# Recognition of Traveling State Using Internal Structure Information for Lunar and Planetary Exploration Rovers

**Abstract:** The lunar orbiter SELENE discovered giant holes and these have great significance for science and potential utilization, and thus should be priority targets of future exploration. it is necessary to understand the driving environment and the conditions of slippage when traveling on such terrain. In this research, we develop a system that detects slippage from changes in the strain acting on the legs and identifies the running condition, just as an organism recognizes the walking state from its internal senses. As a first step, the interrelationship between strain and slippage during running is verified by an experimental approach.

# 月・惑星探査ローバのための内部構造情報による走行状態認識

概要：月周回衛星「セレーネ」が発見した巨大な穴は，科学的意義や潜在的な利用価値が高く，今後の優先的な探査対象とすべきものである．このような地形を走行する際には，走行環境や滑りの状況を把握する必要がある．本研究では，生物が内的感覚から歩行状態を認識するように，脚に作用するひずみの変化から滑りを検出し，走行状態を識別するシステムを開発行う．その第一歩として，走行時のひずみと滑りの相互関係を実験的に検証した．

## １. Introduction

Space development has been actively pursued in order to expand the scope of human activities with the development of science and technology. The demand for landing exploration using a rover has increased. However, it’s a dangerous environment for humanity such as extreme temperature, radiation and thin atmosphere [1]. Therefore. it has been required to use a rover for an unmanned exploration mission.

The surface is covered with fine particles called regolith, which causes the wheels to slip when the rover travels. If the slippage is not restrained, exploration efficiency will decrease because the robot will deviate from the planned target path. In the worst case, the rover becomes stacked, and exploration becomes impossible [2]. Stuck means the wheels are buried in the sand and cannot move. In fact, the Mars Exploration Rover MER (NASA, JPL, 2012) became stuck on Mars and took more than a month to escape [3]. Therefore, if the rover can detect the traveling state, it can correct the misalignment of the traveling path and avoid the stuck state.

In order to detect the traveling state, detection systems based on visual information using cameras loaded on rovers have been studied, such as relative position estimation and traveling ground discrimination [4][5]. However, there is a risk that the accuracy of detection will be decreased by the effects such as a Less feature points in the image and Instability of colors. The system cannot respond to sudden slippage because it cannot detect small changes in slippage. It is possible to improve the tracking of the travel path and prevent stuck states if the rover can recognize the travel state. Therefore, a new system for detecting the traveling state is required.

Humans use not only vision but also somatosensory perception to recognize their walking condition.  Particularly, an intrinsic sensation which is one of the somatosensory senses estimates the body motion and position change from the stimulation of muscles, tendons, and joint [6][7]. In fact, humans receive forces applied to the lower limbs as mechanical stimuli called tension and recognize the walking state based on this information. Therefore, we are focusing on this intrinsic sensation and developing a system to detect the traveling state based on the intrinsic sensory detection.

This phenomenon of human muscles also occurs in the legs of a rover. When the rover travels, the force applied to the wheels changes with the ground and traveling state. These forces affect the legs of the rover and change the shape of the leg. We aim to develop a system that detects this change in the shape of the legs and recognizes the traveling state based on the intrinsic sensory information.

In this study, the relationship between the change in the amount of strain, which is the deformation of a member, and the traveling state is confirmed by a travelling experiment in order to develop the system. First, the phenomenon is confirmed by measuring the strain occurred during traveling experiments with a single wheel. In addition, the analysis method of the strain during traveling is discussed by using the strain at this time. Finally, based on the analysis method discussed, the effectiveness of this method is confirmed by measuring the change in strain when the traveling state are set different situation like traveling ground and slippage.

## 2. Measurement of leg strain during travel

In this chapter, the strains acting on the leg when the wheel travels are verified by experiments in which the wheel travels. Then, based on the experimental results, the method of analyzing the strain during traveling is discussed.

