

DESIGN AND VERIFICATION OF A POWDER SPREADING DEVICE FOR IN-SITU 3D PRINTING OF LUNAR SOIL

by

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Lunar soil 3D printing is a key enabling technology for the construction of future lunar research stations. One of its critical challenges is achieving stable and controllable transportation of lunar regolith powder under lunar surface conditions. Based on the requirements of lunar soil 3D printing, this paper analyzes existing powder material transport technologies both domestically and internationally. A powder spreading and delivery solution suitable for future lunar 3D printing is proposed, supported by simulation analysis and experimental validation. The findings provide technical support for in-situ lunar regolith deposition in subsequent extraterrestrial construction processes.

Keywords: in-situ resource utilization (ISRU); lunar 3D printing; lunar regolith deposition

Introduction

Lunar base construction is a hotspot of future competition among major spacefaring nations [1,2]. The United States has officially launched the "Artemis Program", aiming to utilize lunar resources in-situ and establish a lunar base. Europe is actively engaged in lunar south pole exploration, initiated the International Moon Village plan, proposed a space resources strategy, and aims to demonstrate in-situ resource utilization and construction capabilities on the Moon [3]. Russia has proposed five lunar south pole exploration missions and plans to jointly establish a lunar base with China. China's Phase IV Lunar Exploration Program and manned lunar landing missions have commenced, with subsequent plans to establish an International Lunar Research Station (ILRS) and conduct systematic, continuous lunar exploration and related technology verification tests. Therefore, the Moon is gradually entering a new stage of development and utilization, making lunar base construction a core task for future space exploration.

In-situ 3D printing construction on the lunar surface is the primary method envisioned for future lunar base construction. Various countries have conducted a series of studies on in-situ additive manufacturing on the lunar surface, successively developing ground-based simulation construction systems and achieving certain progress. Based on the characteristics of raw materials, forming processes, and methods, existing lunar soil 3D printing technologies [4] can be broadly categorized into material extrusion/jetting, powder bed fusion, laser engineered net shaping, selective microwave sintering, and stereolithography/digital light processing, among others. Among these, methods like

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powder bed fusion that directly utilize in-situ lunar soil resources can significantly reduce the demand for Earth-launched resources and are currently a key development direction.

A lunar soil 3D printing system typically includes a lunar soil powder spreading/delivery device, an energy supply device, and a lunar soil printing device. The lunar soil powder spreading/delivery device primarily realizes the functions of feeding, transporting, and leveling lunar soil granular powder. The feeding function ensures continuous and stable supply of lunar soil granules; the transport and leveling function achieves quantitative and uniform deposition of lunar soil powder, creating favorable conditions for printing.

Currently, in the field of terrestrial 3D printing and industrial applications, a series of powder transport technologies have been developed. In terrestrial 3D printing, powder spreading/delivery modules mainly adopt two methods: mechanical feeding and pneumatic feeding. The performance of mechanical feeding is highly correlated with powder flowability, facing risks such as clogging, bridging, and wall adhesion[5-7]. Pneumatic feeding offers higher precision, but methods requiring carrying sufficient gas sources and providing enough power for fluid medium compression are unsuitable for lunar surface powder feeding missions. Powder feeding technologies in various terrestrial fields like energy, chemical, and metallurgy primarily include rotary spreading mechanisms, vibrating spreading mechanisms, and screw conveyor mechanisms. Screw spreading exhibits periodic fluctuations related to the number of blades at the discharge outlet due to structural constraints, and the spread powder surface requires leveling with a scraper. When a vibrating feeding device rolls or tilts, the chute becomes higher on one side and lower on the other laterally, easily leading to uneven flow rates at the discharge end or even no material in some areas. Screw feeding mechanisms do not require lunar gravity assistance and offer high operational reliability; their single-point outlet is suitable for powder feeding mode, and when used for assisted transport, it can be extended to a spreading mode but cannot guarantee uniformity across the outlet width[8]. Internationally, electrostatic feeding technology is also under development, which requires no complex mechanical components and has a simple structure; however, its current transport efficiency is relatively low.

