SCHEME DESIGN AND EXPERIMENT VALIDATION OF MULTIPLE SAMPLING STRATEGIES ON WEAK GRAVITY ASTEROID

by

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Asteroids hold invaluable scientific information and provide critical insights into the origins and evolution of the solar system, highlighting the significance of asteroid sample-return missions. However, the diverse typology of these asteroids, limited understanding of their surface geology, and extremely weak gravity present substantial challenges, necessitating technologies with high geological adaptability, low reaction forces, and rapid sampling capabilities. In response, six novel and heterogeneous asteroid sampling schemes were developed and rigorously analyzed through comparative studies and test validation, focusing on adaptability, sampling time, reaction force, and sample volume. Results confirm that all six schemes enable rapid sampling under low reaction forces, meeting design objectives. Notably, the rock-breaking and gas-excitation hybrid and the positional kinetic energy-induced directional sampling technique demonstrate superior adaptability, simplicity, reliability, and repeatability, marking them as promising candidates for further research.

Key words: *asteroid sampling, multi-scheme design, test validation*

Introduction

Asteroids hold invaluable scientific information for comprehending solar system origin and evolution, carrying rich scientific information and harboring substantial reserves of precious metals and rare elements with immense utilization potential [1]. Consequently, asteroid sampling and exploration hold significant scientific and engineering implications, prompting global research initiatives and mission developments. The JAXA-developed Hayabusa probe marked the first asteroid sample return mission, targeting the *S*-type near-Earth asteroid Itokawa and implementing a pioneering Touch-and-Go sampling approach utilizing projectile impact-induced sputtering to retrieve approximately 1500 asteroid microparticles [2]. Subsequent missions like Hayabusa 2 targeted the *C*-type near-Earth asteroid Ryugu, successfully obtaining approximately 5.4 g of samples through multiple impact-sputtering techniques back to Earth [3, 4], while the NASA OSIRIS-REx mission explored the *C*-type near-Earth asteroid Bennu, employing gas-excitation sampling technology and collecting 121.6 g of asteroid particulate matter [5, 6].

Sample return is the core objective of asteroid exploration missions. Based on current asteroid exploration missions, the difficulty of sampling is significant, with limited sample vol-

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ume collected [7]. On one hand, this reflects the extreme complexity of asteroid characteristics, making surface sampling highly challenging. On the other hand, it indicates that research on sampling technologies for weak gravitational environments is still in its early stages. This presents an opportunity for researchers to focus on targeted studies and breakthroughs in sampling technologies, expanding the range of applicable sampling methods and techniques.

Multi-scheme design for asteroid sampling

The surface gravity of asteroids is extremely weak, and their shapes are irregular, making attachment and fixation challenging. During asteroid sampling, the forces applied could potentially push the probe away from the asteroid. Additionally, the terrain and geological characteristics of the asteroid surface remain uncer-tain. These factors make traditional mechanical sampling methods, such as drilling and excavation, difficult to implement [8, 9]. Given these challenges, it is necessary to develop and apply novel sampling techniques that minimize the applied force. Furthermore, to accommodate the uncertain surface geology of the asteroid and various sampling detection modes [10], a multi-scheme design approach is required. By decomposing and combining functional modules such as rock breaking, sample collection, sample transfer, and sample retrieval, six new, heterogeneous sampling designs were developed.

Rock breaking and gas-excitation hybrid sampling

This scheme uses a robotic arm equipped with a hybrid rock-breaking and gas-excitation sampler. The sampler employs an ultrasonic impact drill to enhance the surface fragmentation, and high pressure gas is used to blow the debris into the sampler. The sampling design is shown in fig. 1. The specific process is as the probe gradually descends toward the target surface, the sampler extends and contacts the sur-face. The ultrasonic impact drill at the front of the sampler activates, intensifying surface fragmentation. High pressure nitrogen gas is then blown on the surface, fluidizing the debris, which is carried into the sampler by the air-flow. Finally, the sample is transferred and separated from the container via the robotic arm, completing the recovery process.