### 2.1. Experimental environment and condition

The strains on the legs are measured by actually traveling the wheels on different ground surfaces, and the strains on the legs during traveling are confirmed. Fig.1 shows the experimental environment and the single wheel test bed. Two types of ground are used: loose soil and rigid ground. The loose soil is simulated by spreading silica sand No. 5, and the rigid ground is simulated by installing wood. The strains are measured by strain gauges. The strain gages are attached to the top of the leg plate, where it is easiest to detect the strain, using a two-gauge method that isn't really affected by the external influences. The thickness of the leg plate is 3[mm] in order to have very low rigidity and to change the strain more easily. Fig.2 shows the strain measurement state and Table 1 shows the experimental conditions.

### 2.2. Experimental result

Fig. 3 shows the change in strain when the wheel travels on each ground. The results of one trial are shown because the trend is similar for the five trials of each ground. When the strain is positive, the shape is changed by tilting the wheel forward, and when it is negative, the shape is changed by tilting the wheel backward. From the experimental results, different strain changes were confirmed for each ground. These strain changes are classified into two categories. The first is the displacement of the strain amount, and the second is the vibrational change of the strain. Based on these two categories, the analysis method of the strain during traveling is discussed as next section.

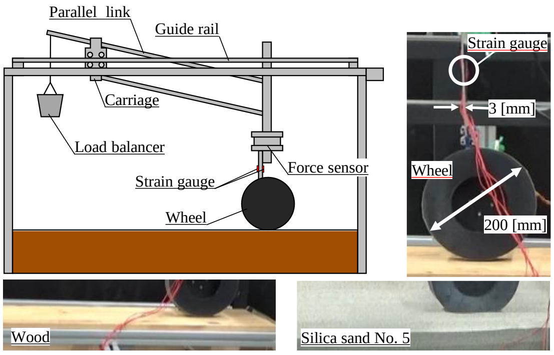



Fig.1 Overview of experimental setting for measurement leg experiment

Table 1 Condition of experiment

| Description (Unit) | Value |
|---|---|
| Slope angle [ °] | 0 |
| Rotation speeds [rpm] | 5 |
| Traveling distance [mm] | 500 |
| Trial | 5 |

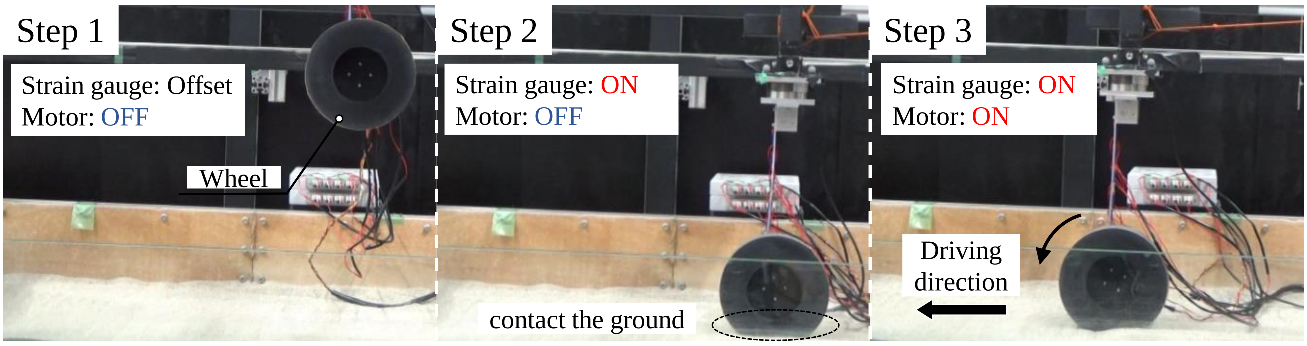
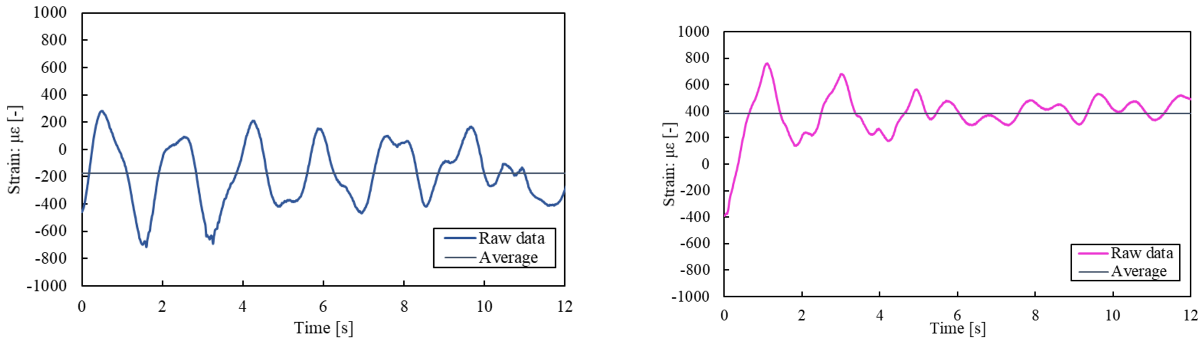