Addressing the in-situ construction needs of China's future lunar base, this paper, considering the requirements for lunar soil 3D printing powder spreading/delivery and the characteristics of domestic and international powder transport technologies, designs a powder spreading/delivery technical solution suitable for China's future lunar surface 3D printing missions and conducts simulation analysis and experimental verification.

Design of the Lunar Soil In-Situ 3D Printing Powder Spreading/Delivery Solution

For different lunar soil 3D printing methods, lunar soil transport and spreading is one of the key technologies that needs to be addressed. Currently, lunar soil 3D printing powder spreading/delivery methods mainly include powder spreading [9] and powder feeding [10]. Powder spreading technology involves uniformly depositing a layer of powder material on the printing platform for melting by a laser or electron beam to form a solid layer; the powder spreading process focuses more on the thickness, uniformity, and precision of the powder layer to ensure the mechanical properties and surface quality of the final product. Powder feeding technology is responsible for transporting powder material from a storage container directly to the target printing point for melting/solidification, primarily requiring consideration of quantitative, directional, and precisely controllable manipulation of particulate matter.

Due to the poor thermal conductivity of lunar soil, limited space energy supply, complex lunar powder states, and the difficulty in precisely controlling high-power-density energy, the powder spreading method is more suitable for the needs of lunar research station lunar soil 3D printing.

The designed powder spreading/delivery solution for the future lunar soil 3D printing device is as follows: A combination of an overhead storage hopper utilizing gravity fall and a rotary feeding mechanism can achieve a simple structure, minimal interference from lunar soil state and the 1/6g

gravity environment, and controllable transport status. This solution mainly consists of a lunar soil storage hopper, a vibration component, a powder feeding component, mounting structure, and a scraper blade. The lunar soil storage hopper is primarily used for storing lunar soil granules, the vibration component assists the descent of lunar soil granules within the hopper, the rotary valve powder feeding component executes the transport of lunar soil granules, the mounting structure provides support and fixation for the in-situ lunar soil 3D printing powder spreading device, and the scraper blade is used to level the lunar soil surface after powder deposition. Its composition and principle are shown in the figure below.

The lunar soil storage hopper has a tapered bottom structure, with all inclined surface angles exceeding 45° , ensuring smooth descent of lunar soil granules. Even under the lunar $1/6g$ gravity environment where transport efficiency decreases, it still far exceeds the required powder feeding rate. The powder feeding component is installed at the outlet of the lunar soil storage hopper, supported by two bearings driving the powder feeding roller, which is rotated by a motor. The powder feeding roller is equipped with multiple sets of powder discharge grooves. When a groove rotates to the top and contacts the lunar soil, it fills with lunar soil; when it rotates to the bottom, the lunar soil falls out from the groove, achieving lunar soil transport. The feeding rate of the powder feeding component is only related to the volume of the powder discharge grooves and the rotational speed, thus effectively eliminating the impact of gravity differences between Earth and Moon on the spreading speed.

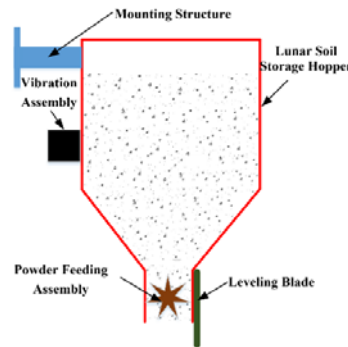


Figure 1 Schematic Diagram of the Powder Spreading/Delivery Solution

Simulation Analysis of Powder Spreading/Delivery and Leveling

Simulated lunar soils developed by various countries (e.g., JSC series, MLS series, TYII series) mostly use terrestrial volcanic ash as raw material, obtained through mechanical crushing, classification, and mineral composition adjustment. Therefore, lunar soil and simulated lunar soil particles have complex morphologies, ranging from spherical to extremely angular shapes. Lunar soil and simulated lunar soil particle morphologies exhibit fractal characteristics, possessing a certain statistical self-similarity at different scales [11]. Based on the shape index and fractal characteristics of simulated lunar soil, a framework non-spherical particle model—the superposed sphere model—has been proposed [12-13].

