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Gas-Driven Regolith-Sampling Strategy for Exploring Micro-Gravity Asteroids

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ABSTRACT Small celestial bodies contain abundant scientific information to understand the origin and evolution of the solar system. The acquisition and analysis of regolith sample is the most direct and effective way to explore the geological construction of poorly known asteroids as remnants of earlier existed planetesimals. China is gradually promoting extraterrestrial regolith sampling technology from asteroids or comets nowadays. To obtain surface regolith from ultralow-gravity asteroids, a novel gas-driven regolith-sampling strategy is proposed, and a prototype was designed and fabricated for experimental validation. In this method, an ultrasonic percussive drill with low-reaction force is designed to break surface regolith to fine particles, and sample mobilization and collection is implemented through highly pressurized gas. Fluid-solid coupling simulation was conducted to evaluate regolith-sampling performance under normal- and micro- gravity conditions. Preliminary experiments, both in room and vacuum conditions, showed that the proposed strategy has good geological adaptability and sample-acquiring ability. This method can provide important technical supports for China's forthcoming asteroid-comet regolith-sampling exploration.

INDEX TERMS Asteroid exploration, deep-space detection, extraterrestrial regolith sampling, fluid-solid coupling analysis, space robot.

I. INTRODUCTION

Space exploration is the ongoing discovery of celestial structure in outer space by means of continuously evolving and growing unmanned robotic probes and human spaceflights [1]. Extraterrestrial regolith collection and ingredient analysis is the most effective and critical way to obtain scientific information of water/life existence and universe evolution [2], [3]. Small celestial bodies (SCBs), known as living fossils in the solar system, are extremely significant carriers in understanding the origin and evolution of our solar system due to their low internal evolution, which more completely remains the early formation of the solar system. Recently, meteorite analysis on the Earth surface reveals the importance of linking meteorites to near-Earth asteroids and improving the methodology to analyze asteroid samples [4]–[7]. Nevertheless, asteroids also contain a large amount of precious metal and rare elements with valuable utilization prospect for solving humanity's energy shortage problem on the Earth [8], [9]. In the past thirty years, nearly twenty probes were launched to explore and discover exotic surface features on SCBs through different methods [10], such as flyby observation, surrounding detection, and soft-landing and sampling exploration [9]. In these missions, the technology of landing asteroid surface [11]–[13], obtaining regolith, and returning collected samples [14] is increasingly drawing the attention of scientists and engineers worldwide. It is becoming a leading cutting-edge technology indicating a country's comprehensive national strength, scientific capability, and technological level [15].

In the past decade, many regolith-sampling robots to acquire regolith from SCBs were proposed and developed. The first asteroid-sampling was successfully completed by the Japanese Hayabusa in 2010, which aimed to utilized

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high-speed projectiles to break surface regolith and then a chamber to collect splashed regolith particles [16]. This success was followed by the European Rosetta mission to sample comet 67 P/Churyumov-Gerasimenko by the SD2 System for *in-situ* analysis [17]–[19], the Japanese Hayabusa 2 mission to sample asteroid 1999 JU3 by the special projecting system in its previous mission [20]–[23], and the American OSIRIS-REx mission to sample asteroid 101955 Bennu with the Touch-and-Go-Sample-Acquisition-Mechanism (TAGSAM) system by releasing high-purity N2 gas flow [24]–[28]. Unlike the drilling method in Rosetta mission that the lander must be anchored, a connection with the target asteroid is not necessary in Hayabusa and OSIRIS-Rex missions. However, question raises as to whether the non-anchored method was able to capture enough material due to geologic diversity and uncertainty. Nevertheless, the sampling depth is also limited for samplers are difficult to penetrate to deep subsurface. Apart from the regolith-sampling robots successfully launched in deep-space exploration missions, there are also many prototypes developed for scientific researches or future missions, such as the drilling, sampling and sample handling system [29], the asteroid sample return spacecraft [30], the asteroid reconnaissance probe [31], the pyramid comet sampler [32], and the bi-blade sampling chain [33]. On top of sampling SCBs, scientists and engineers are also considering ambitious plans to mine asteroids for their abundant rare resources [8], [34]. Up to date, although only the Japanese Hayabusa successfully sampled an asteroid, however, great discoveries have been achieved by these explorations, and even greater discoveries are forthcoming [14], [35].

Different from planets with huge mass, SCBs merely have extremely low mass and irregular surface shapes, which leads to ultra-low gravity, possibly fast rotation and extremely difficult anchoring feasibility [36]. Besides, geological diversity and uncertainty makes traditional drilling or excavating methods difficult and inapplicable in acquiring samples under micro-gravity conditions. To break these limits, novel and reliable methods are critical in sampling SCBs. Gas-driven regolith-sampling method relies on high-speed gas flow to directionally convey and collect regolith particles [37], and is efficient to lift regolith particles with relatively simple device [38]. The conveyance theory is akin to that of pneumatic material conveyor on Earth, which takes inspiration from dune mobilization by natural wind. Wind transportation is the conveying process of loose debris from regolith surface to other places by wind power. The capacity of wind transportation is extremely strong, generally proportional to wind speed, and inversely proportional to debris mass. Except for a strong carrying capacity, even no motors or mechanical transmission components are needed, hence dimension and power consumption are greatly reduced, reaction force is extremely low, whereas sampling efficiency is considerably valuable [39], [40]. In recent years, more and more attention is drawn from scientists and engineers worldwide to sample extraterrestrial regolith through pneumatic method [41].

China has achieved splendid progress in successfully executing the series Chang'E lunar exploration mission, including Chang'E 2 to flyby asteroid Toutatis after lunar surrounding observation, Chang'E 3 to softly land on Moon surface for roving inspection, and Chang'E 4 to explore the far side of the Moon [42]. With considerable technology accumulation, China is actively promoting deep-space missions to explore SCBs nowadays [43], [44]. Previous key developments of extraterrestrial sampling systems by the China Academy of Space Technology include the 2-m deep drill to be carried in the coming Chang'E 5 mission to collect and return lunar regolith samples [45], [46]. Based on this experience, our team embarked on projects to assess sample return from near-Earth asteroids. This work proposed a novel gas-driven regolith-sampling strategy to obtain regolith particles from micro-gravity asteroids, which can be viewed as important technical supports for the future mission. The remainder of the work is organized as follows: Section 2 presents the sampler design philosophy, also including a preliminary theoretical analysis of wind transportation; Section 3 illustrates the method to design and develop the sampler prototype; Simulation and experimental results are given and discussed in Section 4; Section 5 concluded this work.

