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Drilling, sampling, and sample-handling system for China's asteroid exploration mission

Tao Zhang[b,1], Wenming Zhang[a,1], Kang Wang[a], Sheng Gao[a], Liang Hou[a], Jianghui Ji[c], Xilun Ding[b,*]

[a] *Beijing Key Laboratory of Intelligent Space Robotic Systems Technology and Application, Beijing Institute of Spacecraft System Engineering, Beijing 100092, China*[2]
[b] *School of Mechanical Engineering & Automation, Beihang University, Beijing 100191, China*[2]
[c] *Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China*

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ABSTRACT

Asteroid exploration has a significant importance in promoting our understanding of the solar system and the origin of life on Earth. A unique opportunity to study near-Earth asteroid 99942 Apophis will occur in 2029 because it will be at its perigee. In the current work, a drilling, sampling, and sample-handling system (DSSHS) is proposed to penetrate the asteroid regolith, collect regolith samples at different depths, and distribute the samples to different scientific instruments for in situ analysis. In this system, a rotary-drilling method is employed for the penetration, and an inner sampling tube is utilized to collect and discharge the regolith samples. The sampling tube can deliver samples up to a maximum volume of 84 mm^3 at a maximum penetration depth of 300 mm to 17 different ovens. To activate the release of volatile substances, the samples will be heated up to a temperature of 600 °C by the ovens, and these substances will be analyzed by scientific instruments such as a mass spectrometer, an isotopic analyzer, and micro-cameras, among other instruments. The DSSHS is capable of penetrating rocks with a hardness value of six, and it can be used for China's asteroid exploration mission in the foreseeable future.

1. Introduction

Space exploration is important not only to satisfy humanity's curiosity of the great beyond but also has a great significance for the future of Earth and all human beings living on it. Asteroids are the best candidates to answer some fundamental questions relating to the origin of the solar system and the birth of life on Earth. To look for organic materials and signs of past life on asteroids, we need the ability to search beneath the surface regolith where biomarkers are protected from harmful radiation [1]. Apophis is a near-Earth asteroid, and it will reach the nearest distance to Earth on April 13, 2029 [2]. In recent years, China has devoted tremendous efforts toward asteroid exploration, and a unique opportunity to study Apophis will occur in 2029 [2–4]. An asteroid exploration mission has been considered by the China Academy of Space Technology (CAST), and the sampler for the mission will be one of the most important components.

Drilling and sampling are highly efficient methods for exploring subsurface regolith and have played an important role in the search of extraterrestrial lives in recent decades [5]. Ever since the first automated drilling and samples return mission was completed in 1970 by the Soviet Union's robotic Lunar 16 lander, the drilling sampler has been widely used [6,7]. The Apollo Lunar Surface Drill was deployed by the American astronauts to extract regolith column samples in the Apollo 15–17 missions [8]. In Soviet Union's Venera exploration projects, a drill head was first employed to drill the regolith of Venus, and the drilled cuttings were collected for in situ analysis [9]. The sampler, driller, and distribution system (SD2) was developed in 2001 by the European Space Agency (ESA) for the comet exploration mission Rosetta [10–14]. The Curiosity rover, equipped with the Mars Science Laboratory drill to collect Martian rocks and sand, successfully landed on Mars in 2012 [15–19]. China's Chang'e lunar exploration mission aims to drill, collect, and return subsurface lunar regolith samples at a minimum penetration depth of 2 m, in 2017. Many drilling samplers have been under development in recent years to perform extraterrestrial exploration works [20–24]. For ESA's ExoMars exploration mission that will be launched in 2018, a 2 m long multi-string drilling sampler will be employed to collect regolith at

* Corresponding author.
E-mail address: xlding@buaa.edu.cn (X. Ding).
[1] These authors contributed equally to this work
[2] These organizations contributed equally to this work.

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different depths [25–28]. NASA's Mars2020 sample acquisition and caching technologies and architectures are currently under development and will be used to acquire Martian rock samples [29,30]. In addition, a large amount of new-style drilling samplers have been proposed in recent years, such as the Ultrasonic/Sonic Driller/Corer [31], underground mole [32], wood wasp drill [33], and the self-propelled screw drilling mechanism [34]. The drilling sampler plays a unique role in obtaining deep regolith samples; therefore, increasing attention is currently paid to the development of more intelligent, autonomous, reliable, and efficient drilling and sampling systems.

Sampling an asteroid is far more difficult than sampling the Moon or Mars because the gravity of an asteroid is too small to provide the reaction force caused by the sampling action. In addition, asteroids do not have an atmosphere for heat preservation; thus, the temperature of an asteroid is much lower than that of other planets such as Mars. Therefore, the sampling method for an asteroid is more complicated. Several special methods have been proposed in recent years to accomplish a sampling mission. The Hayabusa spacecraft, developed by the Japan Aerospace Exploration Agency, accomplished a round-trip flight to asteroid 25143 Itokawa, and returned samples to Earth in June 2010. During the sampling process, Hayabusa was in dynamic touch with the target asteroid, and a new projection sampling method was employed in the extraterrestrial sampling mission [35–37]. In the Rosetta mission, ESA attempted to anchor lander Philae to the target asteroid which is why, a maximum penetration force of 50 N was provided for the penetration. However, Philae failed to mount the comet in 2014. Therefore, it was unable to provide sufficient penetration force for the SD2 to drill, and did not sample any regolith [38,39]. The Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer (OSIRIS-REx) spacecraft was launched by NASA on September 8, 2016. The Touch-and-Go Sample-Acquisition Mechanism will be employed to acquire samples of target asteroid 101955 Bennu around the year 2020. During this sampling process, a sampler head will obtain a bulk sample by releasing a jet of high-purity N2 gas to fluidize the regolith into the collection chamber, and an articulated arm will retrieve the head [40,41].