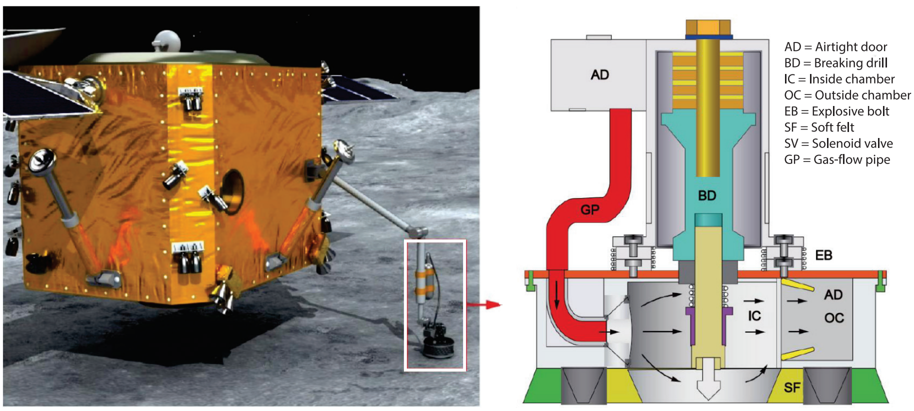

Figure 1. Rock breaking and gas-excitation hybrid sampling design

This method, combining ultrasonic impact drilling and gas-excitation collection, achieves a sampling reaction force of ≤20 N, a sampling time of ≤10 seconds, a sample volume of 10-120 g, and a power consumption of ≤50 W. This approach is characterized by short sampling times, strong adaptability to asteroid surfaces, repeatability, and reliable sampling.

Ultrasonic drilling sampling

In this design, a robotic arm is equipped with a core-drilling sampler that uses ultrasonic impact-driven rotary drilling for core sampling. The robotic arm then transfers the sample to a recovery container. The ultrasonic drilling sampling design is shown in fig. 2.

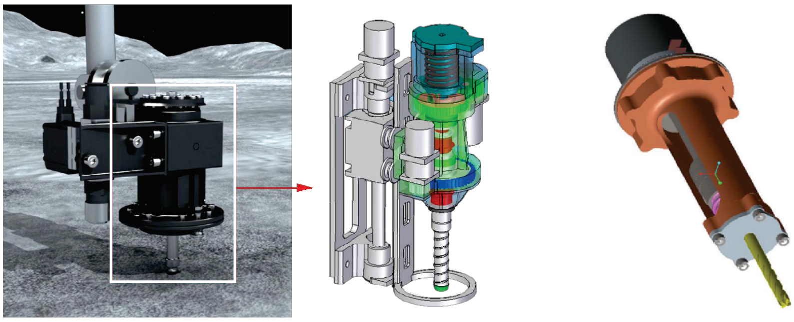

Figure 2. Ultrasonic drilling sampling design

This scheme uses ultrasonic impact rotary drilling to break rock and extract core samples. It achieves a sampling reaction force of ≤20 N, a sampling time of 10 seconds to 5 minutes, a sample volume of 10-80 g, and a power consumption of ≤100 W. This method provides powerful rock-breaking capability, repeatable sampling, and low reaction forces, but the sampling time is relatively long.

Tape adhesion sampling

This design employs a rigid-flexible coupling deployment mechanism to carry an adhesive tape-based sampler. The sampler uses different functional zones of the tape to grind, hold, adhere, and wind surface materials into the sampler, thus completing both sampling and storage simultaneously. The process is as the probe gradually descends toward the target surface, the sampler deploys along the rigid-flexible tube. Upon contact with the surface, the tape sweeps across it, physically adhering and winding planetary regolith on the tape surface. After sampling, only the wound tape is recovered. The adhesive tape sampling design is shown in fig. 3.