II. SAMPLER DESIGN PHILOSOPHY

A. DESIGN CRITERIA

Landing on SCBs is quite different than that on planets with appreciable gravity because spacecrafts need to provide the functionality of maintaining contact with surface regolith, which requires complicated thrusting or anchoring system, and these technologies are extremely sensitive to the specific properties of surface regolith. Whereas the strategy to sample through the touch-and-go architecture eliminates any need for landing and anchoring, facilitating much simplicity for sample handling during proximity, as well as for spacecraft design and operation. No matter which kind of sampling strategy is adopted, a sampler with low reaction force is essential. The proposed applicable way to obtain regolith samples is through a robotic arm augmented with a pneumatic collection device. As no mechanical actuators and drive components are needed to mobilize regolith particles, the operation is thoroughly simple and reliable. To develop the sampler without compromising performance in ultra-low gravitational field, the following design criteria must be considered.

(1) *Micro-Gravity Adaptivity:* For celestial bodies with appreciable gravity, the surface regolith is relatively compacted, providing stability for landing spacecrafts to implement sampling operations. However, for SCBs with micro-gravity, the surface is thought to be too rubble-strewn to have enough consolidated regolith to anchor spacecraft stably for conventional sample acquisition, requiring samplers to be low-gravity adaptivity.

(2) *Excellent Geological Adaptability:* The diversity of asteroid's surface regolith greatly influences the sampler's overall design and operation [35]. Limited to ground-based observations, SCBs' surface regolith is full of

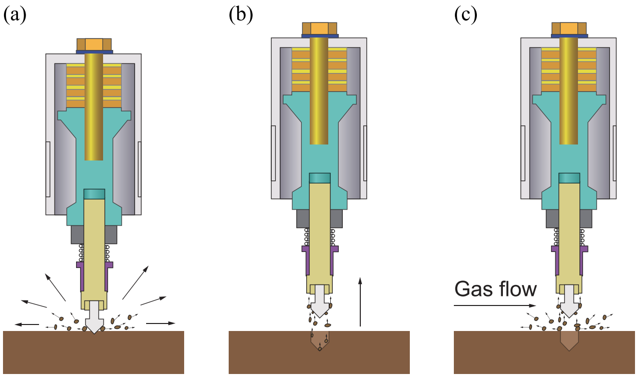

FIGURE 1. **Movement of drilled debris. (a) Sputtering movement at random directions. (b) Adhesive movement in vertical direction. (c) Directional movement by gas flow.**

geological uncertainty. Excellent samplers should be capable of dealing with various adverse terrains, covering rubble piles, bare rocks, loose dust, etc.

(3) *Lightweight and Low Power Consumption:* To explore far SCBs, limited to the carrying capability of rockets and launching cost, the fuel and battery carried to power the spacecraft, and the power generated by solar array cells are highly limited. Regolith samplers should be low power consumption, and the mass and configuration must be highly optimized.

(4) *High Efficiency and Reliability:* The most significant requirement for regolith sampling is to collect considerable mass, retain in-situ characteristics with reasonable fidelity, and encapsulate samples for return reliably. That means samplers should be able to collect expected samples under accounted conditions with high operational performance and reliability.

B. PNEUMATIC REGOLITH COLLECTION THEORY

In order to guarantee the reliability of sample collection in various geological conditions, an ultrasonic percussive drill with low-reaction force is designed to break surface regolith to fine particles, whereas sample mobilization and collection is implemented through highly pressurized gas. A drill works highly efficient even in breaking hard rocks into debris, which enables the sampling system to obtain some material even in extremely dense geological conditions. In micro-gravity condition, the force caused by the vibration of the drill do can cause the movement of drilled debris, as shown in Fig. 1. However, the moving directions are random in such implication, such as the sputtering and the adhesive movements of debris showed in Fig. 1. To ensure that the drilled debris can be efficiently conveyed into the recycling chamber, gas flow is utilized for directional mobilization.

Before designing the prototype, a preliminary theoretical analysis to the force and movement of regolith particles was given. The working principle of gas-driven regolith sampling is simply the mobilization of regolith particles from land surface and transporting them to the collection chamber. When gas flow force exerts on regolith surface under micro-gravity, regolith particles are entrained, known as creeping, ascending and suspending for particles with different sizes (Fig. 2(a)). The extent of movement depends on many factors, such as regolith particles' diameter, density, and gas flow velocity. To improve sampling performance, a reasonable gas pressure and outlet velocity needs to be considered. The desired gas

