

Comparison between traveling performances of track and wheel mechanisms on weak soil

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Abstract : Generally, track mechanisms have a higher traveling performance on weak soils than wheel mechanisms, which have been used for traditional planetary rovers. However, there have not been enough performance tests on the quantitative differences between the mechanisms, particularly for small-sized rovers. In this study, we conducted some performance tests of a single track and four serial wheels, and we present a comparison of their performances for small-sized rovers on the basis of our empirical data.

クローラ機構と車輪機構の軟弱地盤における走行性能比較

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概要 : クローラ機構は従来の惑星探査ローバーに使用されてきた車輪機構に比べ、接地面積が大きいことから軟弱地盤に対する走破性は高いといわれている。しかしながら、両機構の走破性にどの程度差があるのかについて議論を行うためには、定量的な計測が不足していると考えられる。そこで、本研究では軟弱地盤において両機構の走行性能実験を行い、定量的な比較を行うことを目的とした。本稿では、現在までに行ってきた研究成果を報告する。

1 Introduction

In recent times, space agencies of various countries are considering explorations of the moon or mars, not only for the purpose of scientific discovery but also practical benefit. In particular, research methods for studying the soil structures and resource surveys are being actively discussed for the construction of lunar bases or lunar astronomical observatories.

The Japan Aerospace Exploration Agency (JAXA) launched an unmanned lunar orbiter “Kaguya” as part of the Selenological and Engineering Explorer (SELENE) project for analysis of the moon surface through remote sensing. For the next SELENE project, JAXA plans to launch an unmanned lunar lander that can be mounted on a lunar surface rover to survey lunar surfaces. In this project, JAXA is considering adoption of track mechanisms for locomotion of the target rover (Fig. 1(a)) instead of the wheel mechanism (as used in the Mars Exploration Rover, shown in Fig. 1(b)). Generally, the track mechanism has the advantage of being able to traverse on loose soils without getting stuck in weak soil, because the contact area of the track is much wider than that of the wheel. However, typical track mechanisms are usually complicated and heavy in comparison with wheel mechanisms, which is a disadvantage for planetary exploration rovers. If a wheel mechanism is acceptable to a mission, we believe that the wheel mechanism

had better to be used to assure the durability and to reduce a weight of the payload. Therefore, a quantitative comparison of traversability of wheel and track mechanisms is very important.

There are some previous studies on traversability comparisons between track and wheel mechanisms (e.g.,[3]) based on terramechanics [4]. However, many of these studies consider heavier mechanisms (such as tracks for a battle tank). In our previous study, we found that the normal stress distribution under a light robot wheel was different from that of a heavy one [5]. This implies that a comparison of light-weight mechanisms maynot be equivalent to a scaling down of the results of a comparison of heavier mechanisms. However, there are insufficient data on traveling performance in the case of mechanisms with a weight comparable to that of a planetary rover, such as less than 50 kg class.

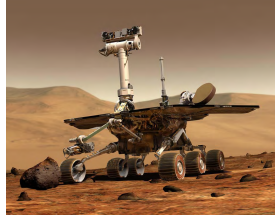
Owing to the aforementioned lack of research, in this study, we aim to compare track and wheel mechanisms quantitatively for light-weight rovers (less than 50 kg class) traveling on actual soils.

2 Evaluation method of traversability

To evaluate a light track mechanism, we developed a single-track testbed (called “mono-track” in this article), shown Fig. 3(a). The weight of this testbed was 6 kg, and traversal tests in the weight range from 6 to



(a) JAXA's tracked vehicle



(b) Mars Exploration Rover

Figure 1: Wheeled and tracked vehicles

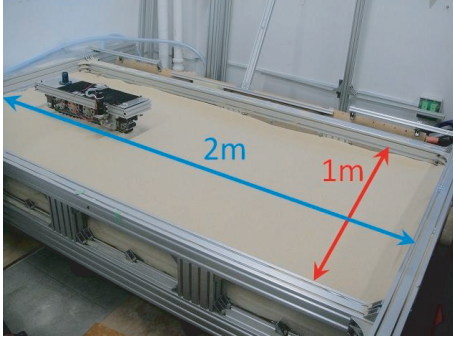


Figure 2: Toyoura sand field

18 kg by the addition of weights were performed on this testbed. The test field of the mono-track was a sand pool in our laboratory filled with Toyoura standard silica sand, shown in Fig. 2.