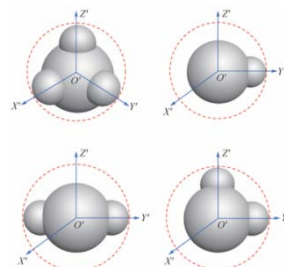


Figure 2 Simplified Model of Simulated Lunar Soil Used in Simulation [5]

When using DEM to analyze the rheological properties of simulated lunar soil during powder spreading, this paper temporarily neglects particle secondary fragmentation, considering each particle as a homogeneous rigid body. According to Newton's second law, the dynamic equations for each particle can be expressed as [12]:

$$m_p \frac{d\ddot{x}_p}{dt} = F_{p,q}^{[c]} + F_{p,q}^{[a]} + m_p g \quad (1)$$

$$I_p \frac{d\omega_p}{dt} = M_p \quad (2)$$

$$m_p = \rho_p \left(\sum_{i=1}^{N_{sp}} V_i^{[b]} - \Delta V \right) \quad (3)$$

$$x_p = \frac{1}{m_p} \sum_{i=1}^{N_{sp}} [m_i^{[b]} \cdot x_i^{[b]}] \quad (4)$$

where m_p is the particle mass, x_p is the particle centroid coordinates, g is the gravitational acceleration, $F_{p,q}^{[c]}$ is the interparticle contact force, $F_{p,q}^{[a]}$ is the interparticle adhesive force, I_p is the particle moment of inertia, ω_p is the particle angular velocity, M_p is the resultant moment on the particle, ρ_p is the particle density, $m_i^{[b]}$ is the mass coordinate of the i -th sphere unit, $V_i^{[b]}$ is the volume coordinate of the i -th sphere unit inside the particle, $x_i^{[b]}$ is the centroid coordinate of the i -th sphere unit inside the particle, ΔV is the total volume of overlapping sections among all sphere units inside the particle, and N_{sp} is the total number of sphere units in a single particle. Inside the Particle

Simulation analysis of the powder feeding process was conducted for 0-1mm graded simulated lunar soil, primarily analyzing the differences in powder spreading under Earth and Moon gravity environments, the morphology of the spread surface, the powder spreading/delivery rate, and leveling performance.

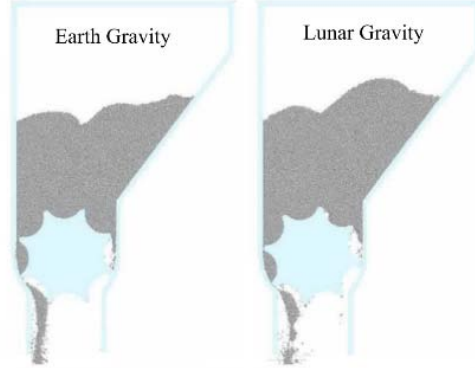
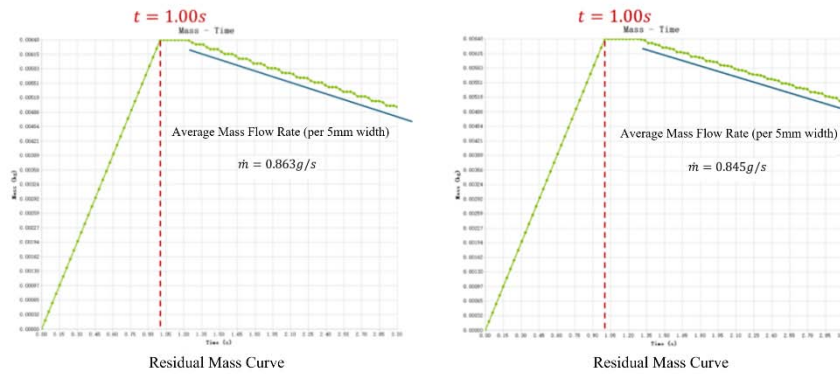


