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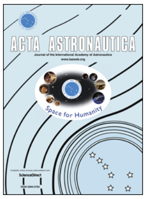

A miniature flexible sampler for subsurface lunar exploration

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ABSTRACT

Lunar subsurface sampling is one of the critical technologies in the advancement of space exploration, and a lunar sampler with low weight, small volume, and low power consumption would significantly reduce the cost of space exploration. Thus, this paper proposes a novel miniature lunar sampler which adopts a flexible tape spring as its sampling arm. Compared with existing rigid-arm samplers, the proposed sampler has the merits of very low weight, reduced volume, and little power consumption. The mechanical design is illustrated in detail, the corresponding flexible kinematics model is built by considering flexibility compensation, and the working space of the sampler is depicted. The performance, e.g. the maximum acceleration, the maximum load capacity, and the sampling depth of the flexible arm, is analyzed through experiments, and each limit is established. In addition, the sampling process is demonstrated with the lab-based experiments, and the feasibility of the sampler is verified.

1. Introduction

Lunar surface sampling is one of the most important steps in subsurface lunar exploration. In general missions, subsequent scientific work can be carried out after successfully sampling the lunar soil [1]. In the early years of lunar sampler design, the lunar samplers were composed of several simple rigid links, such as the Luna 16 and Luna 24 made by the former Soviet Union [2]. Some complicated mechanisms appeared later, such as the sampling arms that were part of the Mars Rover and Opportunity Rover made by the USA, which were constructed with several rigid links, and hence had several degrees of freedom (DOFs) [3]. The sampling arm of the Surveyor craft had the same structure [4]. Another type of sampler used multiple rigid rods as their arms, such as the Multi-Rod Deep Driller made by the Beijing University of Aeronautics and Astronautics [5]. When they are in action, these parallel rods are connected in series to increase the length of the sampling arm, so the sample depth can be very deep. In general, these samplers have the unavoidable disadvantages of high weight, large volume, and high power consumption.

In addition to these kinds of rigid-arm samplers, other types of samplers exist that are very small and work as independent modules, e.g. the Low Reaction Force Drill made by NASA [6] and the Supersonic Rock Drill made by Honeybee Robotics [7]. These are both screw and tube structures. The Contra-Rotor Screw Drill made by JAXA, Japan [8] and the rock-sampling Ultrasonic/Sonic Driller/Corer made by NASA [9,10] are included in this category as well. For these samplers, the lunar soil or rock powder is sampled and contained inside the body of the sampler. Therefore, the restrictions are that the necessary scientific instruments must be installed inside the sampler to make an in-situ analysis, or the entire sampler has to be taken back and delivered to the return capsule. In addition, some biomimetic samplers have also been developed, but their feasibility needs to be further verified, while the same restrictions still exist. Examples of biomimetic samplers include the Carpenter Bee Sampler made by ESA [11] and the Earthworm Shallow Sampler made by Japan [12].

A flexible-arm lunar sampler was first proposed by Southeast University in China [13], and had the merits of very low weight, small volume, and low power consumption compared with the rigid-arm samplers. However, it had only one DOF, hence a specific sample transferring mechanism was developed to deliver the sample from the sampling head to the inlet of the scientific instrument. Later, a multi-DOF sampler with an enhanced sampling arm structure was proposed by adopting two parallel flexible rods [14]. However, the flexible-arm driving mechanism is not reliable and needs further improvements. Therefore, based on these two samplers, a miniature flexible sampler is proposed in this paper, which will improve the reliability and stability of the sampling arm, compared with the samplers in [13,14].

First, we discuss the requirements of the lunar sampler. According to those requirements, a novel miniature flexible sampler is proposed, the key points of its mechanical design are illustrated

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in detail, and the working process of the sampler is demonstrated. Second, a kinematic model is built and a flexibility compensation function, which is obtained by fitting experimental data, is added to the kinematic solution. In addition, the working space is depicted on the basis of the kinematic solution. Third, the position accuracy distribution in the sampling area is analyzed and the performance limits are established experimentally. Finally, sampling experiments are carried out to verify the feasibility of the sampler. The paper is structured as follows. Section 2 describes the mechanical design of the sampler. Section 3 builds the kinematic model, gives the forward kinematic solution, and shows the working space of the sampler. Section 4 analyzes the position error distribution of the sampling head and defines the performance limits caused by the flexible arm. Lastly, Section 5 draws conclusions and points out the direction of future work.

2. Mechanical design

2.1. Requirements for lunar sampling

The constraints on the sampling system, which include weight, volume, and power consumption, are the main concern in lunar exploration. The lunar sampling task would ideally be undertaken by a sampler with little weight, small volume, and low power consumption. Given these requirements, the working space must nevertheless be large enough to sample and deliver the lunar soil. Therefore, the structure of the sampler should be extensible, as long as this is not in conflict with the constraint of small volume. However, the arms of traditional sampling systems are composed of rigid links, and they do not have the capability of contracting into a small volume [15]. So a novel structure and material should be applied to the sampling system to meet the device requirements.