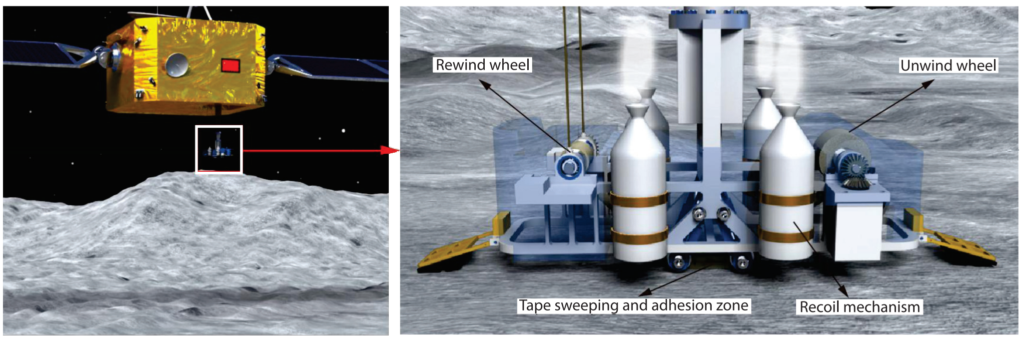

Figure 3. Tape adhesion sampling

This method uses sandpaper for abrasive grinding and tape for physical adhesion and storage. It achieves a sampling reaction force of ≤10 N, a sampling time of 10-60 seconds, a sample volume of 50-120 g, and a power consumption of ≤50 W. This design offers synchronized sample collection and storage, simple operational sequences, and minimal recovery volume.

Positional kinetic energy-induced directional sampling

This scheme employs a robotic arm equipped with a sampler that integrates four interchangeable tools: a brush wheel, a milling cutter wheel, and fine/coarse abrasive wheels. These tools can selectively interact with the asteroid surface. By utilizing centrifugal force for directional collection, the scheme enables the gathering and storage of surface materials. After sampling is complete, the sample container is retrieved. The sampling design is illustrated in fig. 4.

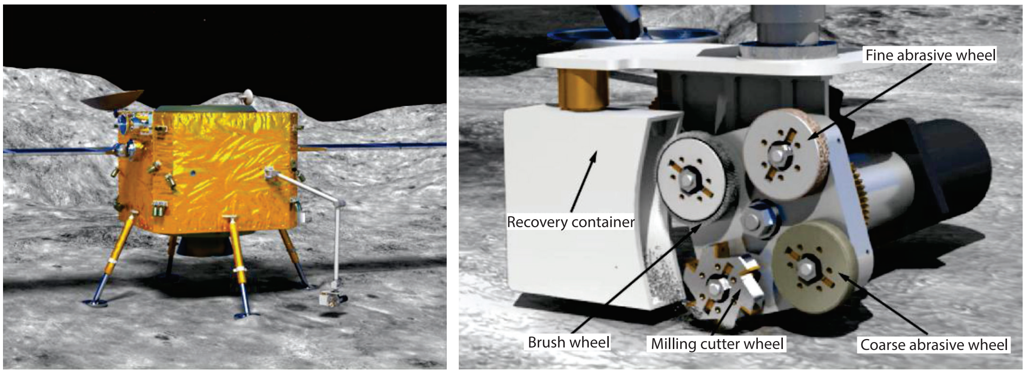

Figure 4. Positional kinetic energy-induced directional sampling design

This scheme utilizes a grinding wheel for rock-breaking and dynamic excitation for directional scraping of the weathered layer and grinding debris. The design ensures a sampling reaction force of ≤20 N, with a single sampling time ranging from 5 seconds to 2 minutes. The sample volume is between 10-200 g, and the power consumption is ≤50 W. The system is characterized by strong adaptability to asteroid surfaces, directional sample intake, and reliable sampling performance.

Electrostatic adhesion sampling

This scheme involves bombarding the surface regolith with a high energy electron beam to ionize it, imparting a positive charge. The collection device then applies a negative charge to enable electrostatic adhesion for sampling. The sampler consists of three modules: the electrostatic recognition module, the electrostatic application module, and the electrostatic adsorption module. The sampling design is illustrated in fig. 5.

