A new subsurface sampling device is proposed for use in small-body exploration. The device proposed has a multi-stage telescopic structure that is extended into regolith using high-pressure gas. High-pressure gas is also used to collect the sample. Since the device proposed has no actuator, it is expected to be highly reliable. We experimentally demonstrated that this device can excavate a dummy regolith layer up to a depth of 1 m and collect sufficient samples located deeper than 1 m for in-situ analysis. These results indicate that the device proposed is a viable candidate for actual exploration missions. 

Key Words: Planetary Sampling, Pneumatic Drill, Telescopic Structure

1. Introduction

1.1. Sampling technologies for small-body exploration

In recent years, several small-body exploration missions, including sample return, have been performed. These missions include Hayabusa,1) Rosetta/Philae,2,3) Hayabusa2,4) and OSIRIS-REx.5) Hayabusa, Hayabusa2, and OSIRIS-REx are asteroid-sample-return missions (targeting the asteroids Itokawa, Ryugu, and Bennu, respectively), and Rosetta/Philae is a comet-exploration mission (targeting comet 67P/Churyumov-Gerasimenko). To elucidate the evolution of the solar system from constituent materials, each spacecraft has a sampling device for collecting materials, as described below:

- Hayabusa and Hayabusa2 (JAXA)

An impact sampling strategy was selected for these missions.6–9) These spacecraft have a sampling device which consists of a sampler horn and a projector. During the sampling phase, a projectile is fired, fragments of surface material are ejected toward the spacecraft, and the ejected fragments are collected through the sampler horn. This strategy is applicable to any asteroid surface, such as regolith and monolithic rocks. In addition, Hayabusa2 is equipped with an impactor to create an artificial crater.10) This impactor, referred to as the Small Carry-on Impactor (SCI), is a small explosive device. After creating the crater, Hayabusa2 will touch down and collect subsurface material from it.

- OSIRIS-REx (NASA)

This spacecraft is equipped with a pneumatic sampling device referred to as the Touch-and-Go Sample Acquisition Mechanism (TAGSAM).11) During the sampling phase, high-pressure gaseous nitrogen (GN2) is released to collect samples. The high energy of the gas will allow a large amount of sample material (up to several hundred grams) to be collected.

- Rosetta/Philae (ESA)

This spacecraft had a drilling and sampling device referred to as the Sampler, Drill, and Distribution System (SD2).12) This device was designed to perform drilling, sample collection, and sample distribution to in-situ analysis instruments. The SD2 can excavate to a depth of 230 mm using a mechanical drill and collect samples via a sampling tube attached to the tip of the drill.

These instruments differ dramatically due to differences in mission parameters, which include:

- Sample return versus in-situ measurement,
- Surface sampling versus subsurface sampling, and
- Differences in the properties of the target small body.

Subsurface samples, in particular, provide rich information about the physical and chemical properties of a small body. For example, asteroids beyond the snow line, such as the Jupiter Trojan asteroids, have volatile constituents. As shown in Guibert-Lepoutre,13) it is possible that water ice exists 1 m below the surface of a Jupiter Trojan asteroid. To obtain such qualitatively different samples, improved subsurface sampling technology is required.

1.2. Subsurface sampling technology

Hayabusa2 and Rosetta/Philae were designed to perform subsurface sampling. However, the SCI of Hayabusa2 may denature some of the surface materials because of the high-speed collision required using the copper impactor. In addition, spacecraft operations, such as SCI deployment and cra-
ter searching, are complicated. The mechanical drill of Philae could not excavate deeply due to the size restrictions of the spacecraft. In recent years, advanced planetary excavation technologies have been investigated.14) These studies mainly assumed that the Moon and Mars are the exploration targets. In other words, the surface conditions of these bodies are known to some extent, and relatively heavy instruments can be used in their exploration. However, these assumptions do not hold for small-body exploration, which has tighter restrictions.

1.3. Objective

To collect pristine samples, including volatile constituents, the surface of a small body must be excavated deeply. In this paper, we propose a new subsurface sampling strategy for use in the exploration of small bodies, such as Jupiter Trojan asteroids.15) This strategy uses an integrated excavation/sampling device that is capable of reaching a depth of 1 m using high-pressure gas. The depth of 1 m has been selected based on the assumption of Jupiter Trojan asteroid exploration. In the following sections, we present the concept of the device proposed along with results of experiments using test models.

2. Concept of Subsurface Sampling Device

In this section, the concept of the subsurface sampling device proposed is explained. The device has two extendable drills, one for excavation and one for sampling. The excavation and sampling strategies using high-pressure gas are first discussed, after which the full configuration of the integrated device is described.