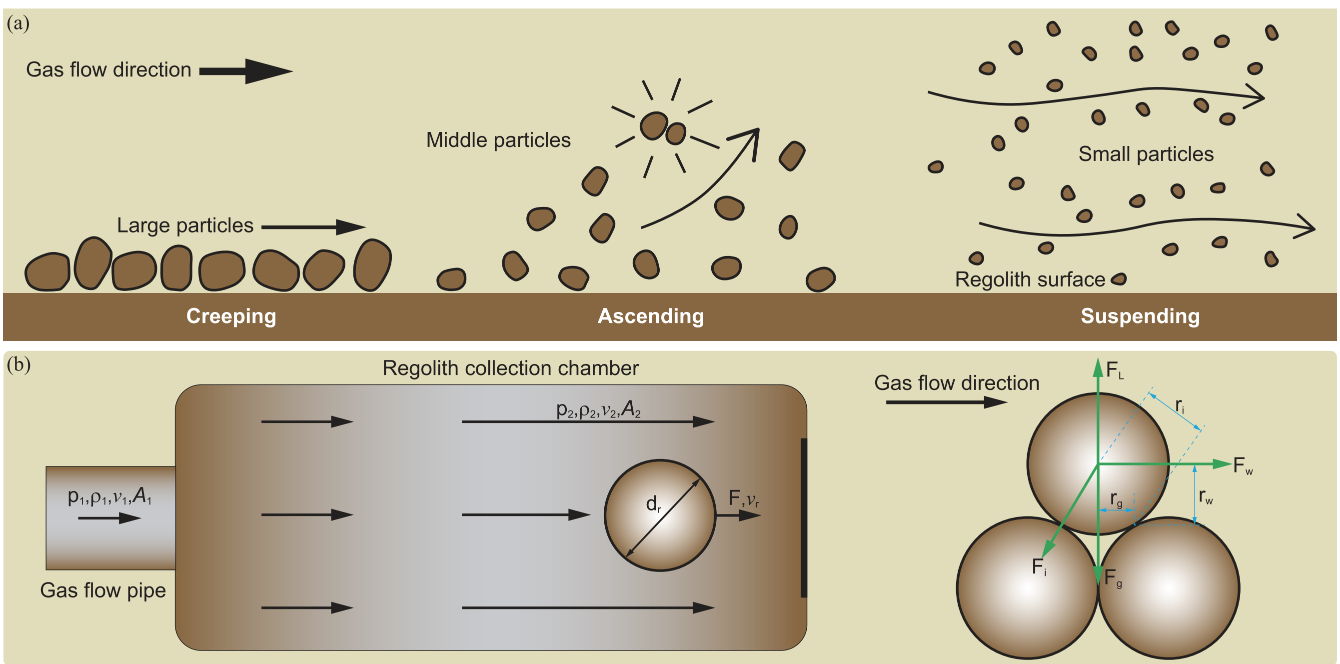

FIGURE 2. **Analysis of gas-driven regolith-sampling process. (a) Aerodynamic force to mobilize regolith particles: larger particles creeping on regolith surface (left), middle particles ascending by gas movement (middle), and small particles suspending in the gas flow (right). (b) Parameters of gas flow in pipe and collection chamber (left), and force analysis of a typical surface regolith particle has physical contact with other particles (right).**

pressure ΔP, controlled by a solenoid valve (Fig. 2(b)), can be calculated with dynamic pressure theory as:

$$\Delta P = \frac{1}{2}\rho_1 v_1^2 \tag{1}$$

where ρ_1 denotes the density of pressurized gas (nitrogen is selected in this work, 1.29 kg/cm^3), and v_1 denotes the gas flow velocity in the valve outlet.

According to the conservation principle of mass, we can easily get:

$$\rho_1 v_1 A_1 = \rho_2 v_2 A_2 \tag{2}$$

where ρ_2, v_2 and A_2 denote the gas density, the gas flow velocity and the sectional area of sample recycling chamber, respectively. The gas flow velocity threshold to mobilize regolith particles can be derived from the force equilibrium of a stationary surface particle (Fig. 2(b)), which is controlled by Newton's second law:

$$m_r \frac{dv_r}{dt} = \sum F_r + m_r g \tag{3}$$

where m_r, v_r and F_r denote the mass, the velocity, and the sum of external forces of the particle. It will be entrained by gas flow when it pivots around the contact point with its supporting neighbor. In normal-gravity condition, at the moving instant, the moment sum of the aerodynamic drag force F_d and the lifting force F_L exceeds that of the inter-particle force F_i and the gravitational F_g force:

$$F_d r_d = \left(F_g - F_L\right) r_g + F_i r_i \tag{4}$$

In micro-gravity condition, the gravitational force can be neglected. We also leave out inter-particle force in the initial analysis for it is almost impossible to estimate the value for a poorly known asteroid. We are planning to conduct sampling experiments in micro-gravity condition, and hope to revise the theoretical analysis in further work. That means any particle can become creeping by the drag force, though the acceleration may be small for large particles. The drag force exerting on a regolith particle submerged in gas flow is given by:

$$F_d = \frac{\pi}{8} c_d d_r^2 \rho_2 v_R v_R \tag{5}$$

where d_r is the equivalent diameter assuming the particle to be a sphere, $\boldsymbol{v}_R = \boldsymbol{v}_2 - \boldsymbol{v}_r$ is the relative velocity between regolith particle and gas flow, and c_d is the drag coefficient. From Eqs. 3 to 5, we can easily obtain:

$$\boldsymbol{v}_r = \frac{\pi}{8 m_r} c_d d_r^2 \rho_2 \int_0^t v_R \boldsymbol{v}_R dt \tag{6}$$

Equation (6) means the particle velocity is proportional to the second power of $\boldsymbol{v}_R$. Considering v_r is much smaller than v_2, then v_r highly relies on gas flow velocity. Preliminary tests were conducted to validate the analysis (Fig. 3), which used a high-speed camera (AMETEK Phantom V611) to record particle velocity.

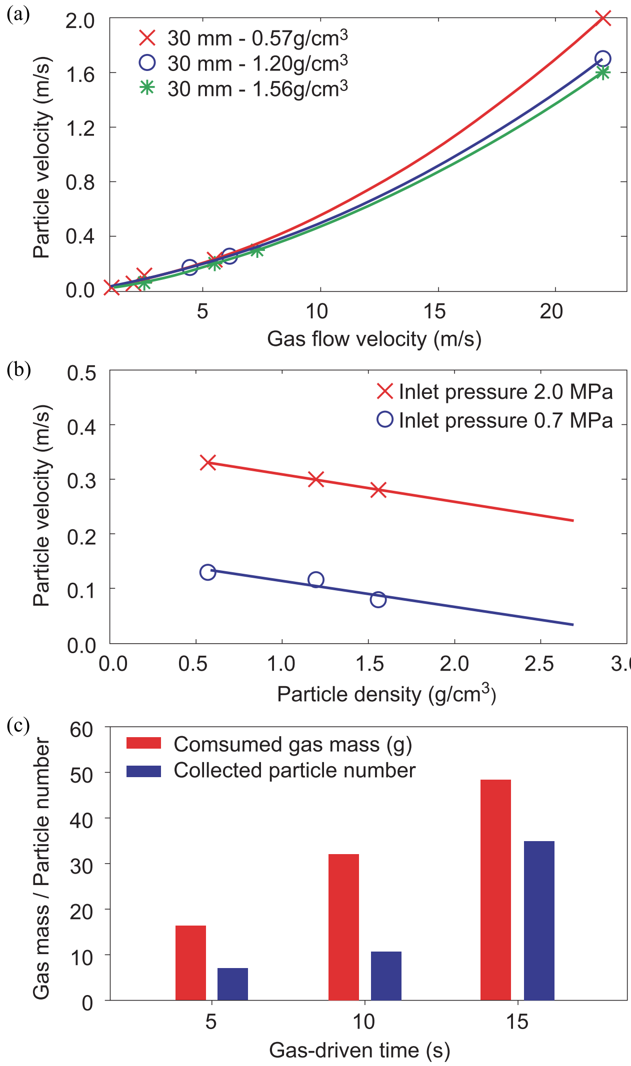

FIGURE 3. **Preliminary validation. (a) Particle velocity versus gas flow velocity. (b) Particle velocity versus particle density. (c) Gas-driven time versus particle collection mass/number.**