Figure 3 Powder Feeding Simulation under Earth Gravity and Lunar Gravity



(a) Earth Gravity (b) Lunar Gravity

Figure 4 Simulation Results under Earth Gravity and Lunar Gravity

From the above results, the average mass flow rates for the Earth gravity and Lunar gravity (spherical particles) conditions, per 5mm length of the hopper at 1 rps rotation speed, are 0.863 g/s and 0.845 g/s, respectively. Scaling to the designed 120mm width, the powder feeding rates can reach 20.712 g/s and 20.28 g/s. The powder feeding rates under Earth and Moon gravity conditions differ very little, indicating that the rotary valve feeding solution can effectively mitigate the impact of the Earth-Moon gravity environment difference.

Analysis was conducted on the surface morphology of the lunar soil after spreading/delivery and the leveling performance. Simulation of hopper rotary valve discharge was performed based on the condition of a rotary valve speed of 1 rps. Furthermore, the process of discharge, accumulation, and leveling was simulated by adding a simulated platform surface perpendicular to the central axis of the hopper at a distance of 40mm, and a simulated scraper blade forming a 2mm gap with the platform surface. After spreading/delivery, the simulated lunar soil surface exhibited a wavy shape, but leveling was basically achieved by the scraper blade.

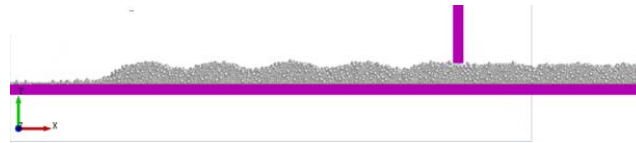


Figure 5 Powder Spreading and Leveling Simulation Results

Powder Spreading and Leveling Performance Test

An engineering prototype of the powder spreading/delivery device and a test system were developed to conduct powder spreading/delivery and leveling tests. During powder spreading, the powder feeding component rotated at 1 rps, and tests were conducted in a normal temperature and pressure environment, consistent with the simulation conditions. The surface state of the simulated lunar soil in the powder receiving tray and its state after leveling are shown in the figures below. Before leveling, the surface of the simulated lunar soil in the receiving tray showed continuous undulations along the direction of tray movement. A scraper blade was used to level the simulated lunar soil surface, with the lower surface of the scraper contacting the upper surface edge of the receiving tray, parallel to the direction of tray movement. After leveling, a flat upper surface of the simulated lunar soil was obtained in the receiving tray.



Figure 6 Test System and Powder Spreading Performance

The position of the rotary valve was controlled each time via the resolver of the feeding motor. The feeding time was set to 10 seconds, and the falling simulated lunar soil was collected at the outlet and weighed. The weight statistics are shown in the table below. As can be seen from the table, the powder feeding rate of this device is uniform, with a speed deviation of less than 2%. Compared with the simulated feeding rate, the deviation between simulation and experiment is about 10.3%. The reasons for this discrepancy may be related to the particle shape and inter-particle forces assumed in the simulation. Subsequent simulations will continuously optimize the simulation model based on the experimental results.

Table 1 Powder Feeding Mass and Time Statistics

No.	Feeding Time (s)	Feeding Mass (g)	Feeding Rate (g/s)
1	10	223.1	22.31

2	10	227.3	22.73
3	10	226.8	22.68

Conclusion

Addressing the needs of in-situ resource utilization on the lunar surface, this paper analyzed various 3D printing powder spreading/delivery equipment solutions. By evaluating the performance and lunar environment adaptability of these solutions, a powder spreading solution suitable for the lunar environment was proposed, characterized by as follows. The solution has a simple structure, low weight, and small volume; Simulation analysis shows that while 1/6 gravity affects the discharge speed from the storage hopper, the powder feeding rates after passing through the rotary feeding mechanism are essentially consistent between Earth and the lunar 1/6g gravity environment; Verified through multiple ground tests, the powder spreading rate error is only 2%, and the feeding rate can be adjusted by setting the rotational speed of the rotary valve; The design scheme for the lunar soil powder spreading/delivery device proposed in this paper has been proven feasible through simulation analysis and experimental verification, and can provide technical support for subsequent in-situ construction on the lunar surface.

