Evaluation of Influence of Surface Shape of Locomotion Mechanism on Traveling Performance of Planetary Rovers

Masataku Sutoh, Kenji Nagaoka, Keiji Nagatani, and Kazuya Yoshida

***Abstract*— The surfaces of both the Moon and Mars are covered with loose soil, with numerous steep slopes along their crater rims. Therefore, one of the most important requirements imposed on planetary rovers is their ability to minimize slippage while climbing steep slopes, i.e., the ability to generate a drawbar pull with only a small amount of slippage. To this end, the wheels/tracks of planetary rovers typically have parallel fins called lugs (i.e., grousers) on their surface. Recent studies have reported that these lugs can substantially improve the traveling performances of planetary rovers. Therefore, in this study, we conducted experiments using lightweight two-wheeled and mono-tracked rovers to provide a quantitative confirmation regarding the influence of lugs on the traveling performances of planetary rovers. Based on our experimental results, we confirmed that, although an increase in the number of lugs contributes to the high traveling performance of wheeled rovers, it does not contribute much to that of tracked rovers. Furthermore, an increase in lug height improves the traveling performances of both types of rovers.**

I. INTRODUCTION

Mobile robots, also called rovers, have played a significant role in NASA's geological investigations of Mars. The use of rovers in these missions has increased the amount of area explored, and has thus increased the scientific return from these missions. However, the lunar and Martian surfaces are covered with loose soil, and numerous steep slopes lie along their crater rims. In such conditions, planetary rovers can get stuck, even to the point of mission failure.

To avoid such problems, many research groups have studied the traveling performance of planetary rovers using terramechanics. Terramechanics is a branch of mechanics that examines the interaction between soil and locomotion mechanisms on loose soil. Terramechanics was systematized by M. G. Bekker in the 1960s [1] and later modified and applied to various types of vehicles by J. Y. Wong [2].

Conventionally, terramechanics has mainly been used to study large vehicles, such as dump trucks. Parallel fins called lugs (i.e., grousers) on the wheels/tracks of large heavy vehicles have little influence on their traveling performance. On the other hand, it has been reported that lugs substantially influence the traveling performance of lightweight vehicles such as planetary rovers [3], [4]. Therefore, it is important to evaluate the effect of lugs on the traveling performance of planetary rovers.

There have been some reports on the influence of lugs on the traveling performance of lightweight wheeled rovers. The influence of lug height, lug spacing, and lug inclination angle on the traveling performance of a wheel was reported by Ding et al. [5]; however, their experiments were conducted using wheels with few different types of lug spacing and contributions to wheel design were limited. Furthermore, a method to estimate the traveling performance of wheels equipped with lugs, which uses the discrete element method (DEM), has also been proposed [6]; however, the researchers have not provided a comprehensive understanding of the influence of lug height or lug spacing.

On the other hand, only a few studies have considered the influence of lugs on the traveling performance of lightweight tracked rovers. While experimental reports regarding the use of lightweight tracked rovers equipped with lugs are available [7], these reports did not evaluate the influence of lugs on their traveling performance.

In this study, the influence of lugs on the traveling performances of lightweight wheeled and tracked rovers are evaluated experimentally using wheels/tracks with different lug heights and different numbers of lugs (i.e., lug spacing). We performed traction tests using both two-wheeled and mono-tracked rovers. In these tests, we measured the slip of wheels/tracks in a sandbox with different traction loads. Furthermore, the experimental results herein are discussed from a theoretical point of view.

In this paper, we introduce the theoretical behavior of lugs on a wheel/track and define the method of evaluating the traveling performance. Finally, the above experiments and discussions are reported in greater detail.

II. THEORETICAL BEHAVIOR OF LUGS ON A WHEEL/TRACK

In this section, the rupture distance developed by lugs is introduced, along with the behavior of the lug on a wheel/track. Furthermore, an increase of thrust through the use of lugs is discussed in terms of the number of lugs and lug height.

