samples across kilometre-scale areas. In addition, missions are likely to include other payloads and where appropriate this should be leveraged, e.g. payloads that perform mineralogical studies and would offer complementary information about samples.

Operations

To further evaluate the potential and viability of the payload, a baseline operational scenario has been considered. This scenario pre-supposes a payload hosted on a static lander, with both the lander and the payload designed to survive the lunar night. It also assumes a landing location at low to mid latitudes where there is equal day-night length. A simple consideration of operations for only one lunar day indicated a poor return in terms of data acquired and therefore, resulted in a baseline requiring multiple lunar days. A location at high latitudes with persistent solar illumination would offer other operational scenarios but will not be considered further here.

Table 1 shows a simple breakdown of, or framework for, the various elements of a multiple lunar day operations plan. The mission profile is divided into three phases. The first lunar day (DAY 1) includes the landing phase. Subsequent lunar days (DAY 2–5) involve recommissioning after the lunar night, conducting a series of experimental cycles, and a decommissioning phase to prepare for the lunar night. The final lunar day (DAY 6) includes recommissioning after the lunar night, further experimental cycles, and a final end-of-life decommissioning phase.

A mission lifetime of six lunar days was selected as a pragmatic compromise between maximizing data acquisition and minimizing resource costs of operating the payload.

As outlined in Table 1, an experimental cycle constitutes a fundamental unit within the mission timeline. An iterative approach is assumed, where knowledge gained from each cycle is utilized to optimize the design of subsequent cycles. This necessitates the downlink of data to Earth at the end of each cycle, followed by a period for human-led analysis and the implementation of adjustments to the planned subsequent cycle. A total duration of 96 h is allocated for each cycle, with approximately 24 h dedicated to data transfer and payload operations, and the remaining 72 h reserved for data analysis and planning for the next cycle.

A further crucial phase to be considered is the payload operation associated with the collection of a lunar regolith sample and processing this through the payload sequence of material handling subsystems. This is termed as the payload sample handling cycle. A simple consideration of the time required for each of the individual steps within the payload sample handling cycle suggests that a total time duration of approximately 4 h would be sufficient to complete the cycle. It is important to note that for this consideration of payload operations, the immediate value is gained from the logical framework for payload operations we have produced and captured in Table 1, not the specific numeric values we give to each step. Such numeric values can be refined in subsequent design iterations.

In summary and given the assumptions stated, a mission/payload lifetime of 6 lunar days would allow a total of 16 experimental cycles and therefore 16 samples to be processed. This indicates that the payload appears to offer a viable approach to generate appropriate data set and knowledge within a reasonable budgetary context.

Summary, conclusions and further work

This work has been performed in the context of renewed interest in human activities on the lunar surface, including developing a persistent human presence. The materials handling of lunar regolith and later materials on the lunar surface underpins much of this activity. It appears that current technology development for lunar use underestimates the risks posed by our current lack of validated knowledge about handling lunar materials in the lunar environment. This work has introduced this situation and argued for the need to generate in-situ lunar materials handling datasets to be used to validate and, when necessary, calibrate our understanding of lunar materials handling. A payload design has been proposed that would take a pragmatic approach to observing and documenting lunar materials handling in-situ and considered mission options to implement the payload on the lunar surface. Additionally, a baseline approach to operating the payload has been outlined.

The work performed indicates to the authors, that it appears viable that data concerning materials handling could be generated in a way that is compatible with future opportunities and resources. The next obvious step is for wider community to engage and confirm this conclusion, that could lead to further development phases.

If pursued further the following are some example areas for investigation. The development of laboratory breadboard versions of the materials handling subsystems should be perused to further understand the use and design. Facilities should be accessed to subsequently allow their testing in more relevant simulating environments including vacuum systems on lunar parabolic flight programs. Additionally, if accommodating the proposed large payload as a single unit presents challenges, options for splitting the payload into smaller versions can be explored. These smaller versions would comprise subsets of the existing eight subsystems and could be deployed across multiple missions.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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Outline case for a payload and mission scenario to perform in situ de-risking, validation and calibration of lunar granular materials handling

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