Acknowledgements

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Nomenclature

m_p -particle mass,[kg]	$Vl_i^{[b]}$ -Volume Coordinate of the i-th Sphere Unit Inside the Particle,[m ³]
x_p -particle centroid coordinates[m]	$x_i^{[b]}$ -Centroid Coordinate of the i-th Sphere Unit Inside the Particle,[m]
g -gravitational acceleration,[m/s ²]	ΔV -Total Volume of Overlapping Sections Among All Sphere Units Inside the Particle,[m ³]
$F_{p,q}^{[c]}$ -interparticle contact force,[N]	N_{sp} -Total Number of Sphere Units in a Single Particle,[-
$F_{p,q}^{[a]}$ -interparticle adhesive force,[N]	
I_p -particle moment of inertia,[kg·m ²]	
ω_p -particle angular velocity,[rad/s]	
M_p -resultant moment on the particle,[N·m]	
ρ_p -particle density,[kg/m ³]	
$m_i^{[b]}$ -mass coordinate of the i-th sphere unit	

References

- [1] Zhai, G. H., *et al.*, Analysis of the Management Mode of the Artemis Program, *Space International*, 1(2024), 1, pp.15-19
- [2] Gong, J. S., *et al.*, Design and Validation of Portable Lunar Intelligent Drilling System, *Thermal Science*, 29(2025), 2B, pp.1301-1306
- [3] Wang, L. S., *et al.*, Preparation and Experimental Study of Aqueous Simulated Lunar Soil in Lunar Polar Region, *Thermal Science*, (2025), 29, 2B, pp.1251-1257
- [4] Wang, C. Y., *Research on High-Precision Additive Manufacturing Technology for Lunar In-Situ Resource Utilization*, Guangxi University, 2023
- [5] Chen, P., Study on the Flowability of Granular Media and Its Discharge Characteristics in Silos, *Southeast University*, 2012
- [6] Beverloo, W. A., *et al.*, The Flow of Granular Solids through Orifices, *Chemical Engineering Science*, 15 (1961), 3-4, pp.260-269
- [7] Brown, R. L., *et al.*, Kinematics of the Flow of Dry Powders and Bulk Solids, *Rheologica Acta*, 4 (1965), 3, pp.153-165
- [8] Li, P., *et al.*, *Design and Application of a Synchronous Powder Feeder for Laser Cladding*, Surface Technology, 2008
- [9] Tian, Q., *Research on Key Technologies of the Powder Spreading Device for Lunar Surface 3D*

Printer, Shenyang Ligong University, 2023

- [10] Hu, S.S., *et al.*, A Review of the Development and Research Status of Powder Feeders for 3D Printing, *Machine Tool & Hydraulics*, 445(2017), 19, pp.185-188
- [11] Li, W., *et al.*, DEM Numerical Simulation of Simulated Lunar soil Spreading Process, *Journal of Beijing University of Aeronautics and Astronautics*, 46(2020),10, pp.1863-1873
- [12] Huang, Y., *et al.*, ThreeDimensionalSimulation of Lunar Dust Levitation Under the Effect of Simulated Sphere Body, *Journal of Terramechanics*, 48 (2011), 4, pp.297-306
- [13] Huang,Y., *et al.*, Radiative Characteristics of Nonspherical Particles Based on a Particle Superposition Model, *Journal of Geophysical Research*, 118 (2013), 20, pp.11762-11769

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