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A novel rigid–flexible link combined lunar sampler and its basic dynamics and control

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ABSTRACT

Lunar surface sampling is a critical technology for lunar exploration, involving in-situ analysis or sample return missions. In this paper, a lunar sampler with the novel mechanical structure is developed, which is mainly composed of three rigid links and one flexible link. By adopting the flexible link, the sampler has some significant merits compared with other conventional samplers, e.g., a small shrinking volume and a large working space. The flexible dynamic model is built for the novel sampler by using the virtual work principle and mode reduction method to analyze its dynamic behavior, and the linear quadratic control model is successfully introduced and applied to control the flexible link. At last, the simulation is carried out and a special mechanism is used to verify the correctness of the dynamic model and the effectiveness of the control method. The sampling experiments show that the flexible sampler is qualified to finish the sampling tasks.

1. Introduction

Lunar subsurface sampling, which is one of the most significant technologies in lunar exploration, has received much attention in recent years. The samplers are used to assist the onsite analysis of the planetary regolith or sample return missions [15]. In general, there are two kinds of planet samplers. One kind uses one rod as sampling arm, such as the Luna 16 made by the former Soviet Union and the Luna 20 made by the USA [16]. With joint type structure, such as the arms of the Mars Rover and the Opportunity Rover made by the USA, which are composed of more than one rod [7]. The sampling part of the Surveyor works with rods connected with each other [4]. The arms of the Low Reaction Force Drill made by NASA [8] and the sampling drill made by Honeybee Robotics [6] are screw and tube structures. The Multi-rod Deep Driller of Beijing University of Aeronautics and Astronautics uses butt joints with multiple rods to take deep samples [5]. These samplers use rigid structures on their arms, so the volume, the weight and the power consumption are all on average bigger compared with the flexible samplers.

The other kind of sampler, like the Contra-rotor Screw Drill made by JAXA (Japan) [17] and the rock-sampling Ultrasonic/Sonic Driller/Corer made by NASA [3,2], uses flexible wire just to supply power and the sampling arm is removed from this kind of sampler. The small single-link flexible sampler made by our research team in Southeast University, China, uses a retractable coiling spring as its flexible arm, which has the advantage of a long working space, small volume, light weight, extremely low power consumption and other extended functions [14,11]. Based on this sampler, the paper proposes a multi-DOF rigid–flexible link combined sampler, which overcomes the weakness of small sampling volume and small drilling force, and increases the stability of the sampler. This is the first time a rigid–flexible link combined sampler for space use has been proposed, and therefore, the dynamic analysis and control has, so far, not been applied to this kind of flexible arm to achieve the sampling tasks.

This paper is organized as follows: Section 2 illustrates the mechanical structure of the sampler in detail. In Section 3, the dynamic model is shown, which also contains the mode analysis since the flexibility of the sampling arm is taken into consideration. And the linear quadratic method to control the flexible link of the sampler is introduced. Section 4 contains the simulations and experiments. Finally, Section 5 states the conclusions plus some ideas for future work.

2. Mechanical design of the sampler

2.1. Overall design of the sampler

The sampler is designed for the 3rd-phase Chang'E Project of China. The overall parameters of the sampler, which should meet

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Table 1
The requirements for designing the sampler.

Total mass	3.5 kg
Length (shrunken)	45 cm
Length (expanded)	170 cm
Width	20 cm (max)
Power	4.2 W (average)/6 W (peak)
Sample depth	10 cm (max)
Sample weight	≥1.5 kg (by multiple times)
Position error	≤5 mm

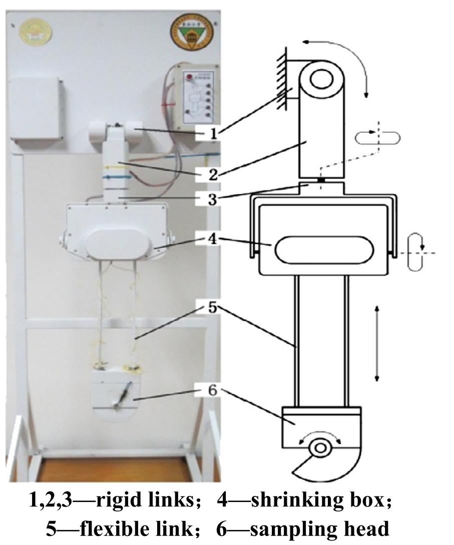

Fig. 1. The illustration of the sampler.