A. Rupture distance developed by lugs

When a lug travels horizontally under a wheel/track, the soil in front of the lug is pushed and brought into a state of passive failure (see Fig. 1). For a passive failure, a slip line is sloped to the horizontal at 45°-ϕ/2, where ϕ is the internal friction angle of the soil. Here, the slip line is the intersection between the sliding surface of the soil and the drawing plane. The rupture distance, l_s, which is the horizontal distance of

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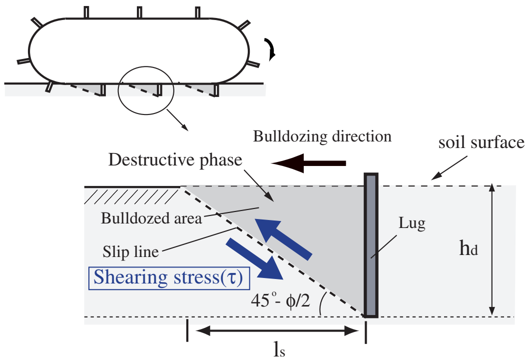
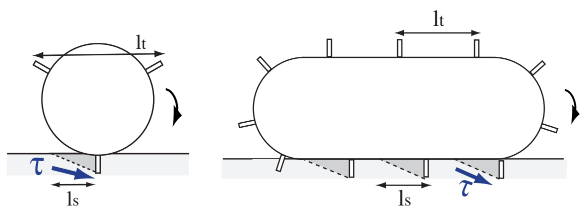


Fig. 1. Estimation model of soil rupture distance by a lug, l_s.



(a) Wheeled rover (b) Tracked rover

Fig. 2. If inter-lug spacing at the tip is larger than rupture distance, slip line does not cross any lug; an increase in the number of lugs contributes to an increase in the thrust of the wheel/track.

the destructive phase of the soil, is derived as [2]

$$l_s = \frac{h_d}{\tan(45° - \phi/2)}, \tag{1}$$

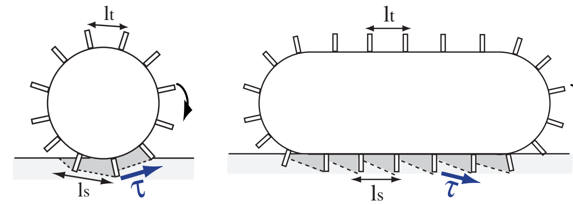
where h_d is the lug height.

B. Thrust developed by lugs

When the soil in front of the lug is brought into a state of passive failure, shearing occurs along the slip line; the wheel/track then obtains thrust from this shearing stress, τ (see Fig. 1). Thus, the length and number of slip lines determines the total thrust developed by lugs.

If the spacing between lugs at the tip, l_t, is larger than the rupture distance, l_s, the slip line does not cross any lugs (see Fig. 2). In this case, the length of slip line is always the same and the number of slip lines increases with an increase in the number of lugs. Hence, we believe that an increase in the number of lugs contributes linearly toward an increase in the thrust of the wheel/track. On the other hand, if l_t is smaller than l_s, a slip line will be drawn between the lugs (see Fig. 3). Therefore, an increase in the number of lugs contributes to a decrease in the length of slip line and increase in the number of slip lines. As the results, we believe that it does not contribute significantly to an increase in the thrust of the wheel/track.

Under a wheel/track, a greater distance from the surface of the ground results in larger normal stress in the soil. Therefore, when a tall lug travels under the wheel/track, normal stress on the shearing surface created by the lug increases, which results in an increase in shearing stress. Furthermore, the length of slip line then becomes longer.



(a) Wheeled rover (b) Tracked rover

Fig. 3. If inter-lug spacing at the tip is smaller than rupture distance, a slip line will be drawn between the lugs; an increase in the number of lugs does not contribute significantly to an increase in the thrust of the wheel/track.

Therefore, we believe that an increase in lug height contributes to an increase in the thrust of the wheel/track.

Based on the above descriptions, we expect that if l_t is larger than l_s, an increase in the number of lugs will improve the thrust of a wheel/track. Furthermore, an increase in lug height also improves the thrust.

III. Method for Evaluation of Traveling Performance

To validate the influence of lugs on the traveling performances of rovers, we define the evaluation method for determining the traveling performance in this section.

For a planetary rover to travel over a slope covered with loose soil, the wheels/tracks of the rover need to generate force in order to pull the weight of the rover, which is called a drawbar pull. A drawbar pull is defined as the difference between the total thrust developed by a rover and the rover's motion resistance. Furthermore, an increase in the slippage of a wheel/track contributes to an increase in the thrust and the motion resistance [2]. Therefore, the amount of slippage has a great influence on the drawbar pull of a wheel/track.

