Mobility Performance Evaluation of Planetary Rover with Similarity Model Experiment

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Abstract - In order to carry out experiments many times on the Earth in consideration of the difference of gravitational acceleration to design the rover properly, we introduce similarity law to design and construct the experimental models. We have produced two experimental models of the planetary rover with 5-wheel suspension system (called "PEGASUS") and 4WD system under for 1G and 1/2G gravity. We have carried out a low-gravity flight experiment in various parameters using the model on the airplane. Assuming that similarity law is true under every gravity environment, we have made relative evaluation on a degree of mobility by the difference of mobility systems. In the result of the flight experiment, it is show that PEGASUS is able to successfully move better than 4WD.

Keywords **-** Planetary Rover, Similarity law, Experimental models, Gravitational acceleration.

I. Introduction

Investigation of the Moon or planets is one of the most effective methodologies to know the possibility as humanity's new activity base. As the result of those many missions, e.g. sensing their surfaces with orbiter or lander, had been carried out, we were able to gain wonderful knowledge. Now, it can be said that more detailed investigation should be started to promote the future space development. [1] On the other hand, almost all countries had to cut down the budget for the development of the space off because of their economical problems. As total cost of missions has been reduced, mission concepts have to be changed to "Smaller, Faster, Better" from large-scale projects like Apollo missions [2]. In order to explore in detail in wider area during longer term with low-cost, using a small-unmanned roving vehicle (shown as 'rover' hereafter), which has a high degree of mobility, is one of the fascinating ideas.

By the capacity limitation of a launch vehicle, the rover should have several limitations such as size, weight, amount of energy, etc. However, in order to explore particularly in wider area under limited energy resource, the rover must have a high degree of mobility and low-power-consumption technology to traverse rough terrain. Therefore, we should understand exactly the kinematics properties of the rover on the planet and establish the effective system for the planet. There will be suitable mobility system under different Gravity, e.g. Moon or Mars etc., from the Earth. We have to carry out experiments many times on the Earth in consideration of the difference of gravitational acceleration [3-4].

In this paper, we introduce similarity law to design and construct the experimental models flexibly and quickly. Using many similarity models, which produce, we observe how the models take action by the difference of gravities and systems. Thus, we make relative evaluation on a degree of mobility.

II. Planetary Rover

The planetary rover is required to carry out scientific measurement at many points on wide planetary surface during its limited lifetime. In order to achieve above requirements, the rover must have a mobility system which has

(1) Mechanism to improve its degree of mobility
(2) Low energy consumption
(3) High stability

These things listed above show a tendency to exaggerate when a rover becomes smaller, because a small rover has to pass over relatively big rocks within relatively low power. In order to examine micro planetary rover in a total system, we have developed a prototype rover called Micro5 [5] shown in Fig.1. The Micro5 has a new suspension system called "Pentad Grade Assist SUSpension (PEGASUS)". PEGASUS has high mobility as well as rocker-bogie suspension [6-10], with very simple mechanism called only-one-joint architecture.

Fig.1 Micro5: the planetary rover with PEGASUS system

Fig.2 AMSL Minirover: the rover with 4-wheel drive system

III. Mobility System

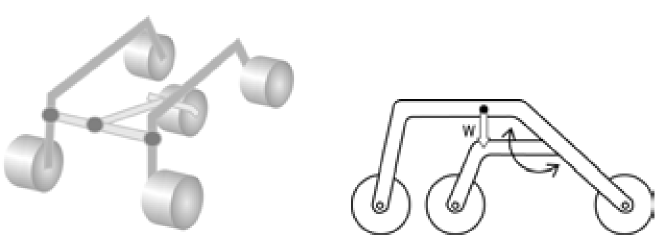
The suspension system is the key issue of degree of mobility. And so, we have discussed a variety of mobility systems for cruising rough terrain. In this chapter, we'll see some typical systems to know what essential points are for improving mobility.

