Research of Reinforcement Deployment Mechanism of Automatic Sampler for Lunar Sample Return Mission

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Abstract. Chang’E-5 detector has successfully completed the lunar sample return mission, and accomplished the first extraterrestrial object drilling sampling detection of China. The deploying process is a key point for the whole mission and the design of the deployment mechanism is significantly important for the system. Compared to traditional deployment, low gravity surface operation and heavy load is the characteristics of this mission. In this paper, a design of reinforcement deployment mechanism suitable for lunar low gravity environment, large load condition is proposed. In this scheme, the planetary force augmentation and fulcrum separation method is adopted, the arm of force is introduced to achieve large load driving by small torque, and the design parameters are determined. The performance of the deployment mechanism is vindicated by dynamic simulation analysis and experimental verification. The research results demonstrate that the deployment mechanism can meet the demand of driving large load with small torque. The deployment mechanism designed based on this scheme has been employed by Chang’E-5 detector and performed perfectly on the moon.

1. Introduction
The lunar soil records the information of the early geological evolution of the planet [1]. The elements contained in the lunar soil are important clues for the study of the earth-moon system and even the internal activities of the whole solar system [2]. At present, the sampling methods of the moon mainly include shallow shoveling and deep drilling [3]. In the completed lunar soil sample return missions, luna-16 and luna-20 detectors of the former Soviet Union adopted avoidance mechanism which will swing a certain angle to reserve the space for the ascender when the sampling process is completed, in order to ensure that the drilling and sampling device will not interfere with the take-off and returning of ascender with the sample [4]. China’s Chang’E 5 lunar exploration project was inspired by the operation plan of the former Soviet Union. The mission objective is to implement the automatic sample return of lunar soil. The research team has started the development of the unmanned lunar autonomous sampler in 2007[5][6]. Chang’E-5 probe has successfully completed the lunar subsurface drilling and sampling mission on December 2, 2020. Because of applied in microgravity environment, the torque of traditional deployment mechanism is small [7][8]. The design scheme of the reinforcement deployment mechanism is put forward for the expected working condition of China’s unmanned lunar autonomous sampler [9][10]. By introducing the arm of force, the driving capacity of the driving source is enlarged at the load
position to achieve large load deployment under low gravity condition of the lunar. In this paper, the deployment mechanism is described in details and the performance of the deployment mechanism is studied by the way of simulation analysis and experiment verification.

2. Deployment Mechanism Profile

The deployment mechanism is installed between the lander and the ascender of the detector. It aims to drive the deployment load to unfold after the sampler completes the collection and encapsulation of the lunar soil sample, providing space for the ascender to rise [11]. The initial position and termination position of the deployment mechanism are shown in the figure 1.

![Deployment Mechanism](image)

**Figure 1.** Position of the deployment mechanism.

Due to the particularity of deployment mechanism, including its special application environment, moving plane, configuration layout, deployment angle, deployment load and initial attitude, it has the following characteristics compared with traditional spacecraft deployment mechanism:

a) Large initialization torque: low gravity environment (the moon is 1 / 6g gravity field), large distance between the rotation center and the center of gravity of the deployment load, leading to large deployment load and large initialization torque.

b) High lightweight requirements: because it is installed on the top of the lander, its weight should be light enough to meet the mechanical environment requirements.

c) ge locking impact: since the initial installation angle of the deployment mechanism is 9.5 °, the angle of deployment in place is 120 °. After 90 ° deployment, the load torque is converted into driving torque. Therefore, when the mechanism is locked, the impact force it bears is large.

In this design: the transmission mode of driving the deployment arm is different from the traditional driving mode. In this product, the deployment wire rope is used as the force increasing mechanism, which increases the arm of force at the action point and reduces the output requirements for the torque of the scroll springs. Meanwhile, the unfolding time is prolonged and the locking impact is reduced. At same time, the technological performance of scroll spring is improved. The difference between reinforcement deployment mechanism and traditional deployment mechanism is showed in figure 2 and table 1.
Reinforcement deployment mechanism       Traditional deployment mechanism

**Figure 2.** Schematic diagram.

**Table 1.** Three Scheme comparing.

| Item                              | Traditional deployment mechanism | Reinforcement deployment mechanism |
|-----------------------------------|----------------------------------|-----------------------------------|
| Load gravity torque               | 15Nm                             | 2                                 |
| No. of scroll spring              | 4                                | 2                                 |
| Operating angle of scroll spring  | 110.5°                           | 600-700°                          |
| Amplification coefficient         | 1                                | >3                                |
| Technological performance of scroll spring | Nonenforceable | Enforceable                      |

3. **Parameter design**

3.1. **Driving torque design**
Based on the working principle and force transmission path of the deployment mechanism, the mechanical model of each stage in the movement process is shown in the figure 3.