Based on the above description, to evaluate the traveling performance of the wheeled/tracked rovers, we adopted a slip ratio, s, based on the drawbar pull as an indicator, which is defined in [2] as

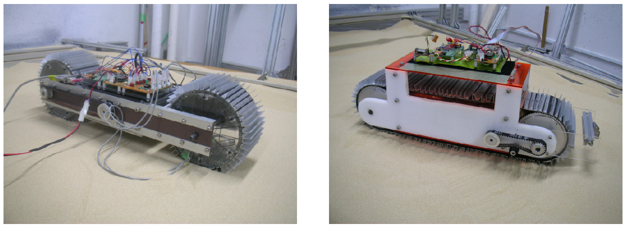
$$s = \frac{r\omega - v_x}{r\omega} = 1 - \frac{v_x}{r\omega} \tag{2}$$

where v_x denotes the linear speed of the rover, r and ω denotes the radius and angular speed of the wheel/track, respectively. The high traveling performance indicates that a wheel/track generates a drawbar pull with only a small slip ratio.

For a track with lugs, the effective diameter of the track is defined by the outside diameter of the track without lugs and the slip ratio is defined using (2). On the other hand, for a wheel with lugs, it is difficult to define the effective diameter of the wheel, or to define the slip ratio using (2). Therefore, the slip ratio of wheels with lugs, s_w, is defined as [8]

$$s_w = \frac{d_d - d}{d_d} = 1 - \frac{d}{d_d} \tag{3}$$

where d denotes the actual traveling distance per wheel rotation, and d_d denotes the traveling distance per wheel rotation on hard ground (i.e., zero slip condition). Here, d_d is



(a) Two-wheeled rover (b) Mono-tracked rover

Fig. 4. Overview of the rovers.

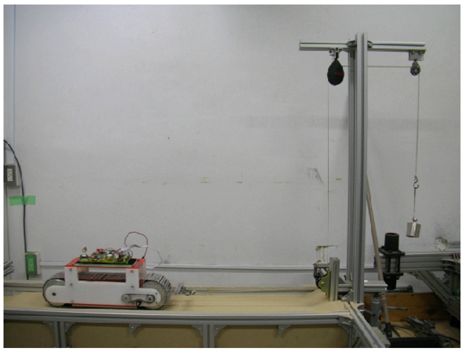


Fig. 5. Traction test: mono-tracked rover moves forward while pulling weight behind it.

geometrically calculated, as previously reported by our group [8].

IV. EXPERIMENTS

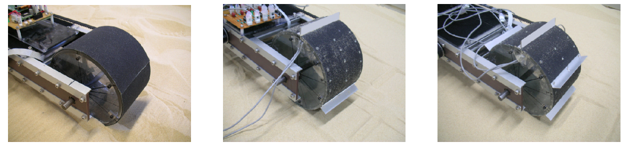
On the basis of the above method, we performed traction tests for two-wheeled and mono-tracked rovers with wheels/tracks with different numbers of lugs of different heights, and evaluated their traveling performance. In this section, the experiments and their results are reported in detail.

A. Two-wheeled and mono-tracked rovers

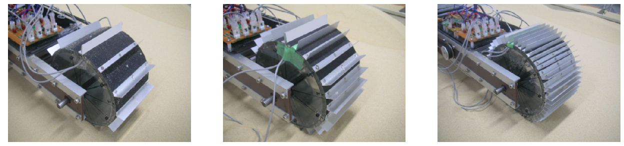
In this study, we developed a two-wheeled rover with a wheel mechanism (see Fig. 4(a)). The distance between the rover's front and rear wheels is 400 mm, and each wheel has a diameter of 150 mm and a width of 100 mm. The rover weight is 4.0 kg.

In addition to the two-wheeled rover, we developed a mono-tracked rover with a track mechanism (see Fig. 4(b)). As a key feature, the designed rover is almost the same size as the two-wheeled rover. The distance between the rover's front and rear sprockets is 400 mm, and the track has an outside diameter and width of 115 mm and 100 mm, respectively. The rover weight is 7.0 kg.

Motion measurement systems with optical sensors and laser sources were mounted onto both rovers in order to measure the actual rover's traveling speed and distance without external devices embedded in the target environment [9]. From the rover's traveling speed/distance, the slip ratio, s, is calculated using (2)/(3).