The experiments employed two methods. One was the slope traversability, conducted to obtain the relationship between the slip ratio and the slope angle. The other was a traversability test on a flat surface with various traction loads to obtain the relationship between the slip ratio and the drawbar pull.

In both methods, the slip ratio s was calculated using the actual body speed v obtained by TMMS (Telecentric Motion Measurement System, developed in our laboratory; [5]) and the circumferential velocity of the target track v_d . The equation for derivation of the slip ratio is

$$s = \frac{v_d - v}{v_d} \quad (1)$$

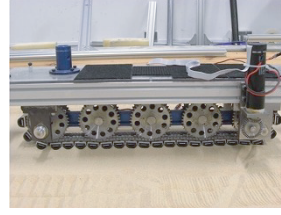
To evaluate a light-weight wheel mechanism, we developed an inline four-wheel testbed (shown in Fig. 3(b)) that was the same size as the mono-track. The conditions of these tests were the same as those of the mono-track experiments.

The aforementioned experiments are reported in the following sections.

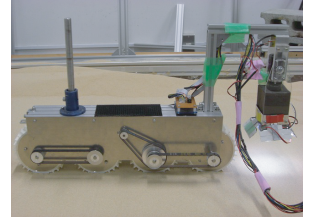
3 Performance tests of mono-track

3.1 Slope traversability tests

Generally, the slope traversability (How large a slope angle can a mobile robot climb up?) is one of the important indices of mobile robots. Our test field can be tilted up to 15 deg. Therefore, we conducted



(a) Mono-track testbed



(b) Four-wheel testbed

Figure 3: Overviews of each testbed

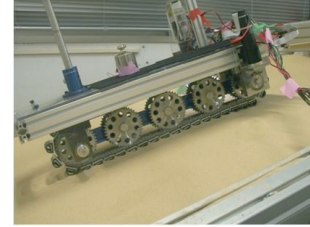


Figure 4: Slope traversability tests for mono-track

performance tests with various tilt angles of the field to obtain a relationship between the slip ratios and the slope angles. Fig. 4 shows an experimental setup. The conditions of the tests were as follows:

1. mono-track weight F_z : 8.8, 11.8, 14.8, 17.8 kg
2. circumferential velocity of track v_d : 2cm/s
3. slope angle θ : 0, 5, 10, 15 deg

In each condition, three trial runs were conducted, and the average values plotted were as shown in Fig. 5. From Fig. 5, it can be concluded that these slope traversability tests are not suitable to study track phenomena in high-slip-ratio regions. However, our test field cannot be tilted over 15 deg for reasons of safety. Therefore, we conducted traversability tests on a flat surface with various traction loads, as described in the following subsections.

3.2 Traversability tests on flat surface

In these traversability tests, we changed the traction loads of the mono-track on flat ground instead of changing the slope angle. In this case, the traction loads were equal to the drawbar pull F_x . The upper figure in Fig. 6 shows the slope traversability test, and the lower figure shows the traversability test on a flat surface with traction loads.