III. PROTOTYPE DESIGN AND DEVELOPMENT

A. OVERAL SYSTEM DESIGN

The biggest highlight of the sampler (Fig. 4) is transient regolith breaking through the high-frequency vibration of an ultrasonic percussive drill, combining with gas-driven regolith sampling to convey drilled regolith debris or weathered layer through high-speed gas flow. It consists of a gas-driven system, a robotic arm, and a sample collection device. The collection device is mainly composed of a sample recycling chamber, a regolith-breaking mechanism, two detaching explosive bolts, and a 3-axis force sensor. Soft felts with large compression ratio are fixed to the bottom of the sample recycling chamber. It ensures the sampler to adapt to rugged terrains, realizes the sealing of bottom gas path, and can adhere to certain surface samples in contact. The prototype has a maximum outer diameter of 158 mm and a height of 160 mm. The sample recycling chamber has a height of 60 mm and a diameter of 140 mm, and the gas pipe has a diameter of 6 mm.

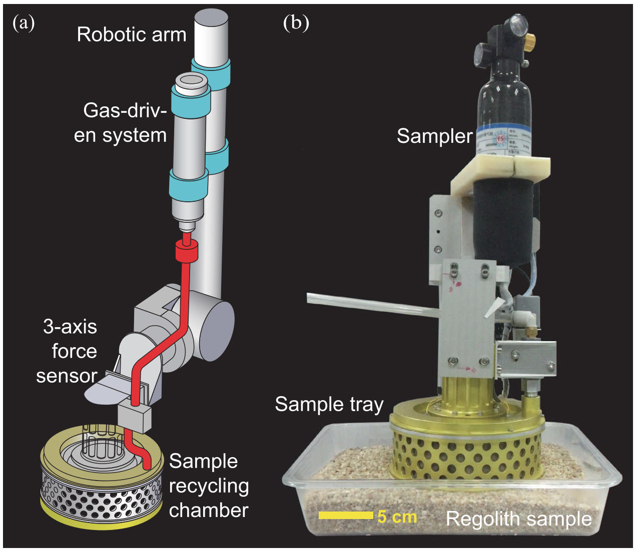

FIGURE 4. Overview of the proposed sampling system. (a) 3-Dimensional model. (b) Prototype.

The prototype for laboratory tests is made of aluminum alloy, with a mass of 3 kg. This design provides a light-weight support for components, and the strength necessary to survive launch and cruise environments.

B. ULTRASONIC PERCUSSIVE DRILL

The proposed ultrasonic percussive drill consists of a piezoelectric ceramic stack, a free mass, an amplitude transforming rod, and a drill bit, as shown in Fig. 5. The working principle is as follows:

(1) Activated by high-frequency sinusoidal voltage, the piezoelectric ceramic stack transfers high-frequency electrical signal to mechanical vibration with corresponding frequency, forming standing-wave resonance.
(2) The transforming rod amplifies the amplitude and accumulate the power of the piezoelectric ceramic, and the longitudinal vibration at the bottom of the rod impacts the free mass, making the reciprocating collision of acoustic wave frequency.
(3) The front-end drill bit is buffeted by the acoustic frequency impaction from the free mass, which transmits stress waves to the contact area of drill bit and rock.
(4) Rock is broke when the contacting stress exceeds its stress of fatigue or fragmentation.

The ultrasonic percussive drill has an outer diameter of 40 mm, a length of 136 mm, a percussive frequency of 12.5 kHz, and an input power of 15 W. The drill bit has a diameter of 10 mm and a length of 36 mm.

To validate the fragmentation efficiency of rock with different hardness grades, we built a test-bed and conducted percussive tests with three kinds of rock (Fig. 6). The percussive operation lasted 5 minutes and the broken mass is: 23 g for porous basalt (compressive strength: 94 MPa), 8 g for dense marble (compressive strength: 120 MPa), and 1 g for dense basalt (compressive strength: 200 MPa). All the broken

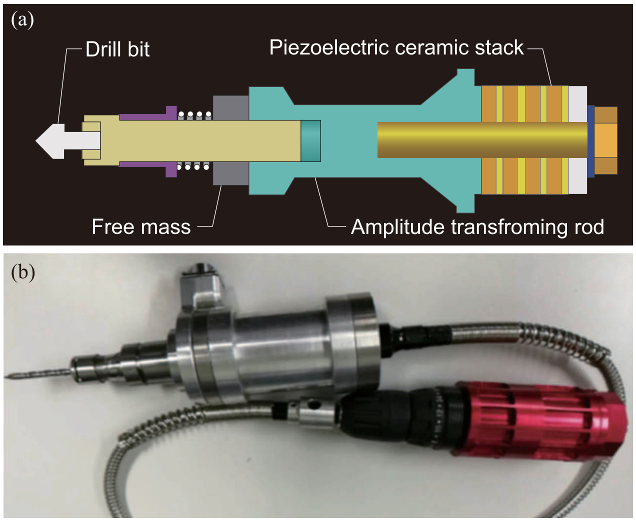

FIGURE 5. Ultrasonic percussive drill. (a) Configuration. (b) Prototype.

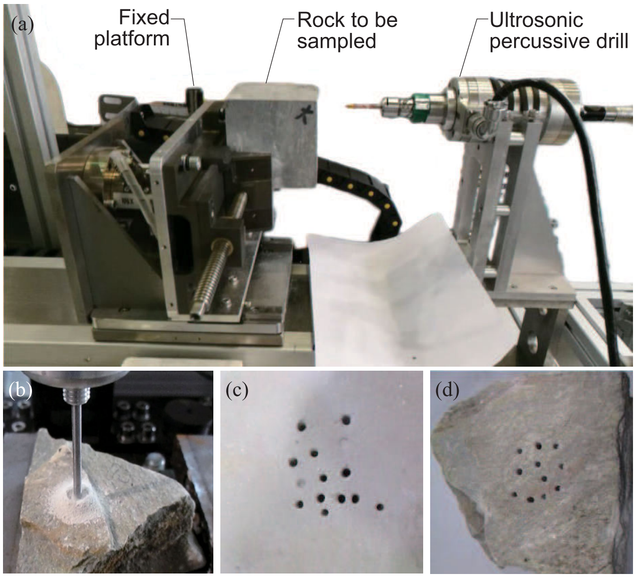

FIGURE 6. Ultrasonic percussive test. (a) Test setup in horizontal direction to eliminate the influence of gravity on penetrating load. (b) Vertical percussive drill test. (c) Dense marble with drilled holes. (d) Dense basalt with drilled holes.

samples are powdered particles with small size, whereas the breaking efficiency was low for dense hard rock.