(a) 0 lugs (b) 3 lugs (c) 6 lugs



(d) 12 lugs (e) 24 lugs (f) 48 lugs

Fig. 6. Wheels equipped with different numbers of lugs (with lug height of 15 mm).

B. Experimental overview and conditions

Traction tests were conducted using both rovers in a sand box. In the traction tests, the rover moved forward while it pulled a weight behind it (see Fig. 5) and the wheel/track of the rover was required to generate the drawbar pull corresponding to the weight. To compare the traveling performances of the wheeled and tracked rovers, which had different weights each other, the traction weights were set based on a ratio of traction weight (F_x) to rover weight (F_z) (i.e., drawbar pull coefficient) [2].

Both rovers, each with twelve types of wheels/tracks, were used during the traction tests. The twelve wheel/track types have two different lug heights, h_d, of 5 mm and 15 mm, and six different numbers of lugs. Fig. 6 shows wheels with different numbers of lugs. The lugs on the tracks are placed at the same spacing as the lugs on the wheels (see Table I). Each lug was made of aluminum, and the rover weight was set to 4.0/7.0kg for different wheel/track types using additional weights.

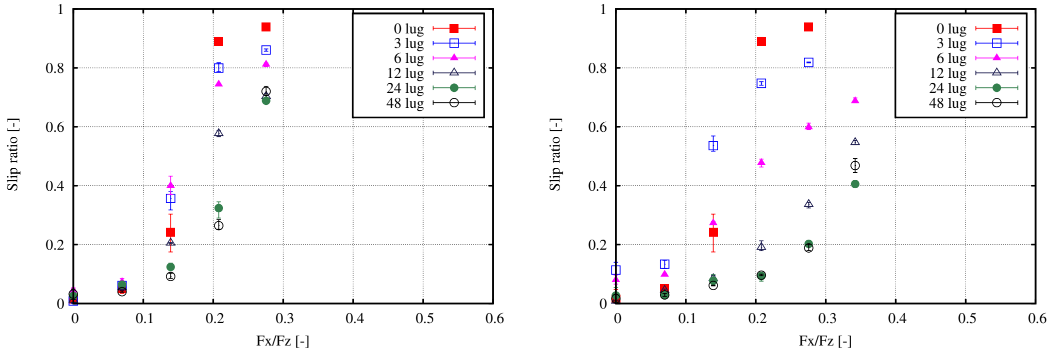
The sandbox has a length, width, and depth of 1.5 m, 0.30 m, and 0.15 m, respectively, and was filled with Toyoura standard sand (JIS R 5200); this sand has very low viscosity, and its particles are almost uniform [10]. The soil rupture distance, l_s, in this sand is listed in Table I. It is determined from lug height, h_d, and from the internal friction angle of Toyoura sand (38°) using (1).

In these experiments, the angular speed of the wheel/track was fixed at 2cm/s, and we measured the slip ratio after the wheels/track stopped sinking. Each trial was conducted under identical soil conditions, and three trials were conducted for each condition.

TABLE I

NUMBER OF LUGS; SPACING BETWEEN LUGS AT THE TIPS, l_t; RUPTURE DISTANCE, l_s.

Number of lugs on a wheel	3	6	12	24	48
Number of lugs on a track	7	14	28	56	112
l_t (mm) (h_d=5 mm)	138.6	80.0	41.4	20.9	10.5
l_t (mm) (h_d=15 mm)	155.9	90.0	46.6	23.5	11.8
l_s (mm) (h_d=5 mm)	10.3				
l_s (mm) (h_d=15 mm)	30.8				



(a) Wheels with 5-mm height lugs (b) Wheels with 15-mm height lugs

Fig. 7. Drawbar pull coefficient (F_x/F_z) vs. slip ratio (two-wheeled rover).

C. Influence of number of lugs on traveling performance of wheeled rover

To evaluate the influence of the number of lugs on the traveling performance of the wheeled rover, we plotted the data for cases with a fixed lug height (see Fig. 7).