Fig.2 Actual condition of the experiment




(a) Rigid surface (b) Loose soil

Fig. 3 State of strain when traveling on each ground

### 2.3. Discussion of the analysis method

From the experimental results, the strains during running are classified into two major categories: the first is the displacement of the strain amount, and the second is the vibrational change of the strain. The analysis method is discussed from these results.

We focus on muscle spindles, which are human receptors. There are intrinsic receptors called muscle spindles inside the human muscle to receive the stimulus of the leg [8][9]. The muscle spindle has a role to sense the rate of muscle fiber expansion and contraction, and the muscle fiber in the spindle has a nuclear chain fiber and a nuclear bag fiber. The nuclear chain fiber can detect the displacement of absolute tension and is mainly used to recognize static phenomena such as postural states. The nuclear bag fibers can detect the speed of muscle fiber stretching and are mainly used to recognize dynamic phenomena. Thus, humans use intrinsic receptors "muscle spindles" to sense posture and walking state from the rate of displacement and stretch of muscle fibers.

These changes in the extension of muscle fibers are applied as a method of strain analysis. Fig. 4 shows the method of analysis. The traveling state is estimated from the displacement of extension and the speed of extension in the leg. Specifically, for the nuclear chain fiber analysis method, the average value of the strain displacements during 5 seconds is used. For the nuclear bag fiber analysis method, the change in strain during the 5 second period is differentiated, and the value of the frequency analysis by FFT transformation is used.

## 3. Verify the interrelationship between traveling conditions and leg shape changes

In this chapter, the strain on the legs when the traveling state changes is verified by experiment. Then, the interrelationship between the traveling state and the strain is verified by two methods: nuclear chain fiber method and nuclear bag fiber method.

