Development and Evaluation of Novel Pulley Suspension Mechanism for Lunar or Planetary Exploration Rover

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Abstract

As an in-situ exploration way, landers and rovers are well used in lunar or planetary explorations. In lunar or planetary exploration missions, it is important to save the weight of spacecraft. Then, the authors go ahead with uniting landers and rovers. In other words, the landing device and the suspension mechanism should be commonalized. As a new mechanism for lander-rover-unite system, a novel pulley suspension mechanism is proposed. This mechanism is theoretically able to equalize the normal forces applied to wheels. The authors calls the proposed mechanism as Load Equalization Pulley Suspension mechanism (LEPS mechanism). In this paper, the detail of the design of LEPS mechanism is described and the mobility of LEPS mechanism is evaluated by way of experiments. The experiments are conducted both on a artificial ground and on a natural volcanic rudaceous terrain in Izu-oshima-island in Japan.

1 Introduction

A lot of landers set their feet on the lunar or planetary surfaces and many rovers traversed surfaces of them. They achieved lots of results, and a lot of new spacecraft are designed all over the world. However, the weight reduction of the spacecraft have room for improvement. For example, the mission payload of Japanese lunar lander "SELENE-2" is 300[kg], which is one-eighteenth of the total weight. The weight of the rover is 100[kg] out of the payload weight 300[kg][1]. As a way of weight reduction, integration of landers and rovers is considered by authors. If landers and rovers are integrated and the total weight is reduced, it will have advantage in cost. It leads increase of carrying capacity for payloads. As a suspension mechanism of rovers, Rocker-Bogie mechanism is well known six wheeled suspension. However, Rocker-Bogie mechanism sometimes got stuck on a weak terrain of Mars[2] and it is not suitable for landing device. Although Mars Science Laboratory landed on Mars with Rocker-Bogie suspension, MSL was assisted by Sky Crane system[3]. Then, a novel suspension mechanism is required in order to land on lunar or planetary surfaces and traverse on the surfaces of celestial bodies safely.

The authors propose a novel pulley suspension mechanism for landers and rovers. The proposed mechanism is called Load Equalization Pulley Suspension mechanism or LEPS mechanism. LEPS mechanism can equalize the forces applied to all the legs or wheels. This mechanism has two functions. The first function is landing gear of landers. Landers have to have robustness to the slope angle of the terrain, initial attitude angle of the lander and initial horizontal velocity of the lander[4] because it is difficult to control them in decent phase. Since lunar or planetary surfaces are not flat, one or two leg(s) of the general lander will touch before the others. Then, reaction force from the ground to the leg(s) generate(s) overturning moment. However, if LEPS mechanism is attached to the lander, the reaction force is transferred to the other legs and they are extended. Therefore, all the legs may touch the ground virtually almost at the same time. That is to say, LEPS mechanism has tip-resistant ability. By using LEPS mechanism as landing device, the robustness of landers will be improved. The second function is suspension mechanism of rovers. If normal forces applied to all the wheels are equalized, the rover will be hardly stuck on terrains and get high mobility. Rocker-bogie mechanism is designed in view of the load equalization, not all the wheels are equalized. Additionally, Rocker-bogie mechanism needs six wheels, but LEPS mechanism needs only four wheels (or more). Then, the lander-rover united spacecraft needs only four legs(wheels). Past landers which have 3 - 4 landing gears such as Surveyor, Phoenix and Chang'e 3 succeeded in landing[5, 6, 7]. By using LEPS mechanism, the spacecraft can follow these proven 4 legs style. Moreover, the reduction of the number of wheels means weight saving , low failure potential, and relaxation of the limit of wheel diameter. Large wheels have high mobility. By using this mechanism as landing device and suspension, tip-resistant feature of landers and mobility of rovers are united. Then a lander and a rover may be integrated and

