Advanced robotic system of hopping rovers for small solar system bodies

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Abstract— Japan has announced the official development of "Hayabusa-2", the second sample return mission to a Near-Earth asteroid. When the development is made smoothly, Hayabusa-2 will be launched in 2014. The predecessor spacecraft "Hayabusa" made a great success when it returned to the Earth in June 2010 with a capsule containing some particles obtained from S-type asteroid "Itokawa." The authors installed a tiny hopping rover called "MINERVA" into Hayabusa spacecraft. With this experience, the authors again plan to install some rover packages to Hayabusa-2. The total concept is the same but this time multiple rover system is considered. Since the target asteroid parameters are different from the previous target, the rover design has to be made from the beginning. We also face to the another technically challenging matters arisen from the point of the distance from the Sun as well as the surface cruel temperature of low-albedo body. This paper describes the basic concept of the rover fitted for the new target, especially focused on its advanced mobile system.

1. Introduction

The solar system has numerous small planetary bodies such as asteroids and comets. The orbit and the composition of the small bodies are considered to be tightly related to the situation when the solar system was born. That is why scientists have been driven for in-situ missions heading for small planetary bodies in these days.

Japan launched the spacecraft "Hayabusa" for the S-type asteroid "Itokawa" in May 2003[1]. It arrived at the target asteroid in 2005 and made some touchdowns onto the surface to collect some materials. Then the spacecraft went back to the Earth in June 2010, when the thermotolerant capsule which had been deployed from the spacecraft was retrieved in the Australian desert[2].

Being inspired by the dramatic success and closing of Hayabusa, Japan suddenly announced the official development of "Hayabusa-2", the second sample return mission to a Near-Earth asteroid of a different taxonomy. When the development is made smoothly, Hayabusa-2 will be launched in 2014[3].

The inclusion of science-equipped rovers into the small body exploration missions will bring the additional knowledge about the target because it enables in-situ surface observation on multiple places. The sample return spacecraft and the surface exploring rover are mutualistic since the mother spacecraft absolutely goes to the immediate vicinity of the target which enables a deployment of the rover onto the surface.

The most of the target small bodies for the sample return missions have a size less than a few dozens of kilometers, of which surface has a very small gravity.

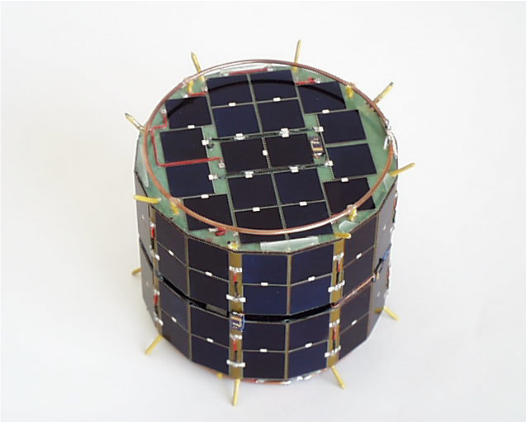
The authors installed a tiny hopping rover called "MINERVA" into Hayabusa spacecraft (Fig.1(a)). MINERVA weights only 591[g] but has an autonomous exploration capability on the microgravity environment on the small solar system bodies. MINERVA was deployed from the mother spacecraft on 12 November 2005 at the vicinity of the target asteroid. But unfortunately it became a solar orbiting satellite since the deployment condition was bad. Nevertheless it worked well, demonstrating an autonomous capability and had survived until the communication link was lost[6].

The authors have proposed to install some rover packages named "MINERVA-II" to Hayabusa-2. Since the target asteroid parameters are different from the previous target, the rover design has to be made from the beginning. We also face to the another technically challenging matters arisen from the point of the distance from the Sun as well as the surface cruel temperature of low-albedo body.