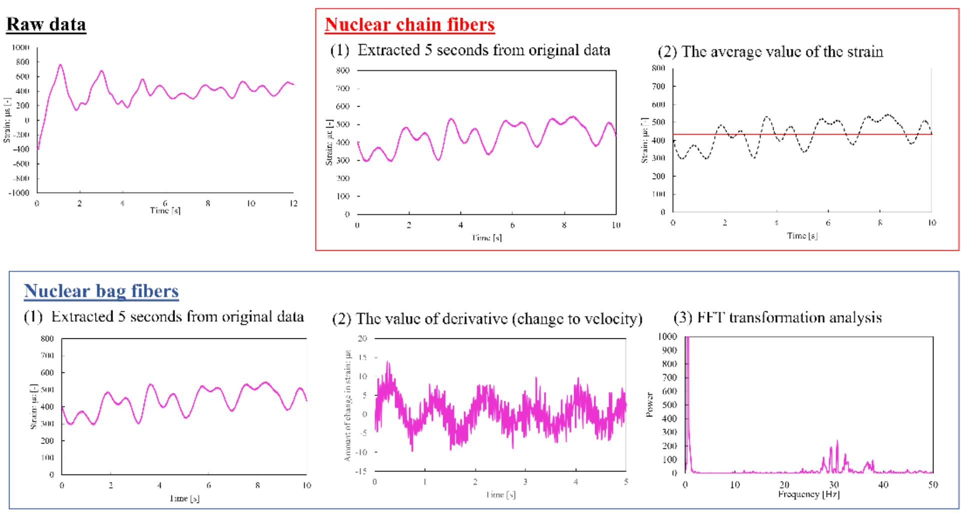



Fig. 4 Method of analysis

### 3.1. Experimental Environment and Conditions

Fig.5 shows a model of a rigid wheel traveling on a loose soil. The slipping ratio is the ratio of the wheel translational velocity: $v_{\omega x}$ to the wheel peripheral velocity: v, as follows Equation (1). As the slip ratio is close to 1, it is difficult for the rover to move forward, and as it is close to 0, the wheel is moving forward. The shear stress, vertical stress, and driving force of a wheel traveling on a loose soil with this slip rate.

$$s = \frac{v - v_{\omega x}}{v_{\omega x}} \tag{1}$$

The driving force $F_x$ of a wheel can be calculated by integrating the x-direction parts of the vertical stress $\sigma(\theta)$ and shear stress $\tau_x(\theta)$ acting on the ground of a rigid wheel from the wheel entry angle $\theta_f$ to the wheel escape angle $\theta_r$, and can be expressed as Equation (2).

$$F_x = rb\int_{\theta_r}^{\theta_f}\{\tau_x(\theta)\cos\theta - \sigma(\theta)\sin\theta\}d\theta \tag{2}$$

The vertical force $F_z$ can be calculated by integrating the z-direction parts of the vertical stress $\sigma(\theta)$ and shear stress $\tau_x(\theta)$ acting on the ground of a rigid wheel from the wheel entry angle $\theta_f$ to the wheel escape angle $\theta_r$, and can be expressed as Equation (3).

$$F_z = rb\int_{\theta_r}^{\theta_f}\{\tau_x(\theta)\sin\theta + \sigma(\theta)\cos\theta\}d\theta \tag{3}$$

Fig.6 shows the theoretical curve of the relationship between the slip rate and the driving force based on the terramechanics. As described above, there is a relationship between slip, driving force and vertical drag. The change in these forces affects the distortion of the deformation of the leg member. Therefore, the interrelationship with the slippage is experimentally verified from the change of the strain.

### 3.2. Experimental Environment and Conditions

In order to verify the interrelationship between the traveling condition and the strain on the leg, the strain is measured when the traveling ground and the travelling state are changed, and verified by nuclear chain fiber method and nuclear bag fiber method. In this experiment, the strains are measured by changing the vertical force: $F_z$ for loose soil and rigid ground, and by changing the slip ratio: s for loose soil.

Fig. 7 shows the experimental environment. The vertical drag force is changed by changing the load of the load barancer to 18 N, 27 N, 36 N, and 54 N, and the Slip ratio is changed by changing the load of the traction load to 0 g, 100 g, 200 g, and 300 g. The loose soil is simulated by spreading silica sand No. 5, and the rigid ground is simulated by installing wood. A motion capture system is used to measure the moving speed of the wheels. The test bed is the same as the one used in the experiment in Chapter 2. Table 2 shows the detailed experimental conditions