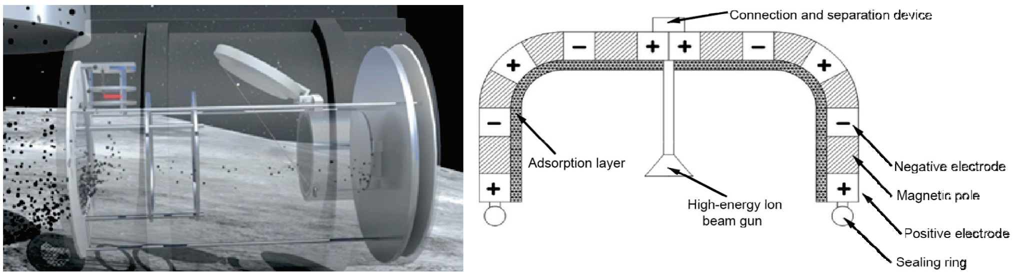

Figure 5. Electrostatic adhesion sampling design

This scheme uses electrostatic force as the sampling power, with no sampling reaction force. The single sampling time is ≤60 seconds, with a sample volume of 1-10 g and power consumption ≤100 W. It is characterized by simple operation and the absence of reaction force.

Mesh netting grasping sampling

This scheme employs a rigid-flexible coupling deployment mechanism to carry the sampler. The sampler forms soft samples through directional energy-focused explosive fragmentation, then collects the samples using a mesh netting grasping mechanism. Finally, the collected samples are retrieved by a cable-driven recovery system.

The specific operation process is first, the probe determines the sampling area. The probe then gradually approaches the asteroid, emitting a positioning target to the asteroid surface. The rigid-flexible coupling deployment mechanism extends the sampler to the asteroid surface. Once the mesh net contacts the surface, the energy-focused explosive package is unlocked. The probe moves a safe distance away, triggering the explosion, which disperses the debris. The probe then returns to locate the position and the sampling mechanism collects the samples. Once sampling is complete, the shape-memory composite material is unlocked, and the cable reel retracts the connection rope to recover the samples. The entire sampling process can be completed in a short period. The sampling design is shown in fig. 6.

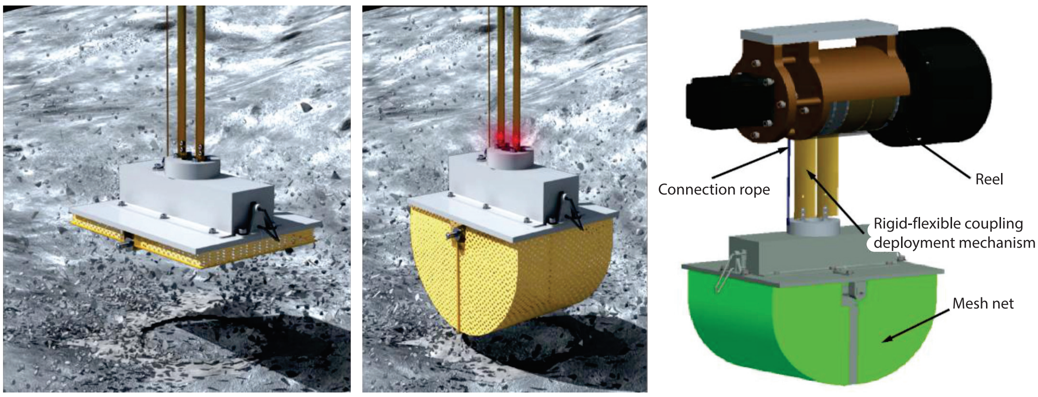

Figure 6. Mesh netting grasping sampling design

This scheme employs a one-time grasping mechanism to collect surface debris. The designed sampling reaction force is ≤5 N, with a sampling time of ≤10 seconds and a sample volume of 20-200 g. The power consumption is ≤20 W. It features the ability to convert the uncertain characteristics of the asteroid surface into a controllable sampling state, with minimal reaction force.

Comparison of multi-scheme design

The characteristics and performance metrics of the six design aforementioned schemes are com-pared and analyzed, as shown in tab. 1.