As can be seen in Fig. 6, F_z decreases as the slope angle θ increases in the slope traversability tests. However, F_z is always constant in the case of traversability tests on a flat surface with traction loads. Therefore, we assume that virtual slope angle can be obtained by the following equation:

$$\theta = \tan^{-1} \frac{F_x}{F_z} \quad (2)$$

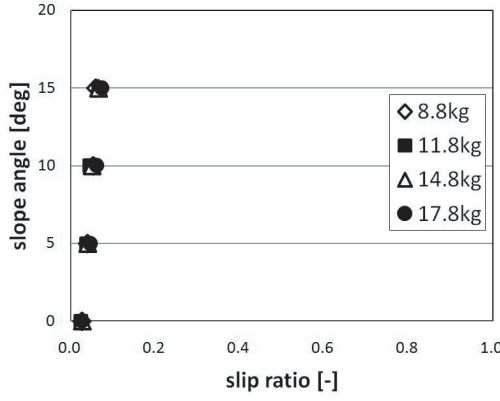


Figure 5: Obtained relationship between the slip ratio and the slope angle in slope traversability tests of mono-track

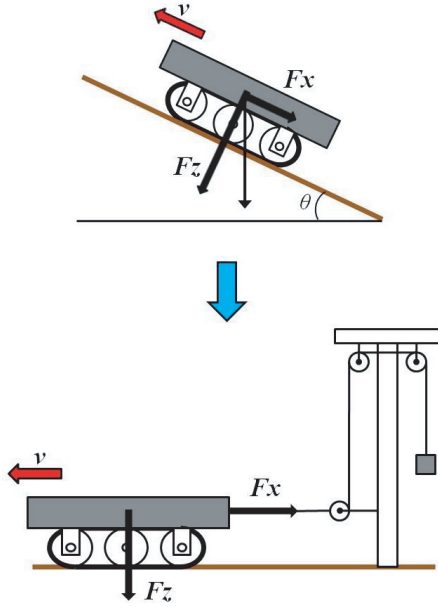


Figure 6: Basic concept of traction test

It should be noted that virtual weight of the mono-track increases as the traction load increases, because $mg = \sqrt{F_x^2 + F_z^2}$.

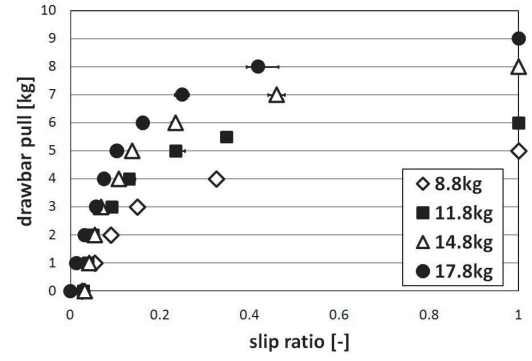
We conducted performance tests in three categories on a flat surface with various traction loads to obtain the relationship between the slip ratios and virtual slope angles in equation (2).

1. Variable parameter is body weight

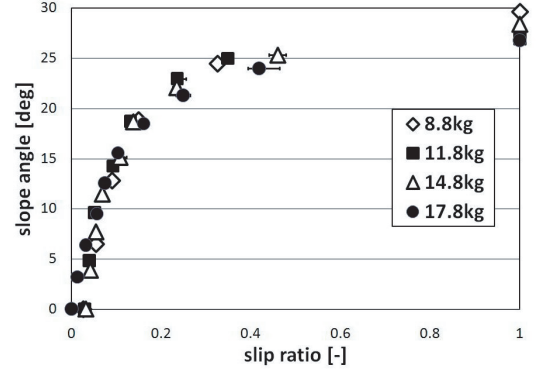
The first test category included various weights and various traction loads. The conditions of the tests were as follows:

1. circumferential velocity of track v_d : 2cm/s
2. mono-track weight F_z : 8.8, 11.8, 14.8, 17.8 kg
3. traction load F_x : 0.0, 1.0, 2.0, 3.0, 4.0, 5.0, 5.5, 6.0, 7.0, 8.0, 9.0 kg

In each condition, three trial runs were conducted, and the average values were obtained. When the mono-



(a) Relationship between the slip ratio and the drawbar pull



(b) Relationship between the slip ratio and the virtual slope angle

Figure 7: Trial run results of mono-track in the case that parameters are body weight and traction load

track did not move, we terminated increasing traction loads in the weight condition of mono-track.

