DESIGN AND VALIDATION OF PORTABLE LUNAR INTELLIGENT DRILLING SYSTEM

by

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The exploration, collection, and utilization of the Moon's abundant resources are increasingly becoming a focal point of research for countries around the world. As China stands on the brink of launching its inaugural manned lunar mission, the task of drilling and sampling on the lunar surface is paramount for astronauts and represents the sole avenue for procuring pristine and genuine lunar regolith samples. To meet the needs of future sampling missions, this paper designs a portable lunar intelligent drilling system, which features multiple working modes, ease of operation, and superior ergonomic performance. A prototype was developed, and relevant experiments were conducted, demonstrating its excellent performance, its core recovery rate can reach 75.3%.

Key words: *lunar drilling sampling, portable, intelligent drilling, experimental verification*

Introduction

Space is an inexhaustible treasure trove of resources for humanity, and the material and information resources of deep-space celestial bodies have become the focus of strategic resources for major world space powers. As the only natural satellite of Earth, the Moon has unique regional characteristics, irreplaceable spatial advantages, rich mineral resources and energy, and is the outpost for human deep-space exploration and extraterrestrial resource development [1, 2].

It is the most direct and effective way to understand the composition of lunar soil, the formation and evolution history of the Moon, and to collect the sequential and fidelity lunar soil samples by drilling [3]. This approach is also crucial for the establishment of permanent space settlements or interstellar bases, which are essential for humanity's future in space. According to China's lunar exploration project plans [4], by 2030, China aims to accomplish its first manned lunar landing, conduct scientific investigations and experiments on the Moon, and master key technologies including *landing, patrol, sampling, research*, *and return*, thereby developing an independent capability for manned lunar exploration. As manned missions to the Moon are progressively implemented, the convenience of man-machine collaborative sampling

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on the lunar surface is highlighted, making the portable lunar intelligent drilling system an indispensable tool in this endeavor.

This article combines the uniqueness of astronaut participation carry out the design of a portable lunar intelligent drilling system, and conducts tests and verifications on key components, aiming to provide a reference for China's manned lunar landing scientific exploration mission and lay a technical foundation for lunar scientific research and development.

Overview of deep space sampling technology

Since the Apollo 11 lunar exploration sampling campaign in 1969, the USA, the former Soviet Union, ESA, Japan and India have sampled the Moon, Mars, comets and asteroids in the past 40 years. Due to the different exploration missions and objectives, the penetration methods and sampling methods of the drilling samplers also vary greatly. From the perspective of sampling action principles, they can be divided into four major categories, fig. 1: kinetic penetration, impact penetration sampling, spiral drilling sampling, and autonomous excavation.

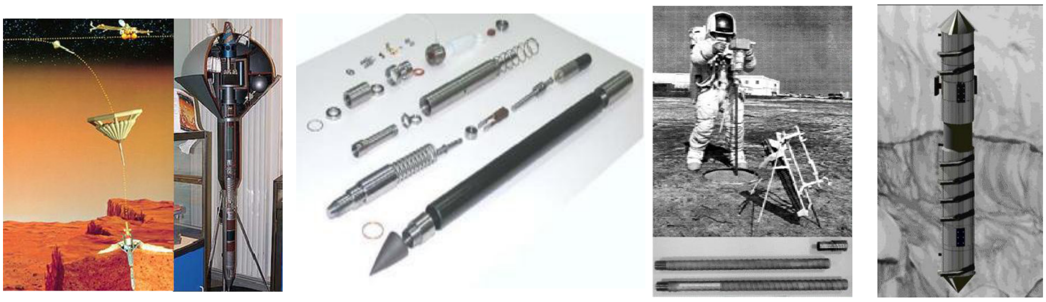

Figure 1. Extraterrestrial body sampling methods; (a) kinetic penetration, (b) impact penetration sampling, (c) spiral drilling sampling, and (d) autonomous excavation