Table 1. Comparison of multiple design schemes for asteroid sampling

Item	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5	Scheme 6
Scheme name	Rock breaking and gas-excitation hybrid sampling	Ultrasonic drilling sampling	Tape adhesion sampling	Positional kinetic energy-induced directional sampling	Electostatic adhesion sampling	Mesh netting grasping sampling
Applicable sampling mode	Adherence and touch-and-go	Adherence	Adherence and touch-and-go	Adherence and touch-and-go	Adherence and touch-and-go	Adherence and touch-and-go
Reaction force	≤20 N	≤20 N	≤20 N	≤20 N	0 N	≤5 N
Sampling time	Single operation ≤10 seconds	Single operation 10 seconds to 5 minutes	Single operation 10-60 seconds	Single operation 5 seconds to 5 minutes	≤60 seconds	≤10 seconds
Sample volume	10-20 g	10-80 g	50-120 g	10-200 g	1-10 g	20-200 g
Power consumption	≤50 W	≤100 W	≤50 W	≤50 W	≤100 W	≤20 W
Scheme charac-teristics	Short sampling time, strong adaptability, reliable and repeatable sampling	Low reaction force, repeatable sampling	Coupled rigidflex posture positioning, light-weight, direct flexible recovery	Strong adaptability to asteroid surface characteristics, repeatable sampling	Suitable for dielectric snd non-dielectric particles, zero reaction force	Directed blasting followed by quick clamping, with manual control of asteroid surface material
Applicable sampling targets	Soil, gravel, boulders, water ice, metallic rock; applicable to *C*-, *S*-, *D*-, *M*-type asteroids	Soil, gravel, boulders, water ice, metallic rock; applicable to *C*-, *S*-type asteroids	Soil, gravel, boulders, metallic rock, applicable to *C*-, *D*-, *M*-type asteroids	Soil, gravel, boulders, water ice, metallic rock, applicable to *C*-, *S*-, *D*-type asteroids	Small particicles soil, gravel, and fine grains; applicable to *C*-, *D*-type asteroids	Soil, gravel, boulders, metallic rock; applicable to *C*-, *S*-, *M*-type asteroids

The aforementioned analysis reveals that all six schemes share the following characteristics:

- they meet the requirements of different exploration modes, including adherence or touch-and-go operations,
- they feature low reaction forces, compact designs, and low energy consumption, and
- they can adapt, either as standalone schemes or in combination, to the diverse geological characteristics of various asteroid types.

Among them, the rock breaking and gas excitation hybrid sampling scheme and the positional kinetic energy-induced directional sampling scheme demonstrate excellent adaptability to different targets, support repeatable sampling, and offer high sample volume, making them promising directions for further research.

Multi-scheme test validation

Based on the design of multi-scheme, six samplers were developed, and a testing platform for sampling force loading was constructed. Underground gravity conditions, experiments were conducted on different sampling targets such as various particle gradings, low gravity particles, and rocks, as shown in fig. 7. The results of the sampling tests are presented in tab. 2.