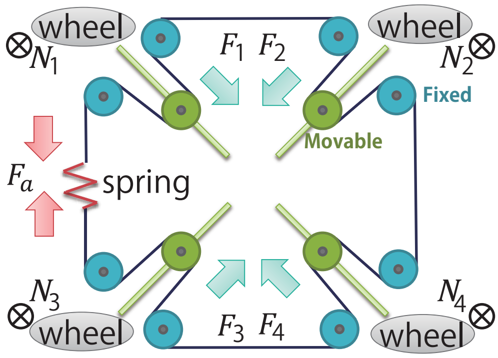
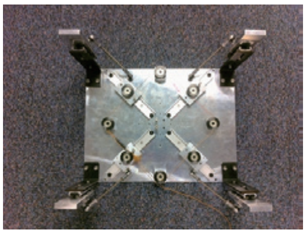
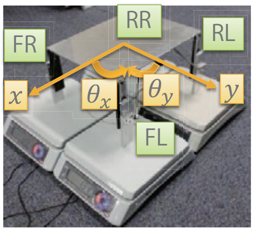


Figure 1. Conceptual diagram of LEPS mechanism



(a) Back side



(b) Coordinate system

Figure 2. Small test model

this will lead the weight saving.

In this paper, suspension function of LEPS mechanism for rovers is mainly discussed as a part of functions. First, improvement of LEPS mechanism is reported in light of some results from the preliminary experiments of static performance. After that, quasi-static performance is evaluated from experiments.

2 Load Equalization Pulley Suspension Mechanism

2.1 Principle of LEPS mechanism

The conceptual diagram of LEPS Mechanism with four wheels is shown in Fig. 1. Basic load equalizer is applied to suspension mechanism. The proposed suspension mechanism consists of fixed pulleys, movable pulleys, a spring and a wire. The wheels are connected to the movable pulleys by the link mechanism with each other. The proposed suspension can equalize all forces which are applied to each movable pulley and is extendable to any number of wheels. Since the reduction of the number of wheels leads to low-cost operation or we can use large diameter wheels, four-wheel system is selected in this paper. The basic principle of the proposed mechanism is

Table 1. Specifications of the small test model

Item	Value
Size	400×300×260 [mm]
Mass	5.2 [kg]
Stroke	80 [mm]
Spring Constant	3.43 [N/mm]
Deviation	No wheel, Leg only

Table 2. Conditions of preliminary experiment

Item	Condition
Suspension	Use / Disuse
Weight position (4 [kg])	Disuse / Center / Front
Step (60 [mm])	FR& FL / FR

expressed by simple equations. If we assume that all normal forces from the ground N_i $(i = 1, 2, 3, 4)$ are equal to each forces applied to the movable pulleys F_i.

$$N_i = F_i \tag{1}$$

The body mass M is supported by four wheels in the field that the gravitational acceleration is g.

$$\begin{aligned} Mg &= N_1 + N_2 + N_3 + N_4 & (2) \\ &= F_1 + F_2 + F_3 + F_4 & (3) \end{aligned}$$

Because all the pulleys are connected to the spring F_a by the wire, all F_i are equal.

$$2F_1 = 2F_2 = 2F_3 = 2F_4 (= F_a) \tag{4}$$

Therefore, all the normal forces from the ground are theoretically equalized.

$$N_1 = N_2 = N_3 = N_4 = \frac{Mg}{4} \tag{5}$$

2.2 Preliminary experiment of LEPS mechanism

Basic performances of LEPS mechanism have already been evaluated with a small test model[8]. The small test model is shown in Fig. 2 and specifications are shown in Table 1. LEPS mechanism attached to the small model (Fig. 2(a)) is slightly different from Fig. 1 but basic principle is not different. First, deviation of applied normal forces was evaluated. Adhesion coefficient is used as a basis for evaluation of traversability[9]. In the experiment, the evaluation index was defined based on adhesion coefficient. The evaluation index for deviation of applied normal forces Ψ is expressed as below,

$$\Psi = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(N_i - \bar{N}\right)^2} \tag{6}$$