A. Conventional 4-wheel drive system

As you know well, a 4-wheel drive (4WD) shown in Fig.2 is the most popular system for an automobile to traverse rough terrain. We call this conventional 4WD here after. There are many rovers adopted this system for its locomotion, e.g., ISAS/Nissan rover [11-12], Nomad [13-14], AMSL Minirover [15], etc. Conventional 4WD has no mechanisms to improve its mobility, but has just one provides torque to each wheel distributively. It's simple and light in weight, however, it doesn't have high degree of mobility compared with following systems.

B. PEGASUS system

As above, the micro planetary rover is required to have both a simple and light weight mechanism like 4-wheel drive system and a high degree of mobility like rocker-bogie suspension system. In order to achieve these opposed requirements, we propose a new suspension system named "Pentad Grade Assist SUSpension (PEGASUS)". A developed rover prototype Micro5 equipped with PEGASUS system is shown in Fig.3 (a). PEGASUS consists of a conventional four-wheel drive system and fifth active wheel. As shown in Fig.3 (b), the fifth wheel is attached to the end of a link, and the other end of the link is attached to the body with a passive rotary joint. PEGASUS needs only one joint rather than the rocker-bogie that needs 4 joints. In general, joints are heavy parts and easily lead to trouble in space environment. So, the architecture called "Only-One-Joint" would be one of advantages.



(a) Frame model of Micro5 *(b) Mechanism of PESASUS system*

Fig.3 PEGASUS (PEntad Grade Assist SUSpention) system

The system is designed to distribute the load of weight equally to all five wheels when the rover climbs up on the step-alike terrain. It means that the fifth wheel supports the load taken to the front wheels when the front wheels climb up rocks, and it also supports that taken to the rear wheels when the rear wheels climb up the rocks. As shown in Fig.4, when the rear wheel climb a step, forward force generated by the traction of the fifth wheel (shown #1 in Fig.4) pushes the rear wheel backward as (#2). These forces produce nose-dive moment (#3), then the moment turns to a vertical force of the front wheel (#4) to support traction. This is the reason why PEGASUS has extremely high mobility. This system realized such high mobility in simple and light mechanism. [16]

In the following chapter, we discuss the performance evaluation compared with above system through the experiment, which is carried out by some similarity models.

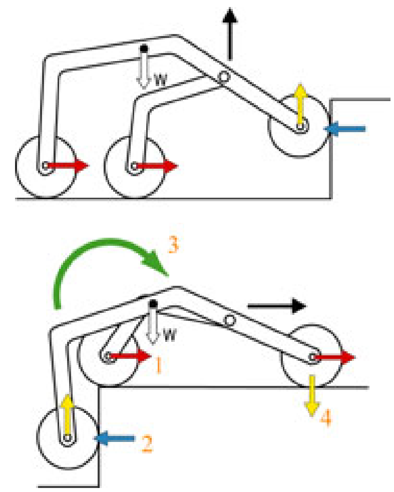


Fig.4 Kinematics of PEGASUS to climb a step

IV. Similarity Law

When it is difficult to experiment with the real model, the similarity model is often used. The similarity models must be physical similarity of its real phenomenon, e.g. Time, Power, Speed, Temperature, etc., as well as geometric similarity. By carrying out a model experiment, we'll infer the real phenomenon from the experimental result.

In the case of a lunar rover, we mate the relation of the physical parameters, which acts on the rover, between on the moon and on the earth. [17] When planetary rover moves on the moon, the physical powers taken into consideration are shown bellow.