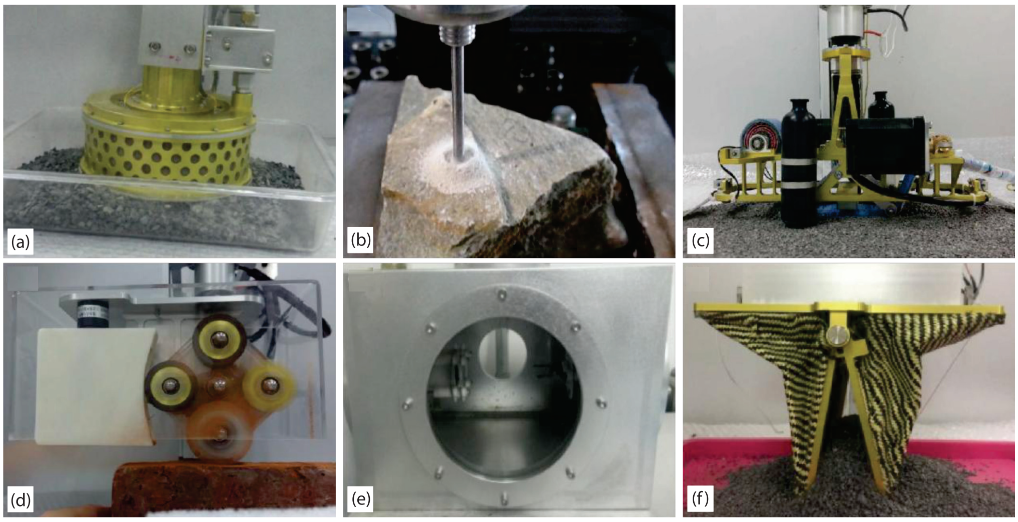

Figure 7. Test validation of sampling with multi-scheme prototypes; (a) rock breaking and gas excitation hybrid sampling, (b) ultrasonic drilling sampling, (c) tape adhesion sampling, (d) positional kinetic energy-induced directional sampling, (e) electrostatic adhesion sampling, and (f) mesh netting grasping sampling

Table 2. Test validation results of multiple sampling schemes for asteroids

Project	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5	Scheme 6
Sheme name	Rock breaking and gas-excitation hybrid sampling	Ultrasonic drilling sampling	Tape adhesion sampling	positional kinetic energy-induced directional sampling	Electrostatic adhesion sampling	Mesh netting grasping sampling
Performance test results	– Reaction force ≤ 10 N – Particle single sample volume: 23-81 g, rock surface sampling amount ≤ 1 g – Sampling time ≤ 10 seconds	– Reaction force ≤ 20 N – Sample volume: 8-27 g, rock surface sampling amount ≤ 1 g – Sampling time: 5 minutes	– Reaction force ≤ 20 N – Particle single sample volume: 11-38 g, effective sampling on rock surfaces – Sampling time: ≤ 60 seconds	– Reaction force ≤ 20 N – Particle single sample volume: 27-139 g, effective sampling on rock surfaces – Sampling time: 5-20 seconds	– No reaction force – Sample volume: 0-1 g – Sampling time: 60 seconds	– Reaction force ≤ 5 N – Particle single sample volume: 4-115 g – Sampling time: 5 seconds
Advantages	Sort sampling time, strong adaptability to targets, reliable sampling, and repeatable sampling	Low reaction force, repeatable sampling	Strong adaptability to targets	Sort sampling time, strong adaptability to targets, reliable sampling, and repeatable sampling	No reaction force	Strong adaptability to targets, larger single sample volume
Existing issues	Rock fragmentation efficiency needs improvement	Sampling efficiency is low	Almost no rock fragmentation capability	Rock fragmentation efficiency needs improvement	No large particle sampling capability	Cannot perform repeated sampling

The validation results indicate that:

- All six samplers are able to complete sampling in a short period of time with low reaction force, meeting the design expectations.
- Gas excitation is a low reaction force, fast, simple, and effective method for sampling and sample transport. When combined with rock breaking methods, it enhances the adaptability to the target, though the collection efficiency is relatively low under rugged surface conditions.
- Kinetic energy-induced directional sampling is also a low reaction force, fast, simple, and effective sampling method, which is more reliable than gas excitation in rugged terrain conditions.
- Ultrasonic drilling can effectively fragment rocks and obtain powder samples, but the rock fragmentation and collection efficiency still need further improvement.
- Tape adhesion sampling has almost no rock fragmentation capability, electrostatic adhesion sampling can only sample very small particles, and mesh cover sampling cannot be repeated multiple times, all of which have limitations.

Conclusion

To address challenges such as the uncertainty of asteroid surface geological characteristics and the complexity of designing low reaction force sampling mechanisms, six novel and heterogeneous sampling schemes were developed. Test validation demonstrated that all six schemes successfully achieved sampling within a short timeframe and under low reaction forces, meeting design expectations. Among them, the rock breaking and gas excitation hybrid sampling method and the positional kinetic energy induced directional sampling exhibited excellent adaptability to various targets, as well as simplicity, reliability, and repeatability. These two methods are recommended as prioritized candidates for further focused research.

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