Table 1. Successful lunar drilling and sampling missions

Mission name	Apollo 11/12/14	Apollo 15/16/17 [5]	Luna 24 [6]	CE′ 5 [7, 8]	CE′ 6
Plan introduction	Impact penetration	Multi-pole assembly	Single-pole drilling	Single-pole drilling	Single-pole drilling
Maximum depth [m]	0.7	3.05	2.25	1	1
Weight [kg]	1.5~1.6	13.4	0.041	22	25

It turns out that core drilling is an effective method for obtaining deep lunar samples, but successful on-orbit sampling missions have primarily focused on the surface of planets, tab. 1, with the deepest drilling reaching 3.05 m, as achieved by Apollo 17. The drilling system, while effective for obtaining deep lunar samples, faces challenges in its current design. The process of assembling the drilling rig and drill pipe is complex and cumbersome, requiring precise splicing operations that are intricate and time-consuming. Furthermore, the drilling pressure during operation is manually provided by astronauts, which not only adds to the difficulty of the task but also results in the astronauts bearing the reaction force and torque generated during drilling. This has led to injuries among astronauts during actual use, highlighting a critical area where the design must be improved to ensure safety and efficiency.

The design of portable lunar intelligent drilling system

Overall scheme design

The portable lunar intelligent drilling system is composed of a drill rig, a drilling support frame, multifunctional sampling drilling tools, and a sample containment vessel. The portable intelligent drilling device on the Moon has two working states. As shown in fig. 2(a), in the deployed working state, astronauts can complete drilling operations with the assistance of the drilling support frame through the man-machine interaction system; as shown in fig. 2(b), in the retracted and folded state, the size is reduced, making it easier for astronauts to carry.

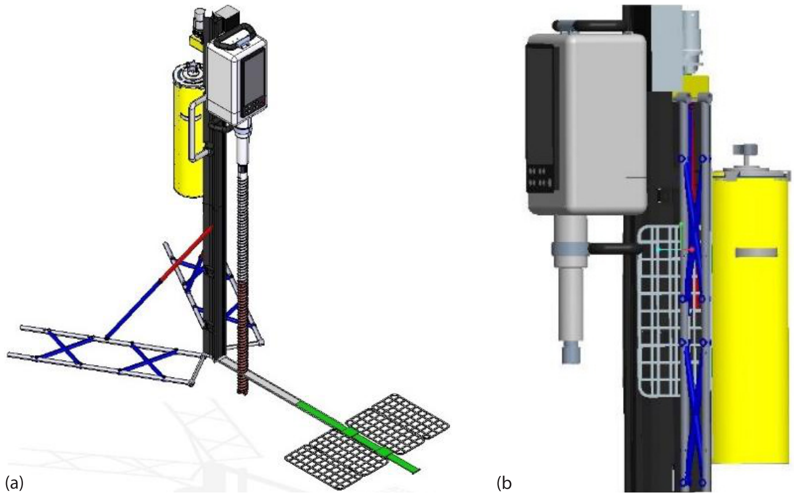

Figure 2. Portable lunar intelligent drilling system working states; (a) deployed working state and (b) retracted state

The drill rig has two working modes: handheld drilling and support-assisted drilling, as shown in fig. 3. The handheld drilling mode is mainly used for sampling shallow subsurface lunar soil and exposed rocks, while the support-assisted drilling mode is targeted at drilling depths of more than 5 m.