(1) Inertia force of rover $F_{ir} = M_r\alpha = M_rL/T^2$
(2) Inertia force of ground $F_{is} = M_s\alpha = \rho L^2V^2$
(3) Gravitational force rover $F_{gr} = M_rg$
(4) Gravitational force ground $F_{gs} = \rho gL^3$
(5) Adhesive force of ground $F_c = cL^2$
(6) External force F

Where,

M_r	: Mass of rover	[kg]
M_s	: Mass of ground	[kg]
T	: Time	[s]
L	: Length	[m]
V	: Velocity of rover	[m/s]
α	: Acceleration of rover	[m/s^2]
ρ	: Density of ground	[kg/m^3]
c	: Adhesive stress of ground	[N/m^2]
g	: Gravitational acceleration	[m/s^2]

A sign with " ′ " show a model. Because we use a soil similar to that on the moon, it's apparent that $\rho = \rho'$, $c = c'$.

Consequently, the similarity law can be defined as follows:

$$\frac{L'}{L}=\frac{g}{g'},\quad \frac{T'}{T}=\frac{g}{g'},\quad \frac{\alpha'}{\alpha}=\frac{g'}{g},\quad \frac{V'}{V}=1$$

$$\frac{F'}{F}=\left(\frac{g}{g'}\right)^2,\quad \frac{Mr'}{Mr}=\left(\frac{g}{g'}\right)^3$$

When the moon is the target of exploration, gravitational acceleration of the moon is 1/6 of that on the earth. Therefore, in the experiment under 1G gravity, an expression of relations can be found as follows:

$$\frac{L'}{L}=\frac{1}{6},\quad \frac{T'}{T}=\frac{1}{6},\quad \frac{V'}{V}=1,\quad \frac{\alpha'}{\alpha}=6$$

$$\frac{F'}{F}=\frac{1}{36},\quad \frac{Mr'}{Mr}=\frac{1}{216}$$

In the experiment under 1/2G gravity, an expression of relations can be found equally as follows:

$$\frac{L'}{L}=\frac{1}{3},\quad \frac{T'}{T}=\frac{1}{3},\quad \frac{V'}{V}=1,\quad \frac{\alpha'}{\alpha}=3$$

$$\frac{F'}{F}=\frac{1}{9},\quad \frac{Mr'}{Mr}=\frac{1}{27}$$

That is, in the gravitational acceleration that experiments, the suitable experiment model is required.

V. Model Experiment

A. Similarity Models

Using an experimental model, we measure the velocity, the number of rotations of a wheel and the gradability, etc. We would make relative evaluation on degree of mobility according to several systems. Therefore, we'll construct the similarity model, which has the above-mentioned typical mechanism.

In fact, we have produced two similarity models that have 4WD system and PEGASUS system. One side is the model (shown as '1/6 Model' hereafter) for 1G gravity, another side is the model (shown as '1/3 Model' hereafter) for 1/2G gravity. We have been cautious of the following points when we design and produce a model.

(1) The origin of an experimental model is next generation of exploration rover called "M5A". We would advance a project, striking a balance between the origin and the model.

(2) An experimental model is equivalent to original model in mass, the position of the centroid, and an inertia moment.

(3) An experimental model has adequate strength and simple structure.

(4) Effective dust-proof countermeasures, e.g. silicone coating etc., on experimental models are taken to carry out experiments on sandy surface.

The small and light weight brushless DC motor is used especially in the 1/6 Model. In order to control the number of rotations of a motor, we have designed the drive circuit board. Then, we can set up widely and safely the velocity of an experimental model.

The 1/3 Model has SH2 CPU board, an interface board, a PWM driver board, and a supply circuit. CPU board controls the DC motor freely.

The resin, e.g. ABS etc., is used as the material of the experimental models, in order to realize weight saving, having adequate strength.

We have successfully produced an experimental model, which fills a similarity law. Figures 5 and 6 show the overview of the model used in the experiment. The specification of a model and original is shown in Table 1.