When the drawbar pull efficient is larger than 0.2 for wheels with lugs 5-mm in height, the slip ratio for the given drawbar pull coefficient decreases with an increase in the number of lugs (see Fig. 7 (a)). That is, the wheels with large numbers of lugs generated the required drawbar pull with a smaller amount of slippage. This implies that the traveling performance improves with an increase in the number of lugs. Fig. 7 (b) shows that for wheels with lugs 15-mm in height, the traveling performance increases as the number of lugs increases from 3 to 24. On the other hand, wheels with 24 and 48 lugs show slight differences in the slip ratio values for different numbers of lugs. That is, an increase in the number of lugs no longer contributes to improving the traveling performance.

In the case of a wheel with lugs 5-mm in height, the spacing between lugs at the tip, l_t, is always larger than the rupture distance, l_s (see Table I). Meanwhile, for wheels with lugs 15-mm in height, wheels with 3, 6, and 12 lugs have l_t that is larger than l_s, while wheels with 24 and 48 lugs have l_t that is smaller than l_s (see Table I). Based on this, the above experimental trends indicates that if the spacing between the lugs at the tip, l_t, is larger than the rupture distance, l_s, an increase in the number of lugs improve a traveling performance over a large drawbar pull coefficient; this corresponds to the discussion presented in section 2. Furthermore, when equipped with lugs whose spacing is at least smaller than l_s, the wheeled rover will have a high traveling performance.

For wheels with lugs 5- and 15-mm in height, when the drawbar pull coefficient is less than 0.2, a wheel without lugs has a smaller slip ratio over a given drawbar pull coefficient than wheels with 3 and 6 lugs. This means that an increase in the number of lugs does not improve a traveling performance.

In the above-mentioned case, where the number of lugs and the given traction weight are small, the wheel obtains its thrust mainly from shearing stress between the wheel surface and soil. However, the lugs dig into the soil beneath the wheel, which increases the wheel sinkage and the motion resistance of the wheel. This decreases the drawbar pull obtained from the surface of the wheel. This is why we observed an increase in the number of lugs decreased a traveling performance.

D. Influence of number of lugs on traveling performances of tracked rover

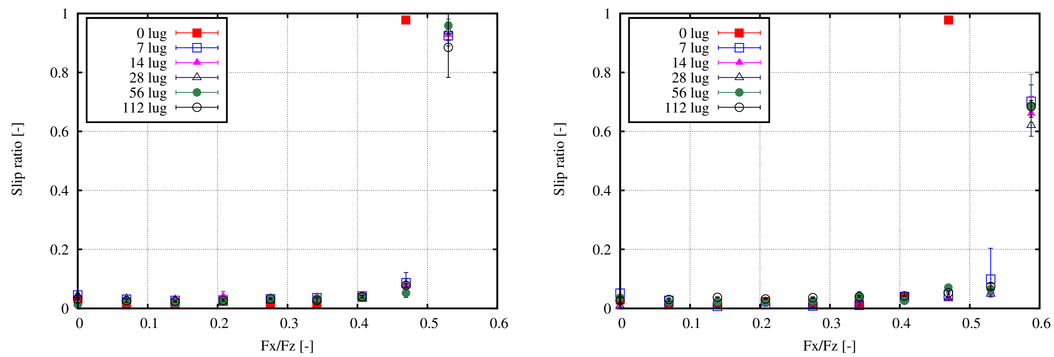
To evaluate the influence of the number of lugs on the traveling performance of the tracked rover, we plotted the data for cases with a fixed lug height (see Fig. 8). According to the figure, the tracked rover had a smaller slip ratio over a given drawbar pull coefficient compared to the wheeled rover. That is, the tracked rover has a higher traveling performance than the wheeled rover. This is because the contact area of a track is much larger than that of a wheel.

According to Fig. 8, tracks with lugs have a smaller slip ratio over a given drawbar pull coefficient compared to a track without lug, i.e., tracks with lugs can pull heavier traction weights. This means that equipping lugs on the surface of a track contributes to a high traveling performance.

For tracked rover, tracks with lugs have almost the same value of slip ratios for different numbers of lugs (see Fig. 8). That is, even when the spacing between the lugs at the tips is larger than the rupture distance, an increase in the number of lugs does not improve a traveling performance.

Fig. 8 shows that the slip ratio rapidly increases at a certain drawbar pull coefficient. According to this, it was determined that the track of a lightweight rover cannot generate a drawbar pull when slippage occurs. In other words, the range of drawbar pull that the track can generate during slippage is very small.

