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A novel rigid–flexible combined sampler for lunar exploration

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ABSTRACT

Subsurface sampling systems for future lunar robotic missions, which include reliable methods of acquiring and delivering samples to scientific instruments or return capsules for further analysis, are of extreme significance to the success of future in-situ and sample return explorations. Thus, this paper presents a novel multi-DOF sampler, which is designed to perform subsurface regolith sampling for lunar or planetary subsurface exploration in the near future. The sampler is mainly composed of three rigid links and one flexible link. Compared to most of conventional samplers, the developed sampler has several significant merits, e.g. small shrinking volume, large working space and low power consumption. Considering the influence brought from flexible links, the modified kinematic control theory is analyzed and applied to the sampler. At last, the lab-based experiments show the effectiveness of the proposed mechanisms and the feasibility of the sampler.

1. Introduction

The lunar subsurface sampling, which is critical to lunar exploration, has received a lot of attention in recent years. Samplers are used to assist the onsite analysis of the planet regolith or sample return missions [1]. At the beginning of the space sampling mechanism design, the structures of those sampling machines are relatively simple and their volumes are much bigger, compared to the modern sampling mechanisms. Based on the conventional mechanical design methods, the computer aided design is more and more commonly used which accelerates and improves the mechanical design greatly. The feasibility and the function of the mechanisms can be verified even before the manufacturing, e.g., the stress analysis and the space violation analysis. Therefore, for the space missions, the sampler is smaller, lighter and even smarter [2,3]. In summary, there are two kinds of planet samplers. Some samplers take one rod as their sampling arms, such as the Luna 16 made by the former Soviet Union and the Luna 20 made by the USA [4]. With joint type structures, the arm of the Mars Rover and Opportunity Rover made by the USA are composed of more than one rod [5]. Moreover, the sampling part of the Surveyor works with rods connected with each other [6]. The arms of the Low Reaction Force Drill made by NASA [7] and the sampling drill made by Honeybee Robotics [8] are screw and tube structures. The Multi-rod Deep Driller of Beijing University of Aeronautics and Astronautics uses butt joints with multiple rods in the process of deep sampling [9]. These samplers use rigid structures on their arms, so it is not feasible to apply the vibration sampling method to them because it may cause damage to the sampler even to the rover vehicle.

For the sampling head of the Contra-rotor Screw Drill made by JAXA, Japan [10] and the rock-sampling Ultrasonic/Sonic Driller/Corer made by NASA [11,12], flexible lines are adopted on sampling arms, so it is not suitable to use the vibration sampling method either. The great inventions and ideas can always come from the existing phenomena and mechanisms. The study of the ancient mechanisms, which have already placed influence on the early design of the space samplers, can also inspire us in designing new mechanism for space sampling [13]. The small flexible sampler made by Southeast University, China, takes retractable coiling spring as its arm. It has the advantages of long working range, small shrinking volume and light weight [14].

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This paper, to begin with, discusses the requirements of the space exploration and the problems of the conventional samplers. Next this paper proposes a rigid link–flexible link combined sampler. For the flexible part of this sampler, two parallel flexible rods, instead of rigid rods, are adopted in mechanical design. Then, the working mechanisms of the sampler are illustrated in detail, including the working principle of the flexible arm and the mechanical structure of the whole multi-DOF sampler. Finally, the sampler is researched by theoretical analysis and some experiments: the kinematic of spatial linkages is studied [15] and the experiment results show the feasibility of the proposed sampler.

This paper is structured as follows. Section 2 describes the problems, requirements and concept of a sampler for lunar surface exploration. In Section 3, a new mechanism for subsurface sampling is proposed and the working principles are studied. Section 4 discusses the feasibility of the proposed scheme by investigating the performance in some experiments. Finally, Section 5 is for conclusions and future work of the research.

2. Lunar surface exploration

2.1. A. Problems in sampling

This paper deals with the surface regolith which is covering the lunar surface. For lunar missions, the constraints on the system including weight, volume and energy consumption should be seriously considered. As a part of the exploration system, the sampler, fixed on the main body of the system, should be designed to be reliable and robust in performing its sampling and delivering work. In addition, the contradiction of small volume and large working space is a tough problem, and so far, hardly any good solutions can be found in existing designs.

2.2. B. Requirements for sampling

Considering the problems mentioned above, for sampling the regolith, the authors proposed a novel sampler based on the rigid–flexible combined structure. The proposed sampler has the following features.

1. The sampler has a small volume in non-working state but a large working space in working state.
2. The sampler can select a sampling site and sample the regolith within a certain area.
3. The sampler is reliable and robust in sampling and the samples can be delivered to the scientific instruments or return capsule as high as 2 m.

2.3. C. Conceptual design

The objective of this study is to design the sampler that can be deployed from lunar missions, even some planetary exploration missions. To prevent the advancement in terms of mass, volume and power, the following design requirements are applied, as listed in Table 1.

Fig. 1 illustrates the preliminary design of the proposed sampler. This sampler has mainly two parts: the rigid arms and the flexible arm. The sensors, vibration actuator, instruments and other equipments can be adopted in the sampling head in order to assist the exploration missions.

3. Working mechanism

In this section, the principle and the function of the sampler are illustrated. In Subsection A, a theoretical analysis is presented in order to verify the feasibility of the flexible arm; in Subsection B, the driving mechanism for the flexible arm is demonstrated, and in Subsection C, a kinematic analysis is developed based on the rigid–flexible combined structure.

Table 1
Requirements for the sampler.

Total mass	3.5 kg
Size (shrunken)	45 (max length) × 20 (max width) cm
Size (expanded)	200 (max length) × 20 (max width) cm
Power	4.2 W (average) / 6 W (peak)
Sample depth	10 cm (max)
Sample weight	≥1.5 kg (by multiple sample)
Position error	≦5 mm