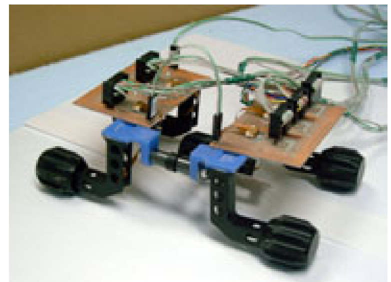


Fig.5 1/6 Model Rover for 1G gravity

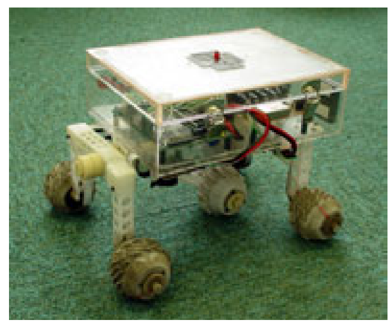


Fig.6 1/3 Model Rover for 1/2G gravity

Table 1 Specifications of a Miniature Rover & Micro5

	1/6 Model Rover	1/3 Model Rover	M5A(tentative)
Body length	92.0 [mm]	220.0 [mm]	620.0 [mm]
Body width	77.0 [mm]	160.0 [mm]	500.0 [mm]
Whole length	112.0 [mm]	270.0 [mm]	770.0 [mm]
Whole width	163.2 [mm]	230.0 [mm]	650.0 [mm]
Minimum Ground clearance	32.5 [mm]	75.5 [mm]	200.0 [mm]
Vehicle high	18.0 [mm]	100.0 [mm]	300.0 [mm]
Wheel diameter	25.0 [mm]	50.0 [mm]	150.0 [mm]
Wheel width	25.0 [mm]	50.0 [mm]	150.0 [mm]
Mass	100.83 [g]	1200 [g]	20 - 30 [kg]
Mobility System	PEGASUS/4WD	PEGASUS/4WD	PEGASUS/4WD
Maximum Speed	10.0 [cm/s]	10.0 [cm/s]	10.0 [cm/s]
Motor	Maxon EC6	Maxon RE13	Maxon A-max26
Gear	Maxon GP6	Maxon GP13A	Maxon GP32B
CPU	PC based(remote)	SH2(onboard)	SH3(onboard)

B. Low-Gravity Flight Experiment

First of all, we have carried out the low-gravity flight examination using the 1/3 model on the airplane. In this experiment, parabolic pattern flight (shown in Fig.7) by airplane provides around 20 seconds of micro gravity condition in the cabin. We have following merits in the aircraft micro gravity flight.

- Can provide many G level conditions (+0.03G to 2.5G)
- Provide many chances of experiment in one flight operation

- Experimenters can on board and control their system and change the settings if necessary

Three following flight experiments were carried out.

1. Climb over the step
2. Sandy slope of around 15 degrees
3. Sandy slope of around 10 degrees with some stones

An example view of the flight experiment is shown in Fig.8. A detailed parameters in the experiment is shown in Table2. Figure 9 illustrates the exterior of the experimental tank and the position of the Model.

The experimental data are acquired as image data from four cameras, which are set in each position (top face, front face, side face, Fig.10) of the experimental tank. We can measure the number of rotations of each wheel and the locus and orientation of models from the image data. Torque generated by each wheel can be calculated from the number of revolutions measured in each wheel. And, we can calculate the slip ratio of the model in sandy area. For the equality in conditions for each suspension systems, size and velocity of models are set to be same. The velocity of the experimental model is set as maximum speed (10.0 [cm/s]). The experimental model starts from the initial position and runs to the end of the experimental tank. In the Flight #2 and #3, we made a sandy slope using the soil called "Simulant", which is produced so as to have equivalent mechanics of the sand on the moon. Also, we cultivated the soil whenever the model had finished running in order to make the state of the soil uniform each time.