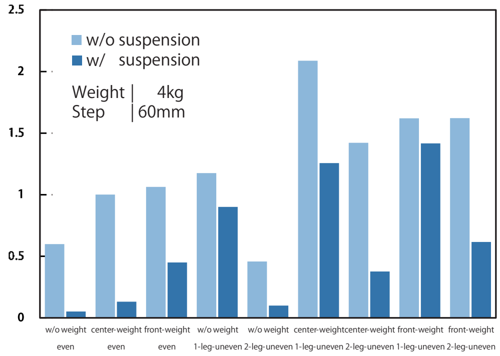


Figure 3. Deviation of applied normal forces of the small test model

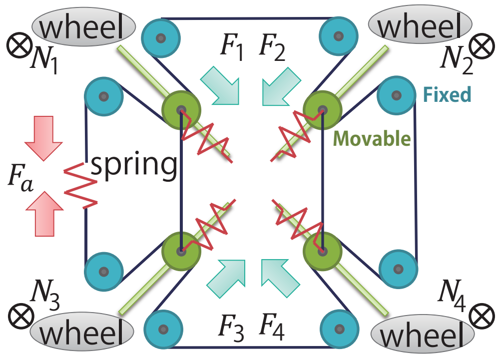


Figure 5. Conceptual diagram of IMPROVED LEPS mechanism

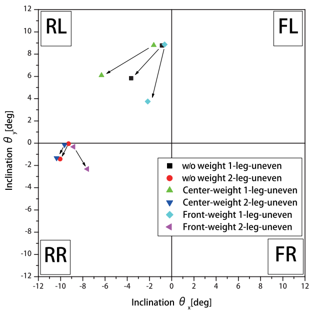


Figure 4. Body inclination of the small test model

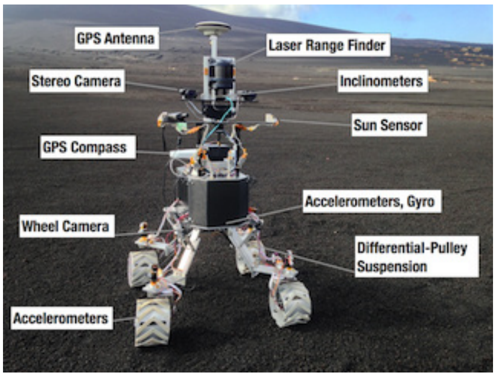


Figure 6. Testbed rover "AKI"

, where n in the number of wheels and $\overline{N}$ is average of normal forces from the ground. Smaller Ψ means higher traversability. It was compared how the deviation changes with or without LEPS mechanism. The test conditions are shown in Table 2. In the test, a 4[kg] weight and a 60[mm] step were used. When the weight was used, the position of the weight was in front or at the center of the small model. When the step was used, one or two of the leg(s) was/were on the step. The test results are shown in Fig. 3. Figure 3 shows that deviation of applied normal forces gets reduced and the traversability gets high by using LEPS mechanism especially on even terrain. Second, the body inclination was measured in the same condition as the first test. The results are shown in Fig. 4, where the coordinate system is shown in Fig. 2(b). The body inclination changed in the direction of arrows in the Fig. 4 by attaching LEPS mechanism. The inclination in the roll direction gets better when LEPS mechanism in on the uneven terrain. However, the body inclination in the roll direction gets worse. LEPS mechanism can only equalize the forces applied to each leg but it can not hold the attitude because balanced position is not always parallel to the ground slope. Then, some springs for attitude restoring are needed for practical use.