C. SAMPLE RECYCLING CHAMBER

The gas-driven regolith-sampling principle is depicted in Fig. 7. As highly pressurized nitrogen is released and flows into the inside chamber, most of the gas is led to open the airtight door to form a path, and then flows into the outside chamber. Regolith particles are flushed into the outside chamber by high-speed gas, and gas exits through the fine screen on the side face of the collection device, whereas regolith particles larger than the screen mesh are remained.

A detailed illustration of the sample recycling chamber is presented in Fig. 8. Based on the sampler configuration, we simulate the gas-flow speed field by ANSYS/Fluent and

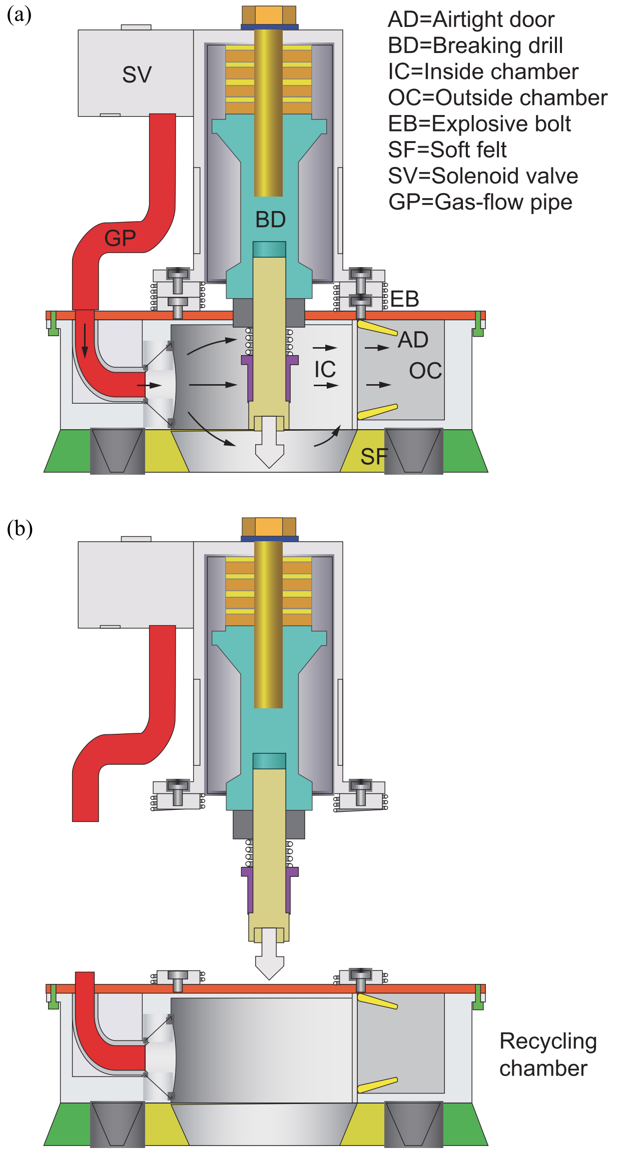

FIGURE 7. **Gas-driven regolith-sampling principle. (a) Sampling configuration for sample collection. (b) Separating configuration for sample return.**

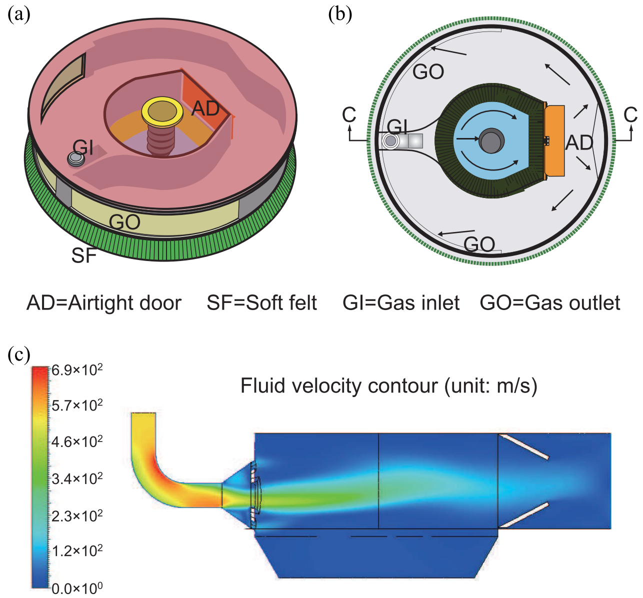

FIGURE 8. **Sample recycling chamber. (a) 3-Dimensional model. (b) gas flow path. (c) Simulation nephogram of gas flow velocity.**

the results are shown in Fig. 8(c). When the bottle pressure is set to 0.4 MPa, the average gas-flow speed inside the sample recycling chamber is almost 200 m/s. According to the proposed design, the sample collection operation is divided into three steps:

(1) *Percussive Regolith-Breaking:* When the sampler reaches out to press against regolith with the collection chamber, the ultrasonic drill starts to penetrate for 30 seconds (10 mm depth) to fragment surface regolith through high-frequency vibration, which is aided by the force from the robotic arm. If the surface regolith is soft weathered formation, the percussion can make regolith particles float. Whereas if the sampling target is hard rock, it can break the rock into fine particles.

(2) *Gas-Driven Sampling:* Highly pressurized nitrogen is released to blow regolith surface, and liquefied debris is mobilized into the sample container and remained by a non-airtight filter; thus, sampling operation is completed in a very short time. The flange of the soft felts also servers for contact sampling as its larger touching area with regolith surface.