2.1. Assumptions

In this study, the target is assumed to be a small body, such as an asteroid or comet. Several images taken by Hayabusa16) and Rosetta/Philae17) suggest that the asteroid Itokawa and the comet 67P/Churyumov-Gerasimenko are covered with regolith. Thus, we herein assume that samples will be collected from the regolith layer on the surface of a small body.

2.2. Requirements

In this study, the requirements for the subsurface sampling device are as follows:

(a) During transit to the small body and sampling location, the device must be short and fit within the spacecraft.

(b) The device needs to excavate the regolith layer without anchoring.

(c) During excavation, the regolith should not enter the device.

(d) The number of actuators should be as small as possible.

Requirement (a) is a launch restriction of the spacecraft. In order to place the spacecraft in the fairing of the launch vehicle, the extension components must be collapsed into a short configuration. Requirement (b) is a restriction of the spacecraft system. In general, the surface of a small body will be unknown, so it is difficult to design a lightweight anchoring system with sufficient reliability. Requirement (c) is a restriction that prevents the mixing of regolith from different depths. The device should collect samples only below the target depth. Requirement (d) is a reliability restriction. To increase the reliability, the use of actuators, such as motors, should be minimized.

2.3. Excavation

Figure 1 shows the concept of the excavation strategy using high-pressure gas. The extension structure consists of a multi-stage telescopic tube, and high-pressure gas is used to extend each stage. During this operation, gas is released from the tip of the device and interacts with the surrounding regolith. This softens the surface of the body and allows the device to easily penetrate the regolith. Moreover, because gas flows from the tip, regolith cannot enter the device. This guarantees that the sample collected is exclusively below the target depth.

The most important feature of this concept is that no actuator is required. In other words, the device proposed is driven by simply opening a solenoid valve (SV) to release the gas. In addition, the direction of the counterforce is the normal direction with respect to the surface of the small body, so no rotational torque is generated. This simplifies cancellation of the counterforce, which can be accomplished using thrusters.

2.4. Sampling

As mentioned above, excavation is performed using high-pressure gas. To be compatible with this excavation concept, it is advantageous to apply a pneumatic drill technique in conjunction with high-pressure-gas sampling. This concept has been extensively investigated for use in Moon and Mars exploration missions.14,18) Figure 2 shows the concept of the sampling strategy. In this strategy, the sample is blown into the sample container by the gas flow, which originates from outside the sample path. We have designed the device proposed to collect samples for either in-situ analysis or sample return.

Fig. 1. Concept of excavation.
2.5. **Subsurface sampling device**

By combining excavation and sampling strategies, we propose a new subsurface sampling device, as shown in Fig. 3. This device consists of the following components:

- **Excavation drill**
  The excavation drill is the main component of the device proposed. This component has a multi-stage telescopic structure, and excavation is performed using high-pressure gas.

- **Sampling drill**
  The sampling drill provides the path of gas flow for sample mobilization. This component includes a multi-stage telescopic structure and is attached to and transported by the excavation drill.

- **Shutter**
  During excavation, the gas discharged should not flow into the spacecraft (top of Fig. 3). To prevent this, a shutter is required. After excavation, the shutter is opened by non-explosive actuators to create the sample path.

- **Sample container**
  The blown sample is captured in a sample container.

- **Projector**
  If the sampling location contains a monolithic rock, the sampling drill will not work. Therefore, to increase sampling robustness, the device proposed contains a projector for breaking monolithic rock (not described herein).

The subsurface sampling procedure is as follows:

**Step 1** Perform excavation using the excavation drill.
**Step 2** Open the shutter.
**Step 3** Perform sampling using the sampling drill.
**Option** If there is a rock, use the projector to break it up before excavation is performed.

To know the actual depth of excavation, a wire rope with several markers could be connected to the tip of the device. By taking a photo of the wire rope after excavation is complete, the excavation depth can be determined. If the excavation/sampling device is used in a sample-return mission, the two drills can be detached by conventional explosive actuators after the in-situ operations are complete.

2.6. **Potential sample analysis strategies**

The samples collected will be analyzed using two basic strategies, in-situ and analysis after sample return. In the Rosetta/Philae mission, the samples collected were analyzed using in-situ measurement devices, such as a mass spectrometer called COSAC.\(^{19}\) In contrast, for the Hayabusa, Hayabusa2, and OSIRIS-REx missions, the samples were or will be returned to Earth and analyzed by state-of-the-art techniques on the ground.\(^{7,20}\) The device proposed is designed to utilize both analysis strategies.

3. **Verification Experimental Procedure**

To verify the concept of the subsurface sampling device proposed, some demonstration experiments were performed. In this study, we considered the nominal operation scenario given as Steps 1 through 3 in Section 2.5. First, we performed experiments with the excavation and sampling components separately to verify their functions. After that, a full-configuration experiment was performed to demonstrate both functions of the device sequentially.