3 Testbed rover -AKI-

LEPS mechanism was improved in light of results from the preliminary experiments. Figure 5 shows the conceptual diagram of improved LEPS mechanism for practical use. First, four springs for attitude restoring are attached. Second, movable pulleys are connected by wires two by two so as to reduce pitching motion range. Improved LEPS mechanism was applied to a testbed rover "AKI". AKI is a testbed rover for ground test of some control theories, odometry, path planning etc. developed by ISAS/JAXA, the University of Tokyo and Kochi University of Technology. A lot of sensors such as GPS compass, stereo camera, laser range finder, inclinometer, sun sensor, accelerometer, gyro, etc. are equipped as shown in Fig. 6. The springs for rear two wheels are stronger than front ones because the center of gravity of the testbed rover was in front of the geometric center. The specifications of full-featured AKI are shown in Table 3.

The legs of AKI consist of Chebyshev link and the parallel link mechanism as shown in Fig. 7. Each Chebyshev link converts vertical motion of the wheel into hori-

Table 3. Specifications of full-featured AKI

Item	Value		
Size	880×830×1500		[mm]
Mass		50	[kg]
Wheel diameter		200	[mm]
Speed		223	[m/h]
Spring constant of LEPS		1.14	[N/mm]
Spring constant of	Front	0.80	[N/mm]
attitude restoring	Rear	0.47	[N/mm]

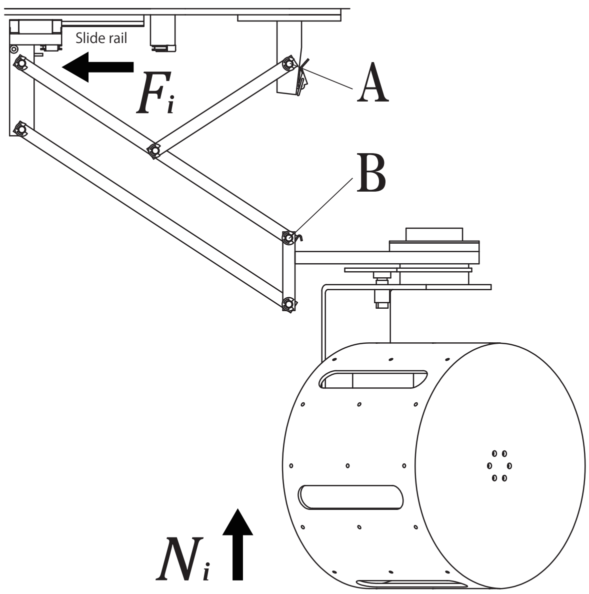


Figure 7. Link mechanism of the leg of AKI

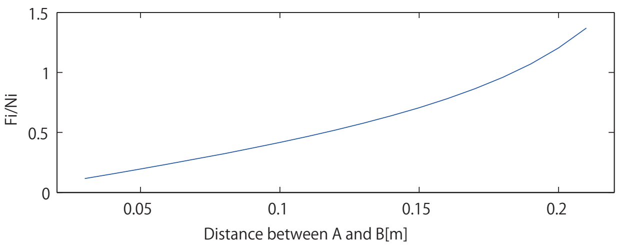


Figure 8. Relationship between N_i and F_i

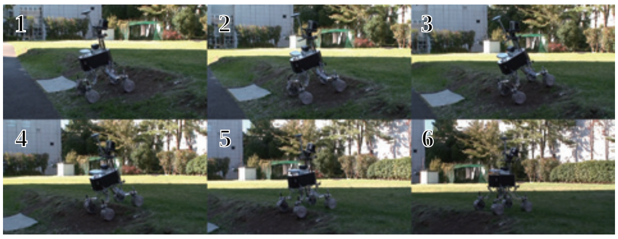


Figure 9. Outdoor test on an artificial hard ground : AKI was climbing 30deg artificial slope.

zontal motion of the movable pulley on the slide rail. The parallel link restrains the attitude of the wheel. The legs behave as prismatic joints. In this configuration, normal forces from the ground N_i and forces applied to the movable pulleys F_i are not equal as sown in Fig. 8. Though this configuration was adopted for because the displacements of the legs are not large and for the reasons such as structural intensity, robustness, simplicity of the wire formation. If N_i and F_i should be equal, the wire must be sterically-disposed.