**Figure 3.** Mechanical model of each stage.
Table 2. Parameter summary list.

| Parameter | Interpretation | Parameter | Interpretation |
|-----------|----------------|-----------|----------------|
| F         | The tension of the rope(N) | l₁        | Length of OB   |
| G         | Load gravity torque(Nm)    | l₂        | Length of OA   |
| Tz        | The torque of deployment mechanism(Nm) | β        | The angle between the line connecting the pull point to the center of rotation and the rope(°) |
| θ         | The angle between the line connecting the pull point to the center of rotation and the horizontal plane(°) | θ        | Rotation angle(°) |
| α         | The angle between the deployment arm and the horizontal plane(°) | k        | Slope of lcb   |
| L         | Distance between center of rotation and rope(mm) | Tq       | The torque of deployment mechanism in initial position(Nm) |

The tension of the rope is:

\[ F = \frac{T}{L} = \frac{G \cos(\theta + \alpha) + 1}{L} \quad (1) \]

Therefore, the torque provided by the scroll spring is:

\[ T_q = F_r = \frac{T}{L} = \frac{G \cos(\theta + \alpha) + 1}{L} \quad (2) \]

The final available driving torque is as follows:

\[ T_q = \frac{\sqrt{-2(a-c)(d-b)-\sqrt{2(a-c)(d-b)^2-4[(a-c)^2-r^2][(d-b)^2]}}}{2[(a-c)^2-r^2]} \text{c+d} \quad (3) \]

\[ \left[ 1 + \frac{-2(a-c)(d-b)-\sqrt{2(a-c)(d-b)^2-4[(a-c)^2-r^2][(d-b)^2]}}{2[(a-c)^2-r^2]} \right] \]

Based on the above calculations and considering other factors such as mounting interface, configuration layout, motion profile, the driving torque and other design parameters of the deployment mechanism are finally determined.

3.2. Margin analysis

According to the torque margin design requirements of spacecraft products, the static torque margin of spring driving mechanism shall be greater than 1. The definition of the static torque margin is as follows:

\[ \eta = \frac{M}{R} - 1 \quad (4) \]

Based on the working environment, initial attitude, resistance torque and other factors of the deployment mechanism, the Torque margin of deployment mechanism under different attitude is calculated. The results are showed in figure 4.
It can be seen from the figure that the torque margin of the deployment mechanism under current driving torque is greater than 2 in all initial attitudes. The most severe working condition of the deployment mechanism is that the initial attitude is -9.93 ° (in this condition, the load center of gravity is horizontal), and the torque margin of the deployment mechanism is the smallest, so it is necessary to carry out dynamic research and verification of the deployment mechanism under this working condition.

3.3. Mechanism dynamic check
The dynamic model of deployment mechanism is composed of locking hinge parts (including hook hinge, locking hinge and locking hook), deployment arm, deployment wire rope, the load and the driving device composed of the drum and deployment wire rope. The virtual prototype model is shown in Figure 5. In this paper, the finite segment method is used to analyze the dynamic characteristics of the wire rope structure with large deformation. Because the locking moment will produce a large impact force, this process is analyzed by simulation. Through the software preprocessing, the arm and lock hinge parts are flexible, and the process is simulated to output the structural deformation and load distribution calculation results.

![Figure 5. Dynamic model.](image)

In the virtual prototype model, which is based on ADAMS, bushing element is used to connect the rope segments between the cylinder segments to simulate the internal force of the deployment wire rope [12].

![Figure 4. Torque margin of deployment mechanism under different attitude.](image)
3.3.1. Deployment wire rope model. In the finite segment method, a section of the wire rope is divided into several rigid small cylindrical sections, and a flexible connection composed of torsion spring, wire spring and damper is introduced to connect the cylindrical sections to complete the modelling [13], as shown in the figure 6.