3.1. **Test models and experimental configuration**

Figures 4 to 7 show the test models of the subsurface sampling device used in the experiments. Each model had a multi-stage excavation drill for reaching a depth of 1 m. Test models 1 and 2, with three-stage excavation drills made of SUS304 as shown in Figs. 4 and 5, were used for component experiments. Test model 3, with a five-stage excavation drill made of aluminum as shown in Figs. 6 and 7, was used for the full-configuration experiment. A thin sampling drill was attached to the structure of test models 2 and 3. In the actual flight system, for mechanical strength, the sampling drill should be thicker (but thinner than the excavation drill).
and the number of attachments to the excavation drill should be increased. The tip of the excavation drill has an orifice 10 mm in diameter (Fig. 8) to increase the interior pressure of the excavation drill during excavation. However, to allow a projectile to be fired through the excavation drill, the diameter of the orifice needs to be larger than that of the projectile. As a reference, we considered the Hayabusa projectile, which had a diameter of 8 mm, for determining the size of the orifice. The sample passes through the excavation drill and is collected in the sample container. The narrowest sample path is the tube connected to the sample container (inside diameter of 4.35 mm). A larger collection tube cannot be used because of the lack of space, as shown in Fig. 3. Figure 9 shows the sample container used in the experiment. The container has 4-mm cubed sample boxes for sample collection. Each sample box has a metal mesh that traps the sample particles entering it. Multiple analyses can be performed by rotating the container. Here, we assume that the device will convey the sample to an in-situ measurement device, such as a mass spectrometer, which requires 0.01 mg of material for organic matter analysis. We also assume that the sample contains at least 1 wt% organic matter, as in primitive carbonaceous meteorites (CI, CM, CR chondrites). Thus, the device should collect a sample weighing at least 1 mg. In addition, another sample path was prepared to collect samples that will be returned to Earth.

The pressure of the gas and volume of the gas tank used in the experiments were determined by trial and error. From the spacecraft system point of view, the smallest possible pressure and tank volume are preferred. In the full-configuration experiment, the parameters were determined by considering this point qualitatively.

3.2 Experimental procedure and conditions

Figures 10 to 12 show the experimental configuration. Testing was performed in a large vacuum chamber. In addi-
tion to the sample container, a sample catcher (plastic bag) covering one collection tube was used to confirm the sampling capability of the device proposed to be used for taking the sample and returning it to Earth. Note that the sample volumes may be limited by the collection tube. The sensitivity of tube diameter to sample size will be tested in future experiments. The test procedure for this experiment was as follows:

Step 1 Charge high-pressure gas into buffer tank 1.
Step 2 Generate a vacuum.
Step 3 Open SV1 and start excavation.
Step 4 Return the pressure in the vacuum chamber to atmospheric pressure.
Step 5 Take photographs.
Step 6 Open the shutter.
Step 7 Charge high-pressure gas into buffer tank 2.
Step 8 Generate a vacuum.
Step 9 Open SV2 and start sampling.

Step 10 Return pressure in the vacuum chamber to atmospheric pressure.

Figure 13 shows the SV control sequence during excavation. If a typical blowdown sequence is applied, the force applied to the regolith would be excessive. In this system, the excess gas is ejected through a three-way solenoid valve.
In the experiments, we used glass beads to simulate the regolith. The advantages of using glass beads are their uniform diameter and stable physical properties. Several previous studies related to small-body sampling and cratering also used glass beads to simulate regolith.\(^\text{22-24}\) In the future, we will link these previous studies and the present work. Moreover, several experiments using various simulations of regolith materials with different physical properties, such as ice, organic grain, and natural rock, will be performed systematically.

4. Experimental Results

4.1. Excavation experiments

Component experiments of the excavation were performed using test model 1 and the experimental parameters listed in Table 1. In all tests, excavation was successfully performed (Figs. 14 and 15 and Table 2), and an excavation 1 m deep was realized in tests 1-2 and 1-3. Unfortunately, test model 1 was slightly bent during fabrication, and this damage prevented the telescopic structure from working smoothly.

Therefore, the volume and pressure required for gas tank 1 cannot be specified using the results of experiments with test model 1.

4.2. Sampling experiments

Component experiments of the sampling drill were performed using test model 2 and the experimental parameters listed in Table 3. In all tests, sampling was performed successfully.

![Image]
cessfully (Fig. 16 and Table 4). Figure 16 shows photographs of the sample box before and after the experiment. The figure clearly shows beads collected in the sample box.

### 4.3. Full-configuration experiment

After the component experiments, we performed a full-configuration test using test model 3, which combines both functions of the device proposed. Table 5 summarizes the experimental parameters used.