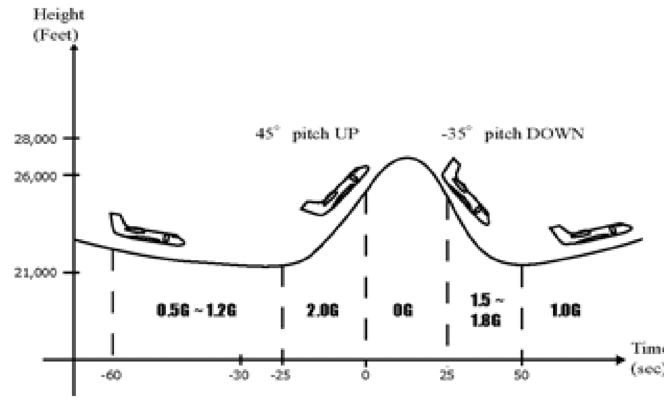
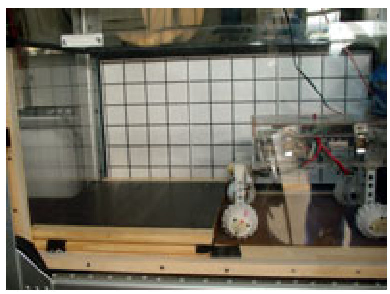
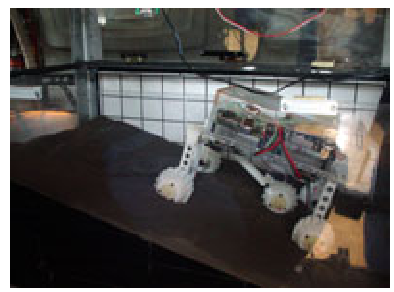


Fig.7 Flight attitude pattern of Parabolic Flight

(a) An overview of the experimental apparatus



(b) A view of Flight #1

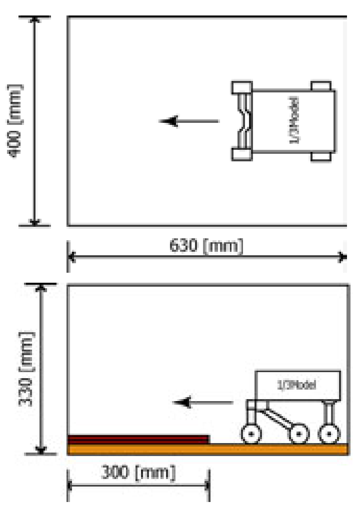


(c) A view of Flight #2

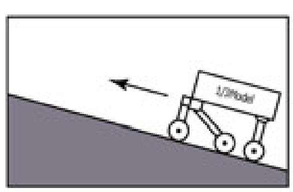
Fig.8 An example view of the flight experiment

Table 2 An experiment parameters of the Flight

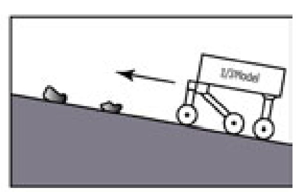
	Fllight #1	Flight #2	Flight #3
G-Level	+0.00 0.05 0.15 0.50	0.05 0.15 0.50	0.05 0.15 0.50
System	4WD or PEGASUS	4WD or PEGASUS	4WD or PEGASUS
Field	Step 15mm or 30mm	Gradent (15 degree) Sand or Sand & 2Gset	Gradient (10 degree) Sand or Sand & Stone