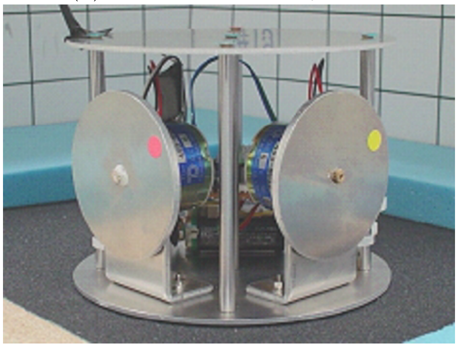
MINERVA in Hayabusa has two actuators inside in order to move, one of which is used as a torquer. By rotating the torquer, a reaction force against the asteroid surface makes the rover hop with a significant horizontal velocity. After hopped into the free space, it moves ballistically. With this mechanism, by changing the magnitude of torque, the hopping speed can be altered, so as not to exceed over the escape velocity from the asteroid surface.

The primary rover of the package has the totally same kind of mobile system. This time two torquers are aligned orthogonally. By simultaneously rotating the torquers, both the hopping speed and direction are controlled. The hopping speed is basically dominated by the magnitude of torques, while the hopping direction is set by the ratio of two torquers.

The authors made some microgravity experiments using a drop tower. The prototype rover was developed and activated on the imitated terrain of asteroid surface when the micro gravity was attained by free-falling the capsule along the tower(Fig.1(b)).



(a) MINERVA in Hayabusa



(b) Prototype model of MINERVA-II used in microgravity experiments

Fig.1 MINERVA and MINERVA-II

2. Hopping Rover

2·1 Mobility under Microgravity

The largest asteroid ever discovered, Ceres, has a diameter of more than 900 [km]. But the majority of small planetary bodies has a dimension with several kilometers or several score kilometers in size.

The gravity on such a small body is on the order of 10 - 100 [μG][1], which is extremely weak compared with that on the Earth. Naturally, the escape velocity from the surface is very slow, supposed to be several score centimeters per second. The rovers to be moving over the small body surface need a mobile system fitted for the milli- or micro-gravitational environment.

The mobility around the small bodies can be categorized into (1) friction-based method and (2) not friction based one (Fig.2). The rover by the latter method does not need to contact with the surface, such as a tethered rover moving along an artificial path (Fig.2(b-1)) or a flying rover using a gas jet thrusting backward (Fig.2(b-2)). This paper considers only the former friction-based mobility because light-weighted rover system can be constructed without vast resources and long survival duration is enabled without fuel.

For the friction-based mobility, there are three forces that act between the rover and the small body surface. Those are gravity, contact force, and friction.

The traction force, which drives a rover horizontally on the small body surface, is obtained by the friction between the surface and the rover. When Coulomb's friction law holds true in a microgravity environment, the traction force f is given by

$$f = \mu N \tag{1}$$

where μ denotes the friction coefficient and N is the contact force between the rover and the surface.

In the case of a traditional wheeled mechanism, frequently used by planetary rovers on the Moon or on Mars, the contact force is opposite to gravity, which results in the following equation:

$$f = \mu N = \mu mg \tag{2}$$

In this equation, m is the mass of the rover and g is the gravitational acceleration on the surface.

Equation (2) indicates that the available friction for wheeled mobility is very small in the microgravity environment (suppose $g \approx 10^{-5}$ [G] $= 10^{-4}$ [m/s^2]). If the traction is larger than the maximum friction, the rover slips. So, the traction has to be so small, which makes the horizontal speed extremely slow.

Moreover, the surface of small planetary bodies will be a natural terrain with an uneven surface. Any small disturbance on the rough terrain would push the rover away from the surface, which robs of the traction. Thus, the rover can not accelerate gradually to have a faster speed.

Mobile systems which keep constantly contact with the surface, like wheeled ones, are not fitted under the microgravity environment because of the two reasons stated above. A more suitable mobile system is desired under the microgravity environment.