Fig. 7(a) shows the relationship between the slip ratio and the drawbar pull. It derives a very common conclusion that, for the same slip ratio, a larger drawbar pull can be generated by increasing the weight of the mono-track.

Fig. 7(b) shows the relationship between the slip ratio and virtual slope angle. The virtual slope angles were calculated using equation (2). As discussed in Fig. 6, the virtual weights of the testbed were changed according to the slope angles. However, all points were almost on the same curve. Therefore, a small weight difference, such as roughly ± 3 kg, does not affect to the slope climbing ability of tracked mechanisms.

2. Variable parameter is circumferential velocity

The second test category included the comparison of different circumferential velocities. The conditions of the tests were as follows:

1. circumferential velocity v_d : 2 cm/s and 4 cm/s
2. mono-track weight F_z : 11.8 kg
3. traction load F_x : 0.0, 1.0, 2.0, 3.0, 4.0, 5.0 kg

In each condition, three trial runs were conducted. Fig. 8 shows the relationship between the slip ratio and the virtual slope angle. In this graph, we can see that the results in two conditions are very similar for

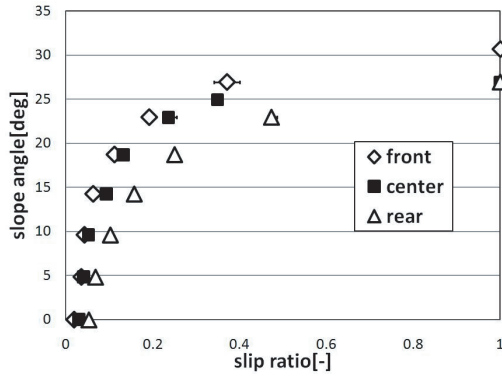


Figure 8: Trial run results of mono-track in the case that parameter is circumferential velocity

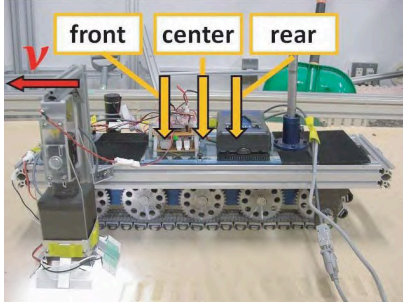


Figure 9: Position of the center of gravity (C.O.G.)

different circumferential velocities. Therefore, we can conclude that the traversability of the track mechanism is independent of its velocity, a conclusion arrived at with conventional theories, such as in Reference [4].

3. Variable parameter is a position of the center of gravity

The third test category included the comparison with different positions of the center of gravity. the conditions of the tests were as follows:

1. circumferential velocity v_d : 2 cm/s
2. mono-track weight F_z : 11.8 kg
3. traction load F_x : 0.0, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0 kg
4. position of the center of gravity (C.O.G.): see Fig. 9

In each condition, three trial runs were conducted, and the average values were plotted as shown in Fig. 10. We can see that there is a large difference in the results for the three positions of the C.O.G. In particular, when the C.O.G. was offset to the rear position, the traversability drastically decreased. This is because, in the case of a rear C.O.G. position, the sinkage of the track in the rear increases and the contact area decreases because of the mono-track's inclination. It derives a losing of traversability on slopes. A snapshot of this situation is shown in the Fig. 11. We conclude

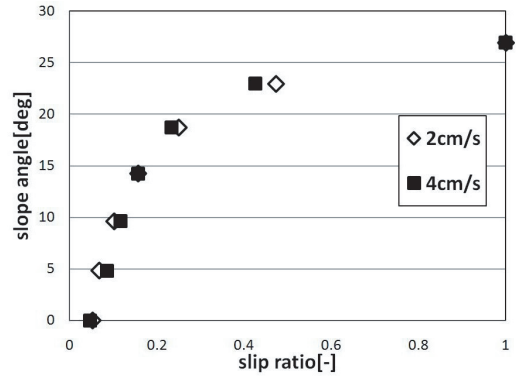


Figure 10: Trial run results of mono-track in the case that parameter is C.O.G.'s position