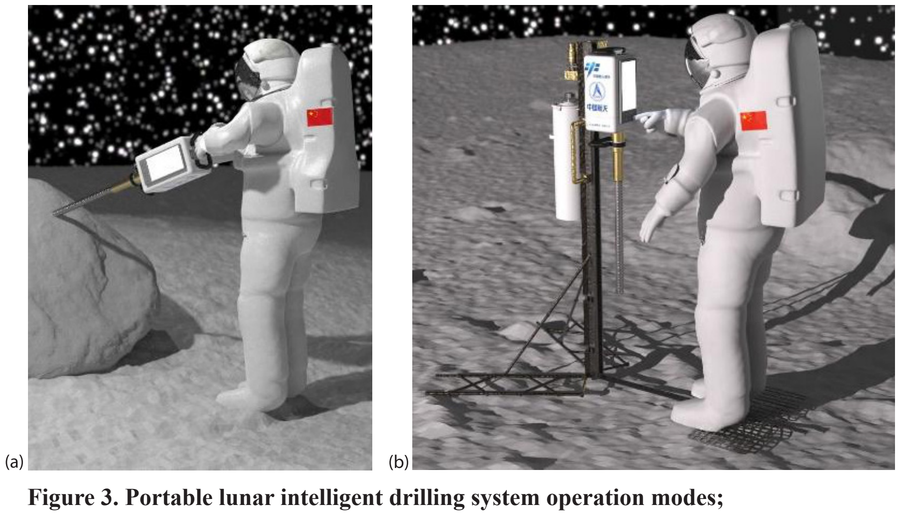

Figure 3. Portable lunar intelligent drilling system operation modes; (a) handheld drilling mode and (b) support-assisted drilling mode

Figure 4. Drill rig structure schematic

The design of drilling rig

The drilling rig is designed with a vertical lay-out, incorporating both slewing and impact driving capabilities. It comprises a slewing impact mechanism, an intelligent interactive module, an energy module, a foldable handle, and several other components. The complete mechanism is illustrated in fig. 4. The drilling rig is enhanced with an intelligent interactive module, and the front-end tool attached to it is capable of multi-parameter measurement. This capability allows for the real-time transmission of measurement parameters to the drilling rig's operation panel, where they can be displayed. Furthermore, it enables the generation of a virtual drilling model, facilitating visual drilling and the adaptive adjustment of drilling parameters to achieve intelligent drilling.

Core drilling tool drill rod design

The chip evacuation requirements of the drill pipe are determined by the working section of the drill bit and the feed rate [8]. During the drilling process, the efficiency of powder evacuation is not only related to the spiral parameters of the screw but also to the rotation speed of the screw. A classic lunar regolith evacuation model is used as the critical speed model [9], which analyzes the force and motion of individual particles to obtain the overall evacuation constraint relationship. To further clarify the impact of rotation speed on the evacuation process, the relationship between screw parameters and screw rotation speed is established. The relationship between the critical rotation speed of the spiral drill pipe and the angular velocity, ω:

$$\omega = \left(1 + \cot\alpha \cdot \tan\theta\right) \sqrt{\frac{\left(\mu_{cd} \cos\alpha + \sin\alpha\right) \mathrm{g}}{\mu_{cs} \left[\cos\left(\alpha + \theta\right) - \mu_{cd} \sin\left(\alpha + \theta\right)\right] R}} + \frac{v_z}{R} \cot\alpha \tag{1}$$

where θ is the friction angle, α – the spiral angle, μ_{cs} – the friction coefficient between the drill cuttings and the hole wall, μ_{cd} – the friction coefficient between the drill cuttings and the drill rod, v_z – the drilling speed, and R – the outer diameter of drill pipe.

Based on the critical speed model, the drill pipe with an outer diameter of 43 mm and core sizes of 32 mm, 30 mm, and 28 mm was designed and developed, with a spiral rise angle of 15.66°.

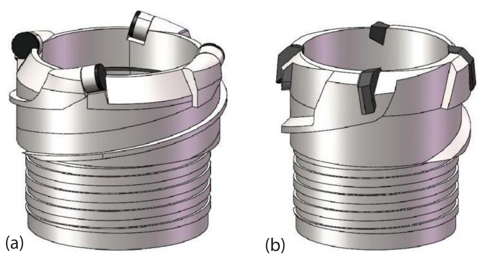

Figure 5. Drill bit; (a) PDC drill bit and (b) special-shaped cutting edge drill bit

Core drilling tool drill bit design

The drill bit matrix primarily serves the function of chip evacuation during the drilling process, with the evacuation force mainly provided by the rotation of the chip evacuation wings, which drive the cuttings along the matrix's baseline direction.