(i) Flight # 1



(ii) Flight # 2



(iii) Flight # 3

Fig.9 Initial condition of the Flight #1,#2,#3

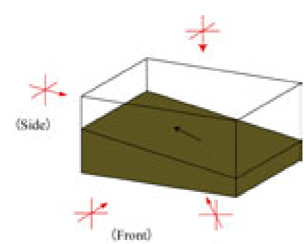


Fig.10 Camera Position

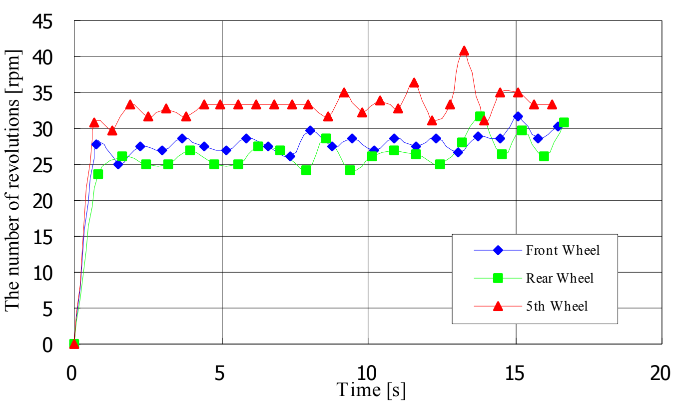
VI. Experimental Analysis

Figure 11 shows the results of model experiment while climbing over the step. In this flight, we had carried out the experiment, which reaches two kinds of step (15 [mm] and 30 [mm]), to survey the effects of the mobility system while climbing over the step.

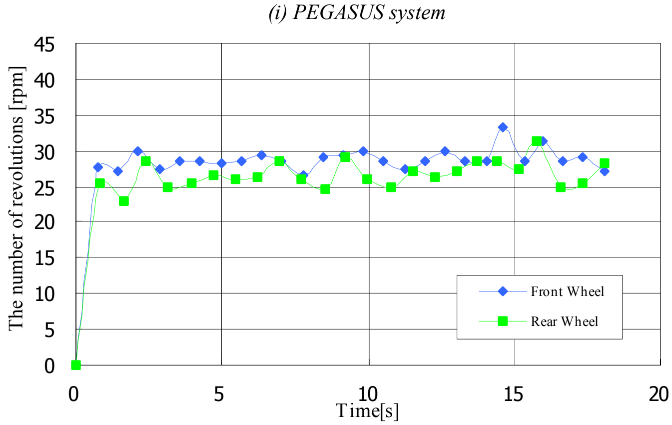
In Fig.11, we express change of the number of revolutions to running time when climbing over the step (30 [mm]). When the models climb over the step of 15 [mm], the both of models with PEGASUS or 4WD could climb over the step smoothly. But, in the step of 30 [mm], the rear wheel of 4WD model slipped and couldn't climb the step. In the meantime, the model with PEGASUS was able to overcome the step although time was taken. By the result, PEGASUS was better than 4WD because of their load distribution capability.

In the Flight #2 and #3, we carried out the experiment of the sandy slope, which would be the most difficult place while running on the moon surface, and evaluated suspensions relatively on a degree of mobility by the slip ratio of the wheel. Figure 12 and 13 show the results of model experiment while going up a sandy slope. In Fig.12, we calculate the slip ratio of the wheel to mileage from the number of revolutions and the velocity of Flight #2 and #3. The slip ratio λ can be found as follows:

$$\lambda = \frac{r\omega - v}{r\omega}$$



(i) PEGASUS system



(ii) 4WD system

Fig.11 Result of the number of revolutions of the wheel at the 0.5G environment

Where,

- r : Wheel radius [mm]
- ω : Turning angle velocity [rad/s]
- v : Body velocity [mm/s]

In the case of the 15-degree of grade, the slip ratio increased as a model ran, and the both model with 4WD and PEGASUS system had stacked. The slip ratio of the model with PEGASUS was smaller than 4WD to some extent, and PEGASUS had ran a distance longer than 4WD. In the case of the 10-degree of grade, PEGASUS and 4WD system ware able to finish reaching slope because the rapid increase in the slip ratio was not seen although the each wheel was sliding. In Fig.13, we describe the slip ratio to the difference of gravitational acceleration while running between the unit distances (about 10.0 [cm] from the start) before carrying out a stack. We can guess that the slip ratio becomes small as gravitational acceleration becomes small.

VII. Conclusion

The planetary rover needs to be equipped with the mechanism which actively or passively improve its mobility because of overcoming its physical limitation. In this paper, we take up a newly developed suspension system called PEGASUS.