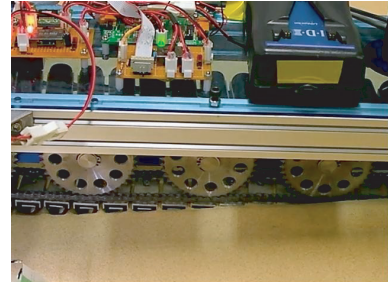


Figure 11: Difference of sinkage between back and forth

that the position of the C.O.G. greatly affects the performance of the track mechanism.

4 Performance tests of inline four-wheel testbed

To compare performance tracks and wheels, we developed an inline four-wheel testbed and conducted the traversability performance tests. A feature of the testbed is that it is almost the same size as the mono-track. Fig. 3 shows an overview of our two testbeds. The wheel width of the testbed is the same as the width of the mono-track. The length between the center of the first wheel and the center of the last wheel is the same as the interval of the sprocket of the mono-track. The radius of the wheel is the same as the sprocket radius plus twice the thickness of the track.

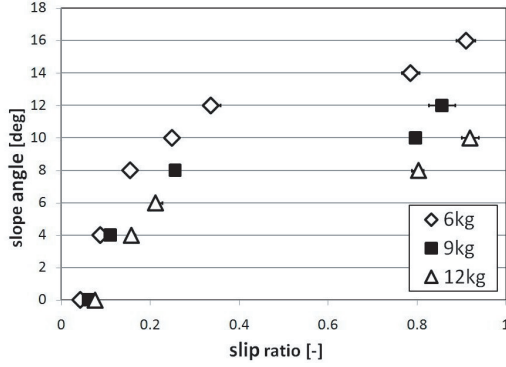
Using the aforementioned wheel mechanism, we conducted slope traversability tests with almost the same conditions as the mono-track tests. The conditions of the tests were as follows:

1. circumferential velocity v_d : 2 cm/s
2. mono-track weight F_z : 6.0, 9.0, 12.0 kg
3. slope angle θ : 0.0, 4.0, 6.0, 8.0, 10.0, 12.0, 14.0, 16.0 deg

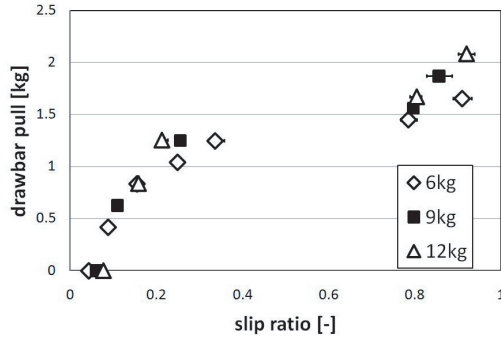
Fig. 12 shows one of the experimental setups of the performance tests. In each condition, three trial runs were conducted, and the average values were plotted



Figure 12: Slope test for inline four-wheel testbed



(a) Relationship between the slip ratio and the slope angle



(b) Relationship between the slip ratio and the drawbar pull

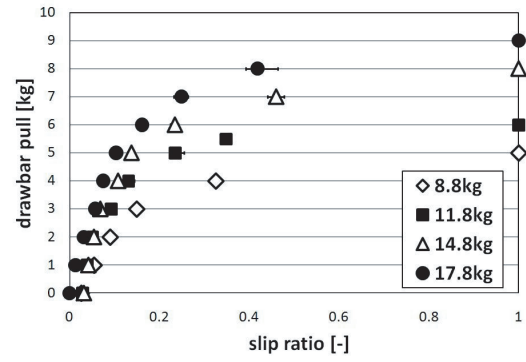
Figure 13: Experimental result of slope test for wheel mechanism

as shown in Fig. 13. Fig. 13(a) shows the relationship between the slip ratio and the slope angle. It derives a common conclusion that the slope traversability decreases with increasing weight of the robot body. Fig. 13(b) shows the relationship between the slip ratio and the drawbar pull. The result derives that increasing weight does not improve drawbar pull, because the heavier weight increases the pulling force but the wheels are sunk deeper, thus decreasing the pulling force.