2.2. Working principle of the flexible arm

Considering the requirements, a miniature flexible sampler is proposed, as shown in Fig. 1. A 2-DOF sampling base, shown in Fig. 2, is designed to extend the working space of the flexible sampler.

The sampling arm is flexible, and is made of tape spring, which is also known as an open cylindrical shell. It can be extended to form a flexible arm or retracted into a small-radius coil in the retraction box, as shown in Fig. 1. The recovery wheel is designed to generate an anticlockwise torque which causes a load on the tape spring, so it can be successfully withdrawn around the recovery wheel. In this manner, the sampler can be as compact as possible when it is in the non-working state, but is still able to have a large working area when in the working state, with the help of the 2-DOF sampling base. In Fig. 2, the 2-DOF sampling base depicts two rotary joints, both of which are driven by DC motors. Kinetic energy is transmitted to the rotary shafts through bevel gears. The rotary angles of the two shafts are sampled by rotary encoders which are fixed at the tips of the shafts. The miniature flexible sampler can be easily attached to the base at the connector.

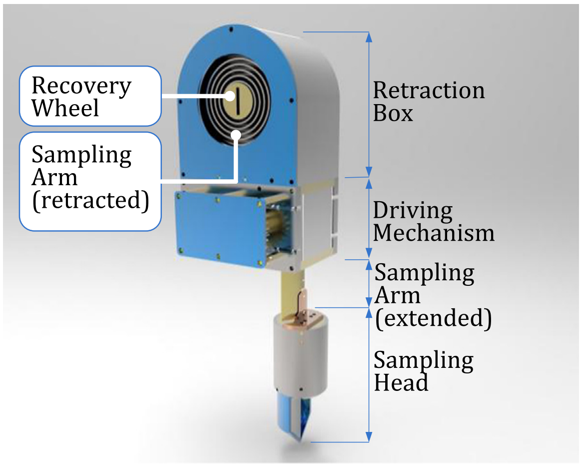

Fig. 1. Flexible sampler.

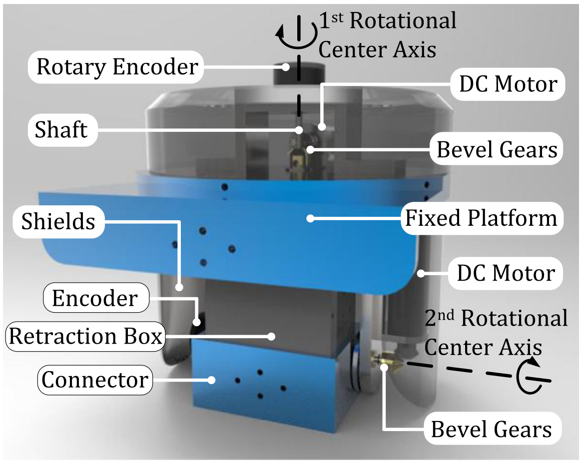

Fig. 2. Two-DOF sampling base.

As shown in Fig. 3, the special geometrical features of the tape spring lead to unique bending behaviors, i.e. it can withstand a small positive bending moment $M+$ and a relatively large negative bending moment $M-$ without buckling. In order to fully utilize this feature of the tape spring, we designed the retraction box and driving mechanism (see Section 2.4) to curve the tape spring in a positive angle during retraction and, on the contrary, to maintain it in a small-negative-angle state when extending it for sampling. Thus, owing to the special features, the small positive bending moment $M+$ makes the retraction process very easy, while the large negative bending moment $M-$ enables a large drilling force. The holes which are punched at the centreline of the tape spring are uniformly spaced. The holes match the drive wheel so the tape spring can be driven reliably and accurately.

When the tape spring is in the negative bending state, the maximum axial load is decided by the thickness t, the radius R, the opening angle θ, and the length L, according to the following empirical formula:

$$F_{\max} = k\cdot\frac{R\theta t^3}{L} \tag{1}$$

where k is the real constant that is determined by the physical character of the tape spring. When the actual drilling force $F < F_{\max}$, the tape spring is stable and will not buckle.

The parameters of the tape spring we are using are listed in Table 1.

2.3. Structure of the sampling head

The sampling head is connected to the free end of the flexible arm via the flange, as shown in Fig. 4. The vibration motor can be used to increase the sampling efficiency, since the vibration energy dissipates greatly when it propagates through the flexible arm from the sampling head to the main body of the sampler. This type of energy dissipation largely reduces the vibration damage or influence on the sampler. By using the vibration sampling method,