![Figure 6. Finite segment model.](image)

In Figure 6, the adjacent two cylinder rigid sections are connected by the shaft sleeve force; \( r_i \) is relative displacement; \( \theta_i \) is relative angular displacement; \( v_i, \omega_i \) are relative linear velocity and angular velocity respectively; \( F_{i}, T_{i} \) are initial force load and torque load respectively. The rigidity coefficients of the Bushing are defined as follows:

\[
\begin{align*}
K_{\alpha} &= \frac{EA}{L} \\
K_{\beta} &= \frac{GA}{L}
\end{align*}
\]

(5)

\[
\begin{align*}
K_{\alpha к} &= \frac{G \pi d^4}{32L} \\
K_{\beta к} &= \frac{EI \pi d^4}{64L}
\end{align*}
\]

(6)

3.3.2. Simulation results. The simulation time is 3.5 seconds, and a driving torsion spring is added to the drum. The function of driving force is:

\[
T_{d} = \begin{cases} 
-K_i (\beta - \beta_i) - C_i \dot{\beta} & 8^\circ \leq \theta \leq 90^\circ \\
0 & 90^\circ < \theta \leq 128^\circ
\end{cases}
\]

(7)

The deployed angular velocity curve is shown in the figure 7.
Figure 7. Deployed angular velocity curve.

It can be seen from the figure that under the existing parameters, the deployment mechanism can realize the avoidance expansion of the large load, and the angular velocity keeps increasing during the expansion process. Meanwhile the locking impact occurs in 2.12s, and the angular velocity along the rotating axis during the impact is 2.174rad/s.

4. Function and performance research

On the basis of simulation analysis, 1/6g gravity simulation test is carried out to verify the deployment mechanism. The simulation trial is carried out in the way of the slant method.

The slant method is to tilt the moving plane of the deployment mechanism by 9.56 ° and to place the mechanism vertically so that the gravity component of the spreading load on its moving plane is 1/6g [14] of the real value. The method is demonstrated in the figure 8. The 1/6g test system is showed in the figure 9.

Figure 8. Working principle diagram of 1 / 6g simulated gravity field obtained by "slope equivalent method"
The method of performance test is that:
1) Fix the deployment mechanism on the 1/6 simulated gravity field and adjust the initial angle to -9.93°;
2) Use the high-speed video to record the whole process;
3) Analysis the angular velocity at the time of locking by images contrast. The result of performance test is showed in the table 3.

Table 3. Nominal attitude performance test of deployment mechanism.

| Initial attitude                        | Load gravity torque | Deploying time | Load angle acceleration at locking time | Product status after test |
|----------------------------------------|--------------------|----------------|----------------------------------------|---------------------------|
| Angle between deployment arm and horizontal plane - 9.93° | 15Nm               | 3.9s           | 85.65°/s                               | Normal                    |

When the angle between the deployment arm and the horizontal plane is -9.93°, it achieves the largest angle acceleration and the minimum margin. It is the severe working condition of deployment mechanism. The test result shows that deployment mechanism can meet the requirement of the severe working condition. Due to existence of 1/6g simulated gravity field’s frictional resistance, there is a certain deviation between the Deploying time and the angular velocity an the locking moment and the simulation results.

5. Conclusions
This paper elaborates on the principle, working process and relevant parameters of the deployable mechanism, which are applicable in the low gravity environment of the lunar surface and applicable with large load. The design is verified both by dynamic simulation and experiment. Following conclusions are achieved by the work:

1) The reinforcement deployment mechanism can accomplish large load driving with small driving torque by introducing the arm of force, and the strength of parts can meet the requirements of locking impact;
2) In the whole moving process, the angular velocity increases gradually due to the change of the arm;
3) In the process of locking, the strongest locking impact occurs in the position of locking hinge and locking hook, and with the help of the hook hinge and deployment arm diminishing the locking impact, it has little effect on the end-load.

4) Research on the adaptability of the mechanism to low temperature environment is carried out to provide technical support for subsequent lunar polar sampling exploration.

Acknowledgments
This work was financially supported by NSFC fund, No.11932001.

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