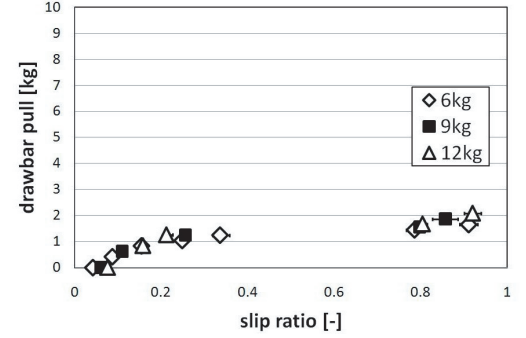
5 Comparison between track and wheel mechanisms

In this section, we compare track and wheel mechanisms from the point of view of traversability.

Fig. 14 shows a comparison of drawbar pull of the mono-track and the four-wheel testbed. Per the



(a) Track mechanism



(b) Wheel mechanism

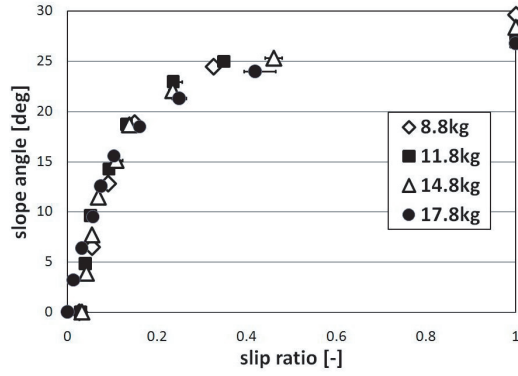
Figure 14: Comparison between the slip ratio and the drawbar pull

graph, the track generates a larger drawbar pull while body weight increases. However, the wheel testbed does not increase its drawbar pull even though its body weight increases. Thus, body weight contributes to increasing drawbar pull for a track mechanism, but does not for a wheel mechanism.

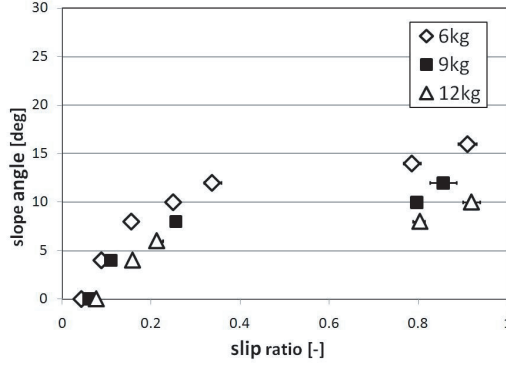
Fig. 15 shows a comparison of the maximum traversable slope angle between the mono-track and the four-wheel testbed. Per the graph, the maximum traversable slope angle becomes smaller while body weight increases for a wheel mechanism, but does not for a track mechanism. Thus, body weight does not affect the traversability of a light-weight tracked vehicle.

Fig. 15 points to a natural fact that the track has a large advantage in case of a heavier body. However, in the case that the sinkage of the wheel is small enough, traversability of a wheel mechanism is close to that of a track mechanism, which is shown in Fig. 15. Therefore, the extent to which the sinkage of the mechanisms affects traversability is important.