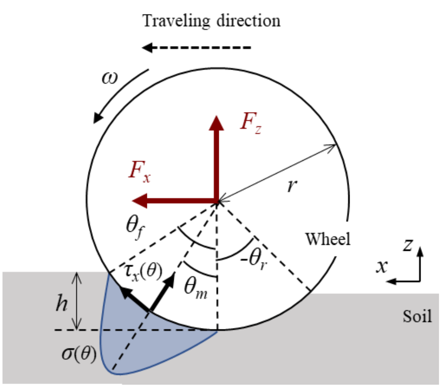



Fig.5 Model of a rigid wheel traveling on loose soil

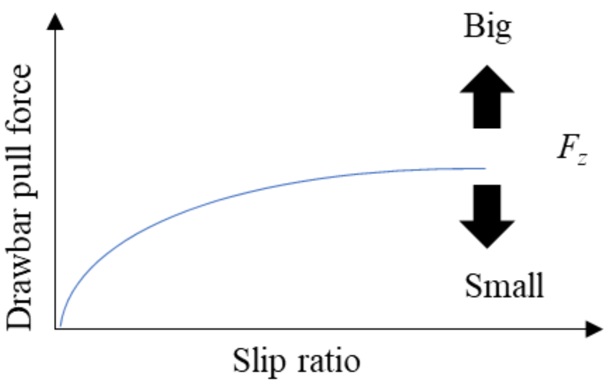



Fig.6 Relationship between drawbar pull and slip ratio

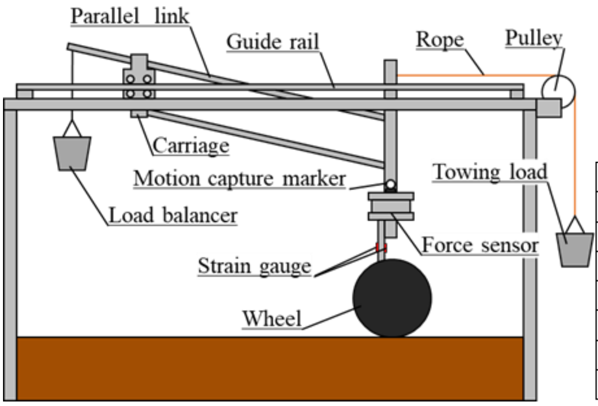



Fig. 7 Overview of experimental setting for
Interrelationship verification experiment

Table 2 Condition of experiment

| Description (Unit) | Value | |
|---|---|---|
| Ground condition | Slilca sand No.5, Wood | Slilca sand No.5 |
| Weight [N] | 18, 27, 36, 54 | 27 |
| Drawbar mass [g] | 0 | 0, 100, 200, 300 |
| Slope angle [ °] | 0 | |
| Rotation speeds [rpm] | 5 | |
| Traveling distance [mm] | 500 | |
| Trial | 5 | |

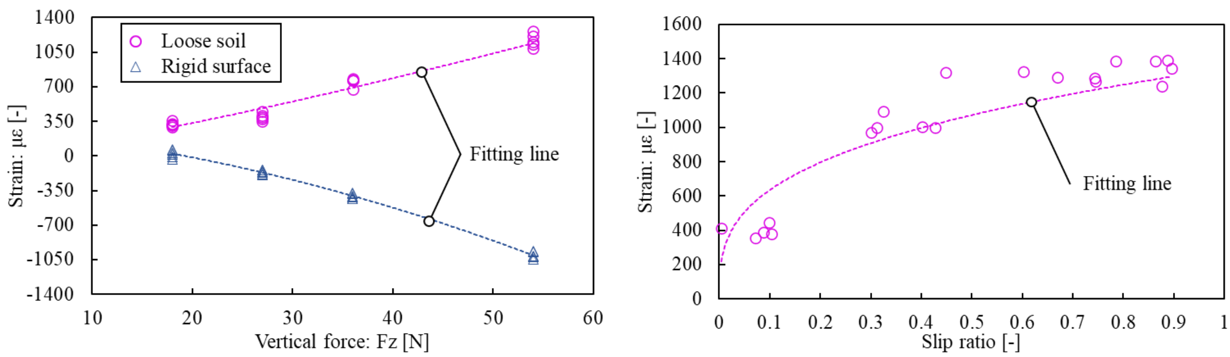
### 3.3. Experimental result -nuclear chain fiber method-

Fig.8-(a) shows the results of the nuclear chain fiber analysis for each type of ground when the vertical force is changed. the average value of the strain displacements change linearly with the increase of vertical force. Fig.8-(b) shows the results of the nuclear chain fiber analysis loose soil when the slip rate is changed. The strain changes logarithmically with the increase of the slip rate. The driving force is increasing logarithmically as well as the strain, thus the average value of the strain displacements change linearly with the increase of driving force.

As a result, from the relationship that the strain increases linearly with the increase of the vertical force and the driving force, it is possible to detect the change in the force applied to the wheel during traveling from the strain. Therefore, it is possible to recognize the traveling state by using the nuclear chain fiber analysis to detect the change in the force applied to the wheel during traveling.