In the presented study, a drilling, sampling, and sample-handling system (DSSHS) is designed to perform the following in situ operations: penetrating the regolith, collecting and distributing samples, checking the volume of the sample, and heating the samples to different temperatures. In the second section, a conceptual diagram of China's asteroid exploration mission is briefly illustrated, and the details of the technique to design the DSSHS are presented. In the third and fourth sections, the DSSHS and its methods are respectively introduced. The fifth section introduces the prototype of the DSSHS, and also discusses some experiments. The sixth section concludes this work.

2. China's asteroid exploration mission

2.1. Brief introduction

As published as an outline in *China's Space Activities in 2016*, China will spare no effort in the next five years to develop space technology to obtain samples from asteroids and other deep-space missions. Following the recent termination of the successful Rosetta mission, China plans to send its first probe to an asteroid around the year 2022. This Chinese mission is currently in the demonstration stage. A conceptual diagram of China's asteroid exploration mission is shown in Fig. 1.

According to the current plan, Apophis is the most likely option for such a mission, and China has paid much attention to observing this asteroid in recent years. A probe will be sent to the orbit of Apophis during the first stage, and a lander will then be released to land on the asteroid surface. The lander will be gradually controlled to fly closer toward Apophis, and when a critical height is reached, an anchor with a cable will be ejected at high speed to penetrate Apophis's regolith. A soft landing will be performed when the cable is gradually furled, similar to the Rosetta mission. Three groups of legs are designed to support the lander during the exploration. Subsequently, the lander will be anchored to Apophis, and the cable will provide the reaction force with a maximum magnitude of 50 N during the drilling and sampling processes. A series of in situ analyses will be implemented on the samples collected by the DSSHS. When the missions have been completed, the cable can be cut off, and the lander can detach from Apophis. Alternatively, the lander can be permanently left on the surface of Apophis, depending on the exploration mission.

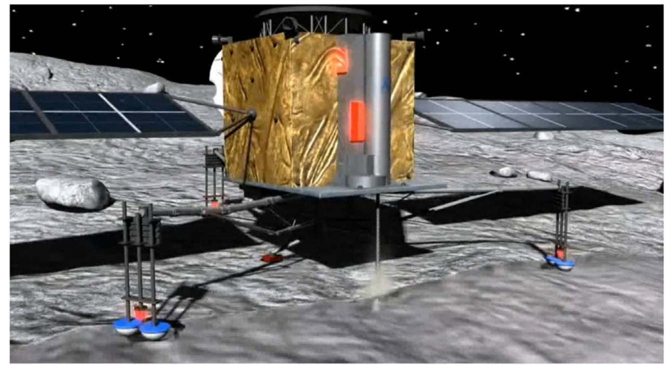

Fig. 1. Conceptual diagram of China's asteroid exploration mission.

2.2. Technical details of DSSHS

The design of the lander will influence the structure of the DSSHS. Therefore, the sampling system must be designed to adapt to the lander. The technical details of the DSSHS are listed in Table 1. According to the sampling mission requirements, the DSSHS needs to penetrate at least 300 mm below the asteroid surface. Samples will be heated to a maximum temperature of 600 °C to vaporize volatile materials. These materials will be analyzed to search for the origin of life or signs of evolution of the solar system. The maximum weight on bit (WOB) is set to 50 N by CAST based on the performance of the prior Rosetta mission. The power, operating time, size, and mass are also set while designing the DSSHS.

3. Drilling, sampling, and sample-handling system

3.1. Scheme of the system

The mechanical component of the DSSHS involves five mechanisms, namely, penetrating, drilling and sampling, volume-checking, sealing and heating, and sample distributing mechanisms, as shown in Fig. 2. The DSSHS can deliver samples to different ovens at a maximum volume of 84 mm^3 with a maximum sampling depth of 300 mm. It can

Table 1
Technical details of the DSSHS.

Parameter name	Technical details
Total size	≤950 mm×330 mm×250 mm
Total mass	≤17 kg
Sampling depth	≥300 mm (300-mm gap)
Penetration force	≤50 N
Sealing force	100 N
Number of ovens	≥16
Single sampling volume	≥35 mm^3
Heating temperature	Low: 180 °C; Middle: 300 °C; High: 600 °C
Sampling material hardness	≥ 6
Power	Average power ≤ 20 W; Peak power ≤ 45 W
Drilling diameter	≥12 mm
Single sampling time	≤2 h