Typically, the bottom of the track mechanisms is contacted to the ground horizontally, as shown in Fig. 16(a). Therefore, for any sinkage level of the track, the efficiency of the drawbar pull is very good because the shear stress of the track effects in the traveling direction. On the other hand, as the sinkage of the wheel increases, the shear stress distribution of wheel



(a) Track mechanism



(b) Wheel mechanism

Figure 15: Comparison between the slip ratio and the slope angle

mechanisms moves forward, as shown in Fig. 16(b). This reduces the efficiency of the drawbar pull. Furthermore, the direction of the normal stress of the wheel becomes opposite to the traveling direction as the sinkage of the wheel increases; therefore, it gives rise to travel resistance. As typical examples, Fig. 17 (weight = 9 kg, slope angle = 10°) shows that the slip ratio of the track is 0.054 and the slip ratio of the wheel is 0.774.

On the basis of the aforementioned description, we conclude that “sinkage” is a key factor for traversability of locomotion mechanisms on weak soils. It derives that, once the sinkage of the wheel is small enough, wheel mechanisms may have an enough capability to traverse on rough and weak soil. Use of large wheels for wide distribution of contact pressure is a feasible idea, but it requires quantitative experiments to determine the relationship between the size of wheels and the drawbar pull.

6 Conclusion

In this paper, we reported traversability comparison experiments for track mechanism and wheel mechanisms on weak soil. In the results of the experiments, we found that the performance of the track mechanism is very high in comparison with the wheel mechanism in the same size and weight category. On the basis of results, we discussed performance of traversability

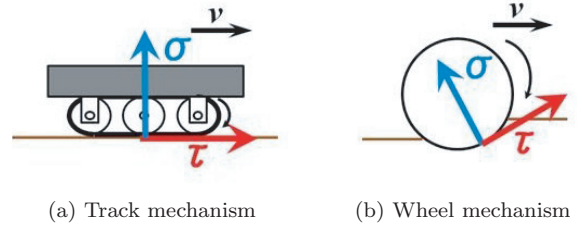


Figure 16: Comparison of efficiency for force generation

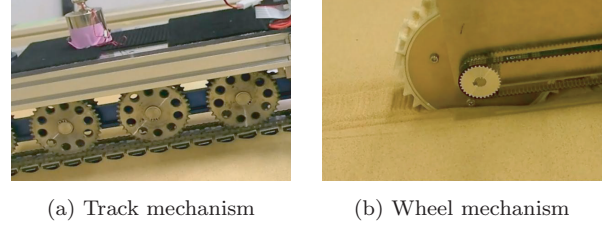


Figure 17: Comparison of sinkage of track and wheel mechanisms

in both mechanisms. In this discussion, we conclude that “sinkage” is a key factor for traversability of locomotion mechanisms on weak soils. In our future work, we plan to conduct quantitative experiments on wheels to measure drawbar pull in wheels of different radii and widths, and determine the extent to which such parameters affect the traversability of wheels.

References

- [1] G. Ishigami, A. Miwa, K. Nagatani and K. Yoshida; “Terramechanics -Based Model for Steering Maneuver of Planetary Exploration Rovers on Loose Soil,” *J. of Field Robotics*, vol. 24, issue 3, pp. 233 - 250, 2007.
- [2] Wakabayashi S et al.; “Design and mobility evaluation of tracked lunar vehicle,” *J Terramechanics*(2008),doi:10.1016/j.jterra.2008.09.002
- [3] J.Y.Wong,Wei Huang;“ “Wheel vs. tracks” - A fundamental evaluation from the traction perspective,” *Journal of Terramechanics* 43(2006)27-42
- [4] J. Y. Wong; *Theory of Ground Vehicles*, John Wiley & Sons, 1978.
- [5] K.Nagatani, A.Ikeda, K.Sato and K.Yoshida : “Accurate Estimation of Drawbar Pull of Wheeled Mobile Robots Traversing Sandy Terrain Using Build-in Force Sensor Array Wheel,” *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp.2373-2378