In these experiments, the lightweight tracked rover had a high traveling performance even without lugs, and showed a very small range within which it can generate a drawbar pull when slippage occurs. Therefore, even if an increase in the number of lugs contributes to an increase in the drawbar pull, the track does not move forward at all if the drawbar pull is smaller than the given traction load. For this reason, we were unable to observe any improvement of the traveling performance from an increase in the number of lugs.



(a) Tracks with 5-mm height lugs (b) Tracks with 15-mm height lugs

Fig. 8. Drawbar pull coefficient (F_x/F_z) vs. slip ratio (mono-tracked rover).

E. Influence of lug height on traveling performance of wheeled and tracked rovers

To evaluate the influence of lug heights on the traveling performances of wheeled and tracked rovers, we plotted the data for different cases with a fixed number of lugs, as shown in Fig. 9.

Figs. 9 (a) and (b) show the slip ratios and drawbar pull coefficients for wheels with 3 and 6 lugs, respectively. When the drawbar pull coefficient is less than 0.2, a wheel without lugs has a smaller slip ratio over a given drawbar pull coefficient than wheels with lugs 5- and 15-mm in height. This means that an increase in lug height does not improve a traveling performance. This is the same reason why, for wheels with a small number of lugs, an increase in the number of lugs does not improve a traveling performance, as presented in the previous subsection.

Figs. 9(c), (d), and (e) show the slip ratios for wheels with 12, 24, and 48 lugs. It can be seen that wheels with lugs 15-mm in height had smaller slip ratios over all drawbar pull coefficients. Therefore, tall lugs contribute to a high traveling performance.

Fig. 9 (f) shows the slip ratios for a track with 28 lugs. According to the figure, it was found that the track with lugs 15-mm in height had smaller slip ratios over the given drawbar pull coefficient. Therefore, tall lugs contribute to a high traveling performance.

Based on the above discussion, we concluded that for a wheeled rover, an increase in lug height contributes to a high traveling performance over a large drawbar pull coefficient. On the other hand, for a tracked rover, an increase in lug height consistently contributes to a high traveling performance.

V. Discussion on Number of Lugs and Lug Height for Planetary Rovers

Planetary rovers are required to travel over steep slopes along crater rims. Therefore, we believe that the ability for rovers to minimize slippage while climbing over steep slopes, i.e., the ability to generate a large drawbar pull with only a small amount of slippage, is important. In this section, we discuss the guidelines for designing rover locomotion mechanisms based on the above requirement.