4 Evaluation of New LEPS Mechanism

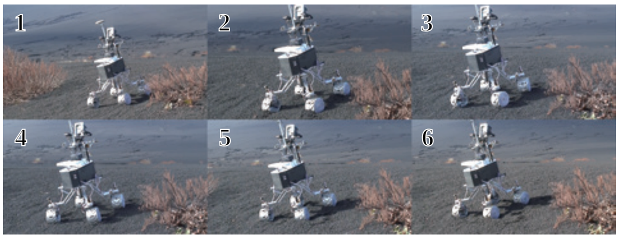
4.1 Outdoor test on an artificial ground

In order to measure the capability of slope climbing and descending angle with full-featured AKI, simple climbing/descending tests were conducted on an artificial hard ground in ISAS/JAXA as shown in Fig. 9. The test result shows that the maximum climbing/descending slope angle is 30[deg].

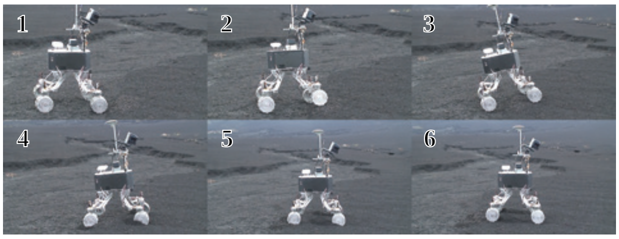
4.2 Field test on a natural terrain

In order to measure the performances and feasibilities in hazardous environment, full-featured AKI traversed on the natural volcanic gravel at Ura-Sabaku desert in Izu-Oshima island in Japan. Because the terrain is covered with scoria gravel, the surface is soft. That is to say, it is appropriate to simulate lunar or planetary hazardous surface exploration.

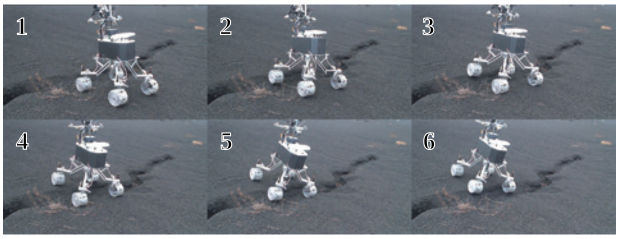
The first test was conducted in case of climbing weak ground slope (Fig. 10(a)). The maximum climbing angle on the weak terrain was 18[deg] but AKI was stuck on the slope. When AKI was stuck halfway up a slope, AKI sometimes succeeded in escaping by steering right and left repeatedly. However, a problem was found. Springs for attitude restoring dose not work well and the attitude of the body was unstable because the springs was not strong enough. Stronger springs can stabilize the attitude of the body, but they weaken the ability of the LEPS mechanism.



(a) Slope climbing test : AKI was climbing 18deg natural slope. AKI once got stuck , went back and got stuck again.



(b) Running up test : AKI was climbing 12cm natural step. Rear wheels got stuck and climbed up.



(c) Groove passing test : AKI was passing 20cm natural gutter. The attitude of the body was stable.

Figure 10. Field test on the natural volcanic gravel

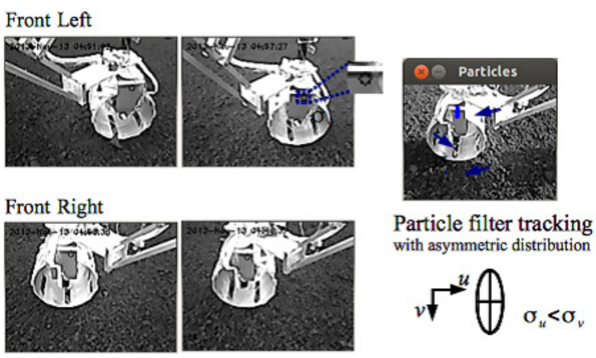


Figure 11. Tracking legs using particle filter

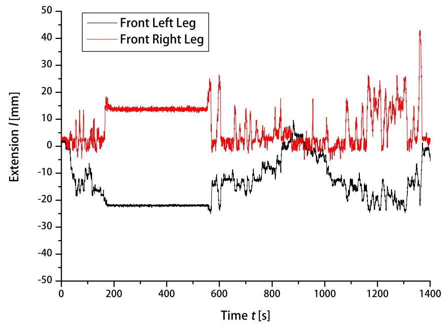


Figure 12. Time history of the extension of front legs

It is trade-off between stability and load equalization.