To minimize the generation of chips during drilling, this paper adopts a planar structure that features four cutting edges symmetrically arranged. The PDC drill bit and special-shaped cutting edge drill bit are designed, as shown in fig. 5. The design specifications for the bit are an outer coring diameter of 43 mm and inner coring diameters of 32 mm, 30 mm, and 28 mm. This refined design aims to optimize the drilling process by balancing the removal of cuttings and the precision of the core samples obtained.

Experiment verification

The experiments were conducted using the drilling rig and drill bits designed in this paper to verify the performance with nominal simulated lunar regolith. Both the PDC drill bit and special-shaped cutting edge drill bit were tested under constant drilling parameters. The drill bit with relatively stable drilling force load characteristics and high coring rate was preferred. The drill rig system and drill bit test pieces are shown in fig. 6.

(a) (b)

Figure 6. Participating products; (a) drill rig and (b) drill bit

From the results of the drilling test shown in fig. 7, it can be seen that the PDC grill bit had the lowest drilling pressure, the maximum drilling pressure is lower than 20 N. But its core recovery rate was only 35%, which did not meet the requirements. In contrast, special-shaped cutting edge drill bit had a relatively stable drilling pressure, with a maximum drilling pressure of less than 120 N, and a core recovery rate of 75.3%, making it the preferred choice for the drill bit structure.

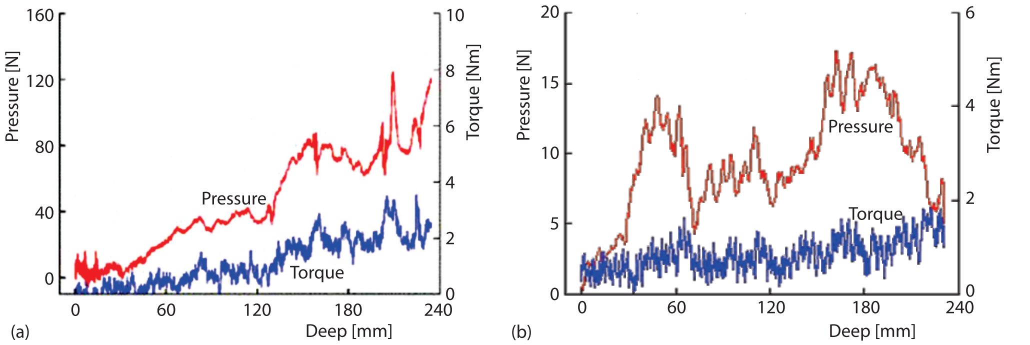

Figure 7. Drilling experimental load curves; (a) PDC drill bit and (b) special-shaped cutting edge drill bit

Conclusion

In anticipation of future sampling missions, this paper presents the design and development of a portable lunar intelligent drilling system, supported by experimental research, with the following key findings: The system features multiple working modes, enabling easy interchange of sampling drill tools to meet diverse drilling objectives, thereby significantly enhancing work efficiency. Additionally, it includes a foldable drilling auxiliary bracket that simplifies astronaut operations, reduces operational time, and mitigates drilling risks. The system is designed with a single motor drive that outputs dual motion, contributing to its lightweight construction, making it highly suitable for deep space exploration missions where weight is a critical constraint. Drill bit selection experiments revealed that the special-shaped cutting edge drill bit excels in drilling stability, core recovery rate, and manufacturability, operating with a maximum drilling pressure of less than 120 N and achieving a core recovery rate of 75.3%.

Nomenclature

g – acceleration of gravity, [ms^{-2}]
R – outer diameter of drill pipe, [mm]
v_z – drilling speed, [ms^{-1}]

Greek symbols

θ – friction angle, [°]
μ_{cd} – friction coefficient between the drill cuttings and the drill rod, [1]
μ_{cs} – friction coefficient between the drill cuttings and the hole wall, [1]

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