(3) *Sample Stowage/Encapsulation:* After gas release and sample collection, a solenoid valve is closed to sever the airflow, and sample mass will be confirmed in the subsequent operations, such as by visual methods. If required mass is obtained, the sample recycling chamber is transferred for stowage and return.

Though the sampling system utilized high-pressure gas to mobilize and collect sample like the OSIRIS-Rex sampler, the advantages of the proposed sampling method are obvious.

1) The system innovatively designs a regolith-breaking drill, which enables sampling operation to be completed even without weathered regolith layer in asteroid surface, greatly enhancing geological adaptability.
2) The sampling gas is designed to flow unidirectionally, which enables samples to be mobilized and collected efficiently, reducing gas consumption per unit time.
3) Flexible and deformable soft felt (double layer) is designed to seal the bottom of the chamber, which also serves as contact sampling. The soft felt deforms when squeezed, forming an enclosed space and enhancing the sampling adaptability of uneven terrain.

IV. SIMULATION AND EXPERIMENT RESULTS

Simulation and laboratory tests were conducted to validate and evaluate regolith collection performance with different material simulants and gravitational conditions.

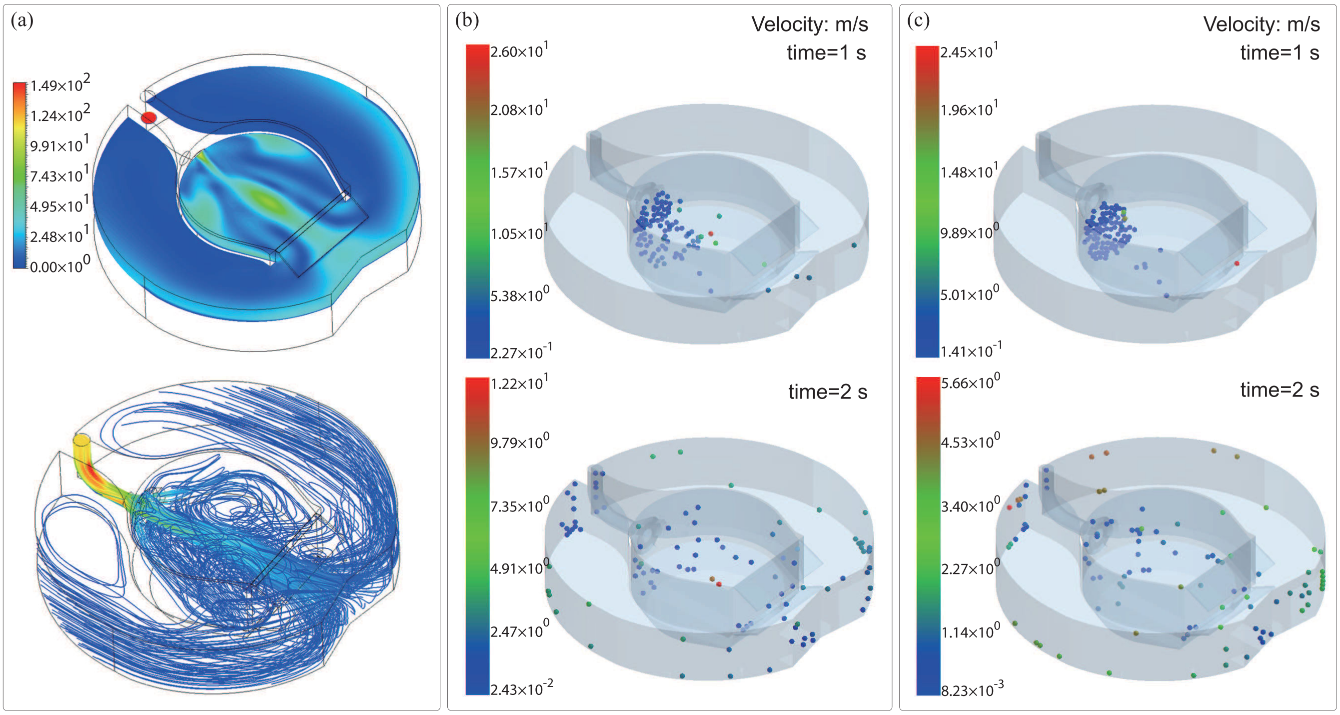

FIGURE 9. Simulation results. (a) Nephogram of gas flow velocity (top) and gas flow streamline (bottom). (b) Particle movement in micro-gravity condition. (c) Particle movement in normal-gravity condition.

A. SIMULATION RESULTS

Simulation initially focused on the strategy validation for mobilizing regolith particles. Fluid-solid coupling analysis was conducted to simulate the mutual movement of gas and solid particles, in which the outlet gas pressure was set to be 0.4 MPa and the normal gas-driven time was 3 seconds. Regolith particles were hypothesized to be spheres with a diameter of 1 mm, a density of 2700 kg/m^3, a Poisson's ratio of 0.3, and a shearing module of 30 GPa. In this simulation by ANSYS/Fluent, 100 particles randomly distributed on the bottom of the sampling device at the initial state. During the movement of particles, there were collisions between particle and particle, and particle and collection chamber wall, forming contact force. Here, Hertz-Mindlin non-slip contact model was used to mimic the contact behavior. The simulation result is presented in Fig. 9, which shows that the proposed strategy is efficient in collecting particles in normal- and micro- gravity environments.

As can be seen from Fig. 9(a), gas velocity and gas flow trajectories on both sides of the chamber are basically symmetrically distributed, forming a strong vortex in the central and bottom areas. Gas flows out from the exits on both sides, the direction of air flow is consistent with the design, the circulation process is smooth, and there is no flow dead zone. Figs. 9 (b) and (c) show the state of particles' motion at different gravitational conditions. As can be seen, at the same time, the moving distance of particles in micro-gravity condition is a bit longer than that in normal-gravity condition, and the number of particles entering the outside chamber is also much more. Besides, the maximum velocity in micro-gravity condition (12.2 m/s) is also larger than that in normal-gravity condition (5.7 m/s). The simulation results in normal-gravity and micro-gravity are compared in Table 1.

TABLE 1. Sampling results comparison by simulation.