Especially due to the latter reason, mobility which is specialized in hopping seems advantageous for the surface of small bodies. After a rover hops, contact with the surface is unnecessary.

Once hopped into free space with some lateral speed, the rover can move to an other place with a ballistic orbit by the weak gravity. The lateral speed is also obtained by the friction acting during a short period after the actuator starts and before the separation from the surface. The friction by the hopping mechanism is given by

$$f = \mu N = \mu(mg + F) \tag{3}$$

where F denotes the artificial pushing force which makes the rover hop.

By enlarging the pushing force, the hopping mechanism is able to attain a larger speed which can not be attained in principal by the wheeled mechanism.

[1] 1 [G] is equal to the gravity on the Earth (9.8 [m/s^2]).

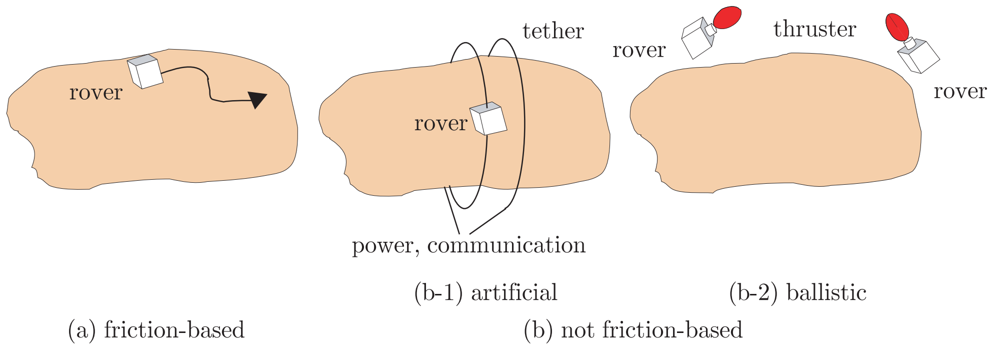


Fig.2 Mobile systems in microgravity environment around small planetary bodies

The maximum allowed speed is the escape velocity from the surface. If hopped with larger speed than the escape velocity, the rover will never return to the surface, which would conclude the continuous exploration.

2·2 Hopping Methods

As you can easily imagine, there are dozens of ways to make a rover hop. Most of them have a moving part outside. By striking or sticking the surface with the moving part, repulsed force from the surface makes a rover hop (Fig.3(a)). This kind of mobility was used in the Phobos rover.

In 1988, former Soviet Union launched the twin spacecraft for the Martian satellite Phobos. One spacecraft had a hopping rover named PROP-F[4]. PROP-F was to explore over the Phobos surface by hopping. Unfortunately the mother spacecraft was lost just after the deployment of the rover onto the Phobos surface. It was unable to know whether the rover worked well over the surface, since there was no data obtained from the rover.

PROP-F had a spring mechanism for hopping. The spring is wound by the motor and released against the surface to make the rover hop. The rover has only one spring mechanism. Thus the hopping action is possible only with the right attitude on the surface. The rover has another mechanism to adjust its posture. After hopped into the free space, the rover moves ballistically, goes back to the surface, bounds a couple of times, and becomes still again. Then the attitude is recovered to the right position in order to make another hop.

2·3 Torquer Rover

The proposed mobile system by the authors is shown in Fig.3(b) [5]. By turning the rover by its internal torquer, reaction force against the surface makes the rover hop.

The advantages of this so-called "torquer rover" are shown in the followings.

- There is no apparent actuator outside the rover. Because the actuator is sealed inside the body, no consideration is required on the contamination by dusts which may exist on the small body surface.