In order to research the behavior of the rover when driving on the moon, we should carry out a running test under 1G gravity with 1/6 Model based on similarity laws. However, it's

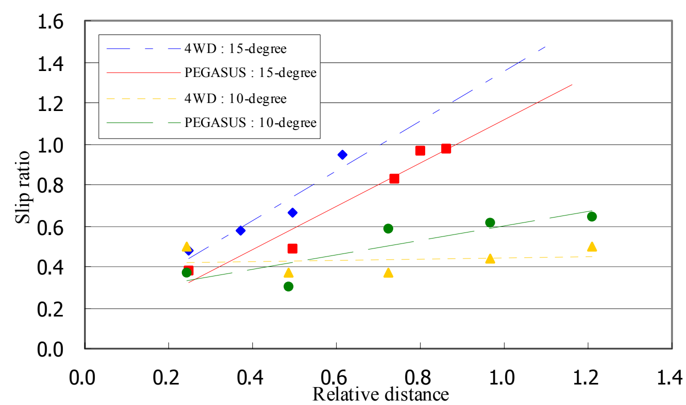


Fig.12 Slip ratio at the 0.5G environment

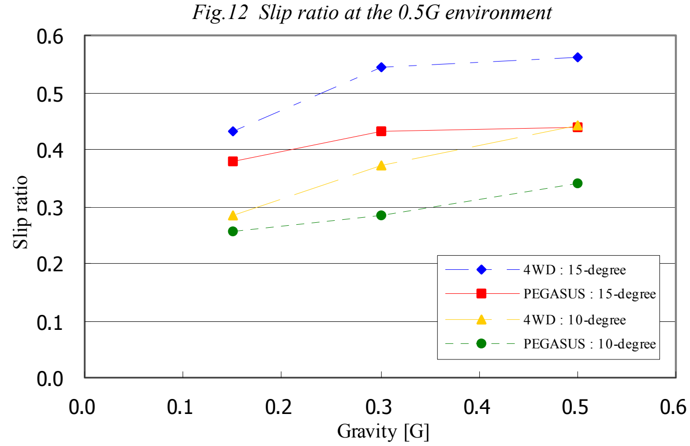


Fig.13 Change of the slip ratio by the difference of gravity

difficult to produce the model with an exact size, because of 1/6 Model is extremely small and light weight. Thus, we proposed to use 1/3 Model, which is easy to produce and to treat relatively. We carried out low-gravity flight experiment with 1/3 Model to fill similarity laws. In this time, assuming that similarity law is realized under every gravity environment, we have made relative evaluation on a degree of mobility by the difference of mobility systems. PEGASUS has high mobility, with very simple mechanism, and PEGASUS is able to successfully move better than 4WD by similarity model experiment under 1/2G gravity. Although a part of result in the mobility performance is opposite between PEGASUS and 4WD, we think it's due to the character of the low-gravity flight experiment and the mechanical problems of the models. In the case of running on the sandy slope, we guess that the horizontal power on the basis of sandy slope increases as the gradient becomes large, and it causes increase of the slip ratio. In the result, the experimental model must have reached to be stacked.

On the other hand, we could check a variety of influence on the degree of mobility, which the difference of gravitational acceleration does. For example, the model bob up and down at the moment its front wheels get in touch with the step to climb over in microgravity, and the slip ratio of the wheel changes by the size of gravitational acceleration, etc. As far as the slip ratio concerned, we guess that the slip ratio increases as a gravitational acceleration increases, because the experimental model gains weight in the same gradient as a gravitational acceleration increases.

We have checked that there was a difference in a degree of mobility between PEGASUS and 4WD in the experiment under 1/2G gravity. But we don't know whether similarity law is realized also under other various gravities. In the future, we'll carry out an experiment under 1G gravity with another 1/6 model rover. We'll reconfirm that PEGASUS was high degree of mobility in comparing with low-gravity flight experiment and look into similarity law. Also, we'll develop the new mobility system by carrying out the experiment with the model of various patterns.

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