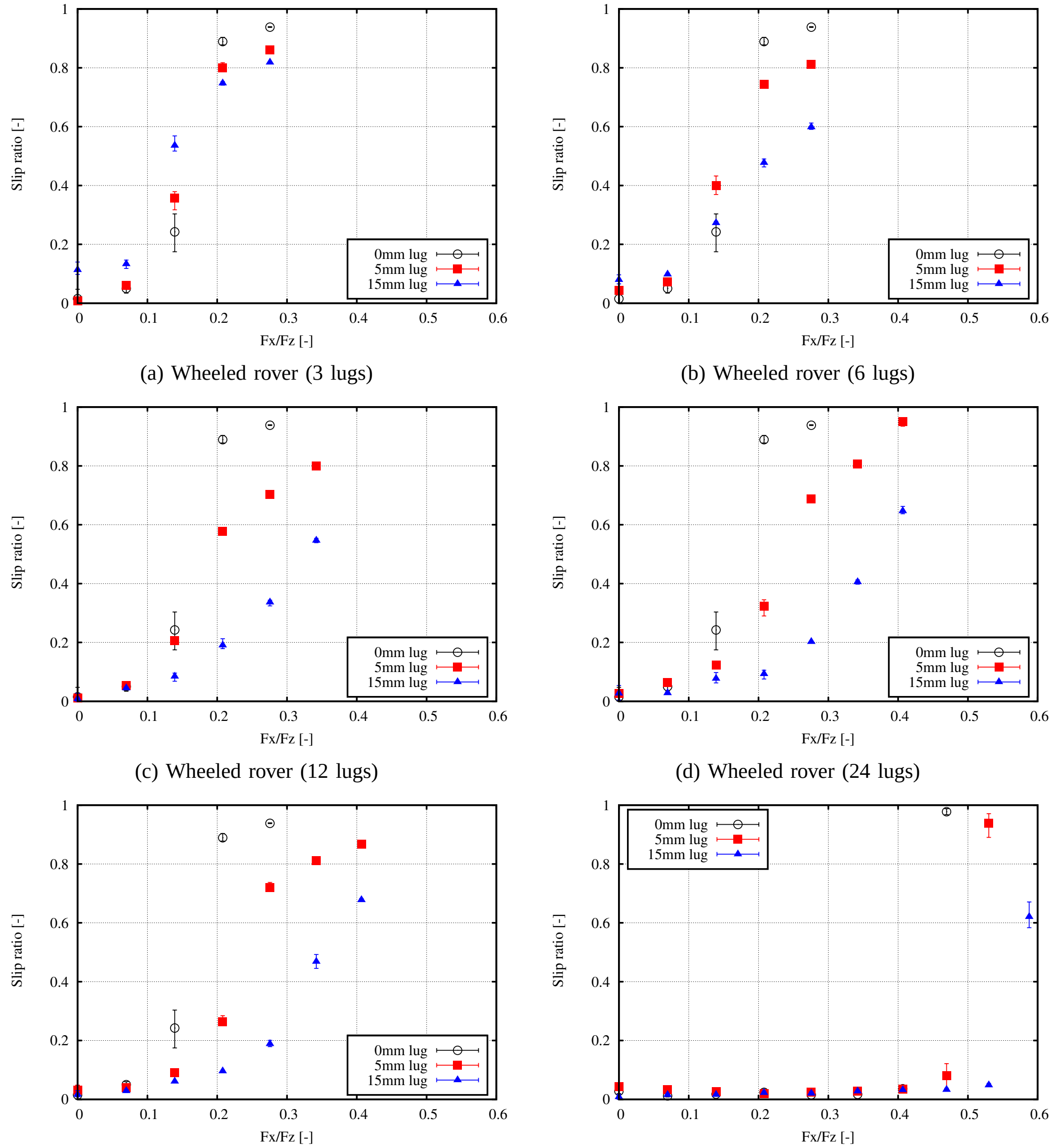
According to the experimental results, for wheeled rovers, when a wheel is required to generate a large drawbar pull, wheels equipped with lugs whose spacing at the tip is at least smaller than the rupture distance will have a high traveling performance. Thus, at the design stage of wheeled rovers, it is important to equip the wheel's surface with lugs, and the spacing between the lugs at the tip should be smaller than the rupture distance.

For tracked rovers, on the other hand, while equipping lugs on the surface of the track also contributes to a high traveling performance, an increase in the number of lugs does not have much effect. Therefore, at the design stage of tracked rovers, it is also important to equip the track surface with lugs; however, it is not necessary to consider the number of lugs in detail.

For both wheeled and tracked rovers, when the wheel/track needs to generate a large drawbar pull, taller lugs improve a traveling performance. Therefore, at the design stage of planetary rovers, it is important to equip the wheel/track surface with tall lugs. If the lug height is increased, however, the lugs only contact with the ground at certain points, which may even decrease a traveling performance. In this regard, further studies on the influence of lug height will be necessary.

VI. Conclusions

In this study, we performed traction tests using two-wheeled and mono-tracked rovers with wheels/tracks equipped with different numbers of lugs of varying height. We also evaluated the influence of lugs on the traveling performance of both types of rovers. For the wheeled rover, we found that as long as the spacing between the lugs at the tip is greater than the rupture distance, an increase in the number of lugs generally improves the traveling performance. For the tracked rover, however, an increase in the number of lugs does not improve a traveling performance. Finally, an increase in lug height generally increases a traveling performance in both rover types. At the design stage of planetary rovers, we concluded that it is important to equip



(a) Wheeled rover (3 lugs)

(b) Wheeled rover (6 lugs)

(c) Wheeled rover (12 lugs)

(d) Wheeled rover (24 lugs)

(e) Wheeled rover (48 lugs)

(f) Tracked rover (28 lug)

Fig. 9. Drawbar pull coefficient (F_x/F_z) vs. slip ratio (fixed number of lugs).

wheel surfaces with lugs, and that the spacing between lugs at the tip should at least be smaller than the rupture distance. It is also important to equip the track's surface with lugs; however, in this case, the spacing is not important.

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