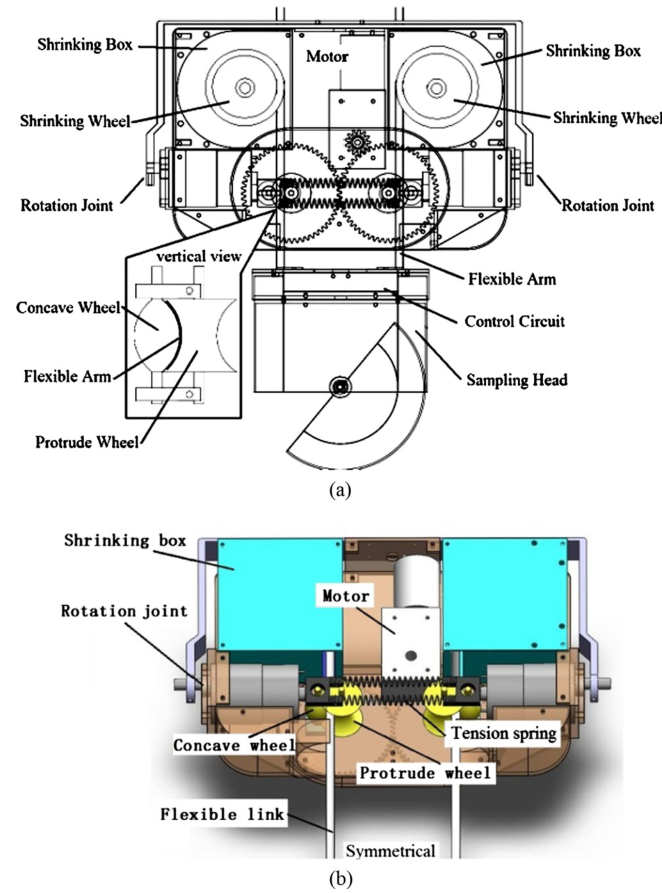

Fig. 2. The driving mechanism for the flexible link.

the requirements of being deployed from lunar explorations, are listed in Table 1.

Fig. 1 illustrates the sketch of the proposed sampler. It has mainly two parts: the rigid links and the flexible link. There are three rotary joints for the rigid links and one translational joint for the flexible link. The novel design is that the flexible link can be coiled into the shrinking box when in non-working state and expanded as two flexible rods when in working state. Thus, the biggest advantage of the sampler is that the volume of the sampler can be very small when it is not sampling or delivering (non-working state). Moreover, the sensors, vibration actuator, and other equipments can be fixed in the sampling head to assist the exploration missions.

The flexible link is made of two parallel tap springs, which are also called the opening cylindrical shells. This type of material is adopted as the main part of the flexible link due to its special properties, namely, it has a big reverse bending moment and a very small forward bending moment. By taking advantage of these two properties when the tap springs are properly fixed, as described in [13], the drilling force can be big enough for sampling and the force necessary to retract can be very small so that the flexible link can be easily coiled into the shrinking boxes.

2.2. Driving mechanism for the flexible link

A symmetrical mechanism is designed to drive the flexible link (two parallel tap springs), as shown in Fig. 2(a). Two pairs of concave wheels and protruding wheels are tightly assembled by four tension springs as shown in Fig. 2(b), in order to steadily clamp two tap springs, which are both in the middle between the concave wheel and the protruding wheel. For each tap spring, while the concave wheel is rolling, the tap spring is able to move in two directions: upward and downward. Two symmetrical concave wheels keep exactly the same velocity due to a pair of spur gears driving them both. Thus, those two flexible rods keep pace with each other and all these motions are actuated by one motor.

Based on the working principle of the flexible link described above, when those two flexible rods move upward, the flexible link stays in a state of positive bending around the shrinking wheels. Thus, the flexible link is easy to be coiled into the shrinking boxes. On the contrary, when they move downward, the flexible link works in the state of reverse bending, so that they can withstand an adequate axial force generated from the sampling head inserting into the regolith.

3. Flexible dynamics and control of the sampler

3.1. Modal analysis of the flexible link

Two parallel tap springs, which construct the flexible link, are equivalent to a single-span beam only when they are parallel and both the free-ends are in a same altitude. Assume that the flexible link only shows its flexibility in the Y-direction. According to the equilibrium equation of the Y-direction vibration and the mechanics of the material, the differential equation of vibration for the beam is as follows

$$\frac{\partial^2}{\partial x^2}\left(EI(x)\frac{\partial^2 y}{\partial x^2}\right)+m(x)\frac{\partial^2 y}{\partial t^2}=0 \tag{1}$$

where $y(x,t)$ is the Y-direction displacement. Suppose that the flexure strength $EI(x)$ and the line density $m(x)$ are constant in the X-direction, Eq. (1) can be simplified. Once the initial condition is given, the mode function of each mode order can be established [18]. For the equivalent beam, one end is fixed on the basis (fixed end) and the sampling head, which can be equivalent to a mass