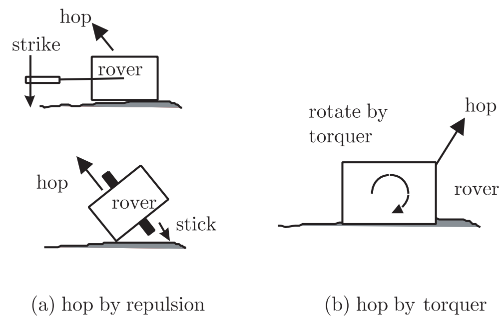


Fig.3 Hopping methods

- The torquer can also be used for attitude control during the ballistic movement.
- A small DC motor is sufficient for the torquer, which enables a small and light rover[7]. This hopping mobility is practical only under microgravity environment. Over a surface with large gravity, it is at a great disadvantage against the traditional wheeled mobility because a too powerful and heavy torquer is needed.
- The posture to hop is always guaranteed when the rover has a few torquers aligned independently. The configuration of torquers is described in section 2·4.

2·4 Designs of Torquer Rover

Several rover designs were investigated. For example as shown in Fig.4, the torquers' symmetric placement on the rover of regular polyhedron provides the ability

- to move regardless of which face is down.
- to control the direction of the next hop by starting some torquers simultaneously regardless of which face is down.

The disadvantage of the above symmetric-shaped rover is the number of torquers, which makes the rover heavier. Plate-type thin rover shown in Fig.5 can reduce the number of torquers. With thinness in depth, the rover probably stops in the attitude of Fig.5(a), which can control the direction of the next hop. Even if the rover stops in the attitude of Fig.5(b), starting a torquer intentionally would lead the rover to Fig.5(a).

Hopping in an arbitrary direction with a given attitude requires actuators with 3-DOF like Fig.4(a). Even with 2-DOF actuators like Fig.5, movement is still possible for any attitude. When the rover has more than two independent actuators, it is not stuck at the single point unless it fell into a hole.

The rover shown in Fig.6 has another configuration with two actuators. It includes a big turn table rotator on which is placed a torquer for hop. It turns the table to set the torquer for the arbitrary direction, which can also control the hop direction. MINERVA rover (Fig.1) in the Hayabusa spacecraft has adopted this configuration.

In this paper, the second configuration in Fig.5 is focused. Thus the reminder of the paper describes the two-torquer rover.

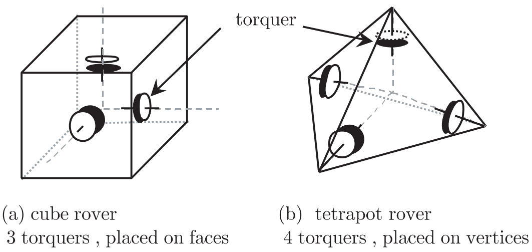


Fig.4 Torquer rover in symmetric shape

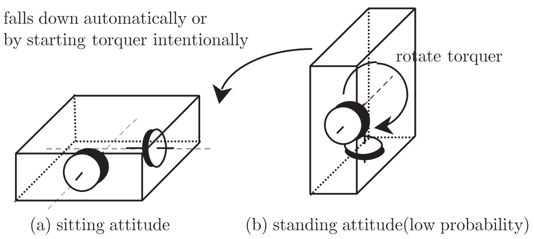


Fig.5 Torquer rover with reduced torquers

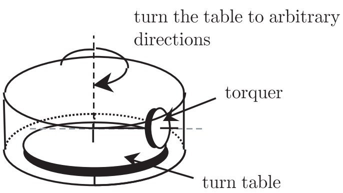


Fig.6 Turn table structure

3. Microgravity Experiments

Microgravity experiments using a drop tower were made to evaluate the hopping performance, which are described in this section.

3·1 Prototype Rover

Fig.1(b) shows the prototype rover developed for the experiments. It has a cylinder shape with the dimension of 135[mm] in diameter and 100[mm] in height. The mass of the rover is 760[g]. Small identical DC motors are used as torquers. They are driven by PWM (Pulse-Width Modulation) scheme to change the magnitude of the output torque. A fly-wheel is attached to the rotor of the DC motor for increasing the inertia of the rotor in order to make the output torque duration longer.