Condition	Initial particle number	Sampled particle number	Sampling time	Sampling ratio
Micro-gravity	100	90	3	90
Normal-gravity	100	81	3	81

The sampling ratio is 90% in micro-gravity when the sampling time is 3 seconds, which is higher than that of 81% in normal-gravity. The simulation demonstrates that regolith particles can be quickly directionally mobilized and collected by the proposed strategy, and a better sampling performance can be achieved in micro-gravity condition. Our further work will continue to investigate the sampling efficiency under different operational parameters, including gravity, gas pressure, sampling time, geological dimensions of the sampling chamber, etc.

B. EXPERIMENTAL RESULTS

Laboratory testing primarily focused on sampling efficiency evaluation for various regolith simulants under different operational or environmental conditions. The initial testing was complemented in laboratory conditions, and only the collection device was used, not including the robotic arm. Because of long exposure to cosmic space, the asteroid surface may be in gravel pile, and "boulder- and dust- ponds" terrain,

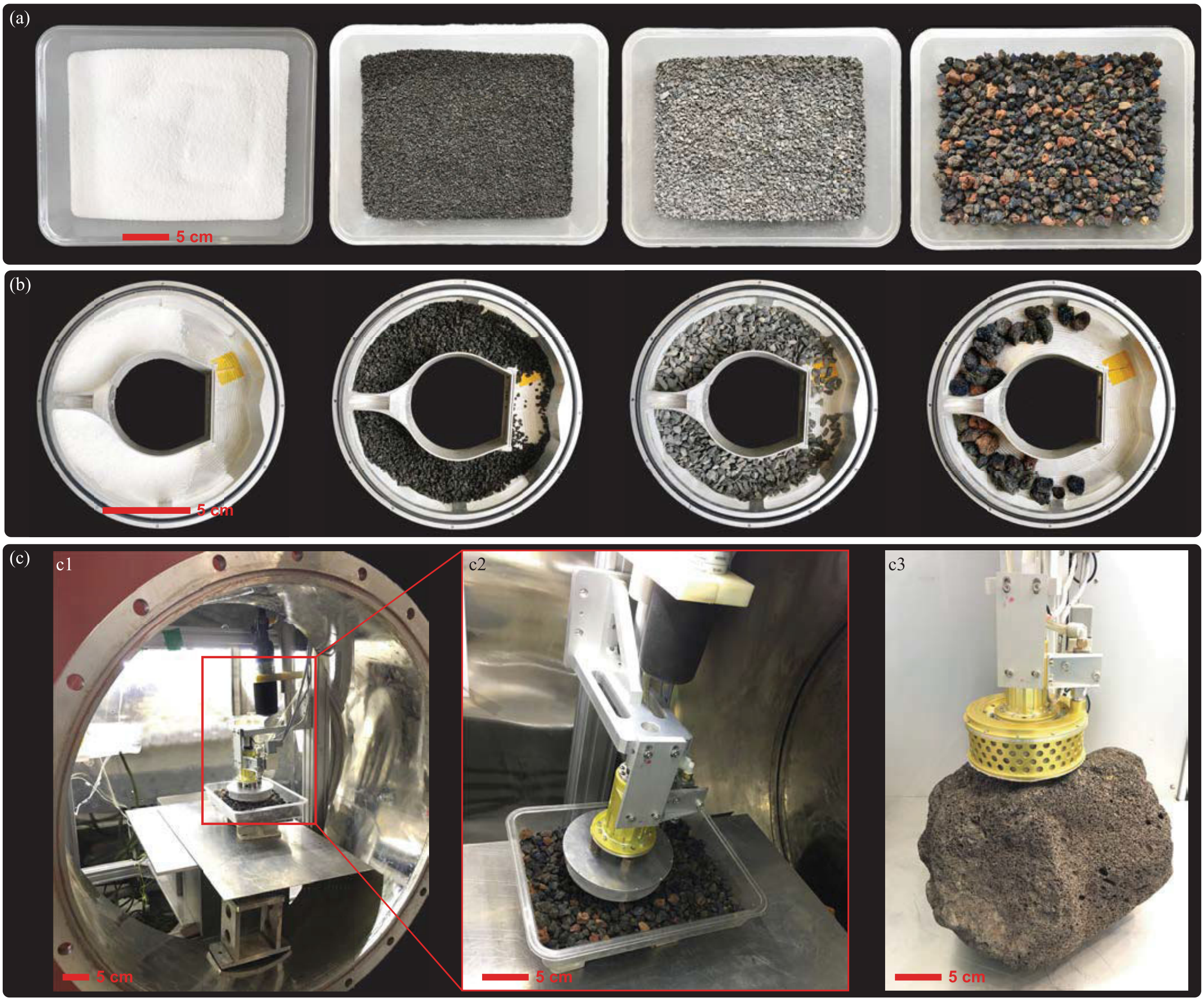

FIGURE 10. Experimental regolith particles and setup. (a) Regolith particles with different diameter distributions (from left to right): light weight particle (low density material to aid in simulating sampling in micro-gravity condition), basalt particle with 1∼2 mm diameter, basalt particle with 2∼4 mm diameter and lava particle with 4∼10 mm diameter. (b) Sampling results of regolith particles with different diameters. (c) Experimental condition in vacuum chamber. The gas pressure was maintained during 3.2∼3.6 Pa during the sampling process. (c1) Vacuum environment simulator (1.5 m diameter and 2 m height); (c2) Sampler in vacuum chamber; (c3) Porous basalt to be sampled.

even entire boulders, may exist [47]–[49]. That means the size distribution of surface regolith may range from millimeters to decimeters. To simulate various surface geological conditions that may exist, the experiments were conducted using regolith particles with different but most-utilized size distributions (Fig. 10): light weight particle (0.9 g/cm^3), 1∼2 mm and 2∼4 mm basalt particle, 4∼10 mm lava particle (0.4 g/cm^3), and porous basalt.

Compared to dense marble or basalt, porous basalt is more brittle and easier to fragment, which is more like the highly weathered material on asteroid surface. The porous basalt used in experiments has a uniaxial compressive strength of 94.22 MPa, an elastic modulus of 60.53 GPa, and a Poisson's ratio of 0.187. For each test, regolith particles uniformly distributed in the middle part of the recycling chamber during the sampling process. A 10 N force was exerted on the regolith samples initially and the normal sample collection time was set to be 3 seconds. Experiments under room and vacuum environments were both conducted, and laboratory results of sampling mass and reaction force are presented in Fig. 11. To mimic sampling in micro-gravity condition, light weight particles are specially used. However, the final sampling mass is calculated according to the equivalent rock particle density of 2.6 g/cm^3. In room condition, each group of parameters was repeated three times.