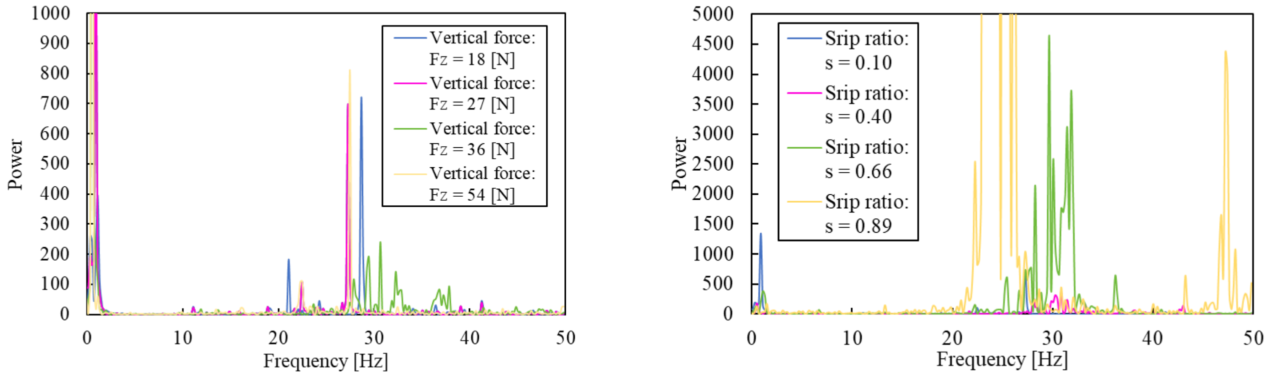
### 3.4. Experimental result - nuclear bag fiber method -

Fig.9-(a) shows the results of the nuclear bag fiber evaluation for loose soil when the vertical force was changed. The results of one trial are shown because the trend is similar for the five trials of each ground. Even though the load changed, loose soil responded strongly in the low frequency range between 0-10 Hz. and in the higher frequency range between 20-50 Hz. Fig.9-(b) shows the results of the nuclear bag fiber analysis when the slip ratio was changed by changing the traction load in loose soil. As in the case of load change, a response was observed in the low frequency range between 0 and 10 Hz, and this response decreased as the slip rate increased. As the slip rate increased, the response increased at a higher frequency between 20 and 50 Hz.




(a) Changing vertical force: $F_z$ (b) Changing srip ratio: $s$

Fig.8 Average value of experiment resurt for each driving




(a) Changing vertical force: $F_z$ (b) Changing srip ratio: $s$

Fig.9 Results of frequency analysis for strains

Therefore, different responses were measured in the low frequency and high frequency ranges by changing the traveling environment and conditions. This result is discussed.

The spectrum in the low frequency range is discussed. The spectrum was larger for loose soil, and the spectrum decreased with increasing slip ratio for loose soil. This phenomenon in the low frequency range is caused by the vibration from the elastic deformation of the legs during traveling. The displacement of the leg increases with the speed because the traveling speed is kept in the state that the slip ratio is small. However, as the slip ratio increases, the traveling speed decreases, and the displacement of the leg per time decreases. Therefore, as the slip ratio increased, the response decreased in the low frequency range. The spectrum in the high frequency range is discussed. The spectrum is large on loose soil, and this spectrum increases with the increase of slip ratio. This phenomenon in the high frequency range is caused by the movement of the particles in contact with the wheels during traveling. As the slip ratio increases, the ground is actively disintegrated by the wheels, and the fine vibrations caused by the ground disintegration are transmitted to the legs.

## 4. Conclusion

In this paper, in order to develop a new system that focuses on human's intrinsic senses to recognize the traveling state of rovers exploring the moon and planets, we verified experimentally the interrelationship between the traveling state and the strain, which is the shape change of the legs.

In the future, the relationship between running state and strain will be verified by traveling experiments using a 4-wheel rover. In addition, a system that recognizes the traveling state from changes in leg strain will be developed.

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