The second test was conducted in case of running up uneven ground (Fig. 10(b)). The front wheels were able to climb up uneven terrain easily, but the rear wheels had difficulty with climbing. The front wheels was able to climb up 300[mm], half again the diameter of the wheels, and the rear wheels was able to climb up the two-thirds diameter of the wheels. This is because the center of gravity of AKI is in front of the geometric center and springs for attitude restoring are different depending on attached position. If the center of gravity is at the same position as the geometrical center of the body and all the springs for attitude restoring have same spring constant, the ability to climb up uneven terrain will get better. In this configuration of the field test, the front wheels climbed up and then the rear wheels sometimes stuck for a short time. After that, the front wheels dug the ground and the rear wheels deform uneven terrain, then the ground got like a slope. Finally, the rear wheels climbed up the slope.

The third test was conducted in case of groove passing (Fig. 10(c)). There were many gutters in Ura-Sabaku desert because of typhoons. The maximum depth of the gutter that the rover can pass was 200[mm], the diameter of the wheels. Additionally, the attitude change of the rover body was small during passing. LEPS mechanism worked well and desired ability to follow the asperity of the terrain was identified. LEPS has high advantage in traversing on grooved terrain.

The final test was conducted in case of long running. The detail of rover trajectory and attitude are reported in another paper[10]. AKI run 170[s] and stopped 380[s] and run 850[s] again. This is the data measured during 4:41:21 - 5:01:41 Nov. 13th 2013 in UTC. Figure 12 shows the time histories of the relative extension l_i of the front legs. The data was acquired from the movies taken by wheel cameras. The position of the legs were tracked using particle filter as shown in Fig. 11. The history of the lengths of right and left legs with conventional suspension is generically almost symmetric, however, the history of LEPS mechanism is asymmetric especially around 900[s]. Since the geometry data of the terrain are absent, quantitative evaluation is difficult. Although, these data represent the feature of LEPS mechanism. Applied force to front left leg was transfered to the others. The asymmetric motion is essential in case of landing on grounds. This motion has possibility that LEPS mechanism is adoptable as a landing device.

Generally, it was found from the field tests that LEPS mechanism is generally acceptable as suspension mechanism of rovers, though some improvements or changes are required for real use.

5 Conclusion

In order to reduce the total weight of lunar or planetary surface exploration spacecraft, the integration of landers and rovers is considered. A novel pulley suspension mechanism "Load Equalization Pulley Suspension mechanism : LEPS mechanism" has two functions which are landing gear of landers and suspension mechanism of rovers. LEPS mechanism as suspension mechanism of rovers is improved using the data of the preliminary experiment of quasi-static performance. Four springs for attitude restoring are attached and movable pulleys are connected by wires two by two for practical use. Improved LEPS mechanism is evaluated with a testbed rover "AKI". AKI with LEPS mechanism can climb up 30[deg] slope on hard ground and 18[deg] on natural weak terrain. AKI can climb up steps whose height are two-thirds diameter of the wheels. The attitude of the body was hardly changed during passing groove terrain whose depth is around same as the diameter of the wheels. The lengths of right and left legs have asymmetric history while long run , and this is the feature of LEPS mechanism.

In the future, more quantitative evaluation should be conducted and comparison with conventional method should be done. Large wheels should be attached with strength of four wheeled system. The integration of landers and rovers should be discussed well and the integrated system with LEPS mechanism should be evaluated soon.

Acknowledgment

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