The results show that higher pressure produces significantly higher sampling mass. The reaction force is controlled in the range of 10∼35 N, which is quite suitable for the sampling strategy with a low contact force. Under vacuum, the jetted gas has greater kinetic energy and the

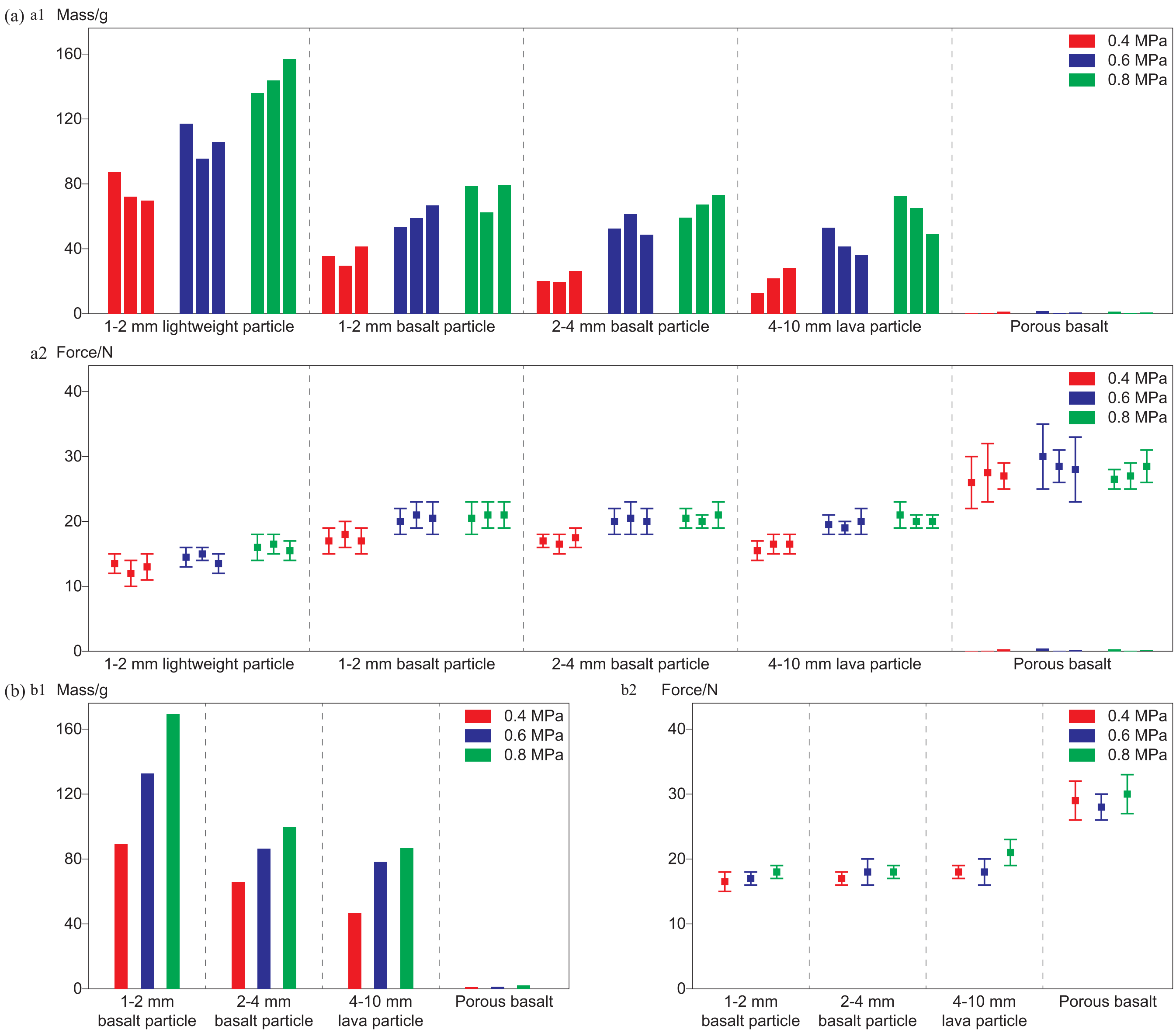

FIGURE 11. Experimental statistics on sampling mass and reaction force. (a) Results in room condition with different gas pressures. (a1) Sampling mass versus material simulant. (a2) Reaction force versus material simulant. (b) Results in vacuum condition with different gas pressures. (b1) Sampling mass versus material simulant. (b2) Reaction force versus material simulant.

movement is much faster, resulting in better mobilizing capability and sampling performance. The reaction forces are near the same than that in room condition, whereas the reaction force is bigger in penetrating porous basalt in both conditions. The results demonstrate that the proposed sampling strategy is efficient in collecting particles with fine diameters, which is in accordance with the simulation. However, the sampling mass is much lower for larger particles. There are possibly two reasons: (i) Larger particles need stronger force to move due to inter-particle force and gravity for the experiments were conducted on the Earth. (ii) Larger particles have larger mass, resulting lower acceleration. Whereas the sampling time is limited, resulting larger particles cannot be mobilized into the sample container timely.

V. CONCLUSION

To fulfill the goal of performing a highly reliable and efficient method to collect regolith sample from micro-gravity asteroids, a gas-driven regolith-sampling strategy is proposed. Simulation was established to analyze the sample collection process under normal- and micro- gravity conditions. The corresponding functions were experimentally validated by regolith samples with different diameters in different gas pressures. The proposed strategy illustrates a novel mechanism for sampling extraterrestrial regolith, which has the advantages of excellent sample acquisition ability, geological adaptability, light weight, low power consumption, low reaction force, and simple and reliable operation. These advantages are significant in overcoming constraints exerted on sample device caused by space environments and spacecrafts.

This novel sampling method can provide an important reference for future sampling technologies to asteroids. Future work will focus on improving the performance and will include more comprehensive testing of the system.

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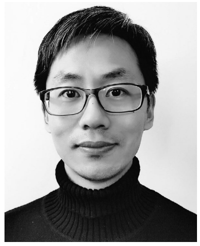

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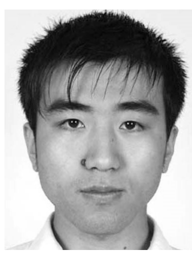

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