In this experiment, excavation to a depth of 1 m was successfully performed, as shown in Fig. 17. The excavation took 0.180 s, and the peak reaction force was 136 N as measured by a pre-loaded load cell. In an actual mission, this reaction force must be canceled by thrusters.

Figures 18 and 19 show the results of the full-configuration sampling experiment. Figure 18 shows photographs of the sample box before and after the experiment. Numerous glass beads, with a total mass of about 4 mg, were collected in the mesh of the sample container, as seen in Fig. 18. Figure 19 shows a photograph of the sample catcher after the experiment. These figures indicate that sampling was successfully performed. The weights of samples collected are listed in Table 6. The sample box collected a sample having a mass of more than 1 mg, which is enough to conduct mass spectrometry. The amount of samples can be increased further if the volume and pressure of gas tank 2 are increased.

### 5. Discussion

#### 5.1. Considerations regarding the flight system

With regard to the flight system, the following considerations are important:

- Dummy regolith selection
  During actual operation, the cohesion of the regolith will apply a resistance force to the device. Therefore, future tests need to use a more realistic regolith substitute.

- Depth of samples collected
  During excavation, regolith cannot enter the excavation drill due to the outward gas flow. Therefore, the sample collection depth is assumed to be deeper than the excavation depth. Future tests must evaluate this point.
Gas selection

The high-pressure gas could contaminate the collected samples. Therefore, the actual mission must use an appropriate gas that does not affect scientific measurements. In general, a noble gas, such as helium or argon, is a good candidate.

Lubrication

To prevent metal surfaces from adhering to each other, the metal used in the device proposed must be lubricated. To prevent contamination, the application of a solid lubricant, such as gold, is a good candidate.

5.2. Assumed mission sequence

The assumed mission sequence of the lander is as follows:
1. Make a landing at the surface of the small body.
2. Take a photo of the surface.
3. If the surface condition is not suitable for excavation, move the lander to a different location using thrusters.
4. Perform scientific observations, including surface sampling.
5. Perform subsurface sampling.

The risk of damage to the lander is high when the device proposed is driven into the regolith. Therefore, subsurface sampling should be performed at the end of the lander operation. Generally, repetition of subsurface sampling is not assumed, since excavation is a fully dynamic operation and the device is damaged during excavation. Selection of an appropriate landing site is critical for increasing the success rate.

A primary advantage of the subsurface sampling strategy we proposed is that an anchoring mechanism is not required. Anchoring to an unknown surface is quite difficult, and a complex and heavy anchoring system needs to be implemented to increase the anchoring success rate. Instead of anchors, the system proposed relies on the counterforce provided by sufficiently large thrusters. By assuming a hard surface, the maximum counterforce can be adequately estimated through ground experiments. In this sense, the success rate of the thruster counterforce without uncertainty is greater than that of an anchoring system with uncertainty.

Table 5. Full-configuration experiment parameters.

| Parameter                  | Unit      | Value   |
|----------------------------|-----------|---------|
| Dummy regolith             | —         | Glass beads (spherical) |
| Dummy regolith size        | µm        | 180–500 |
| Dummy regolith bulk density| g/cm³     | 1.5     |
| Gas                       | —         | GN₂     |
| Gas tank 1 volume         | cm³       | 300     |
| Gas tank 2 volume         | cm³       | 30      |
| Gas tank 1 pressure       | MPa·g     | 5.5     |
| Gas tank 2 pressure       | MPa·g     | 3.0     |
| SV1 opening duration      | s         | 0.4     |
| Vacuum pressure           | kPa       | 1.0     |

Table 6. Mass collected in full-configuration experiment.

| Receptacle   | Unit | Value |
|--------------|------|-------|
| Sample container | mg  | 3.88  |
| Sample catcher          | g   | 0.5   |

Fig. 17. Excavation result of full-configuration test.

Fig. 18. Sample container result of full-configuration test.

Fig. 19. Sample catcher (plastic bag) result of full-configuration test.
6. Conclusion

A new subsurface sampling device was proposed and experiments were performed to verify the concept. The device proposed uses a very simple sampling strategy involving high-pressure gas release by opening solenoid valves. It was experimentally demonstrated that the device can excavate a dummy regolith layer up to a depth of 1 m and collect sufficiently large samples located deeper than 1 m for in-situ analysis. These results showed that the device proposed is a viable candidate for use in actual exploration missions.

Acknowledgments

The authors would like to thank Y. Kebukawa, H. Yano, T. Okada, O. Mori, J. Kawaguchi, S. Hasegawa, and all members of the Solar Power Sail Mission for providing practical comments regarding the sampling configurations and experiments.

The research results were obtained using the Hypervelocity Impact Facility (formerly the Space Plasma Laboratory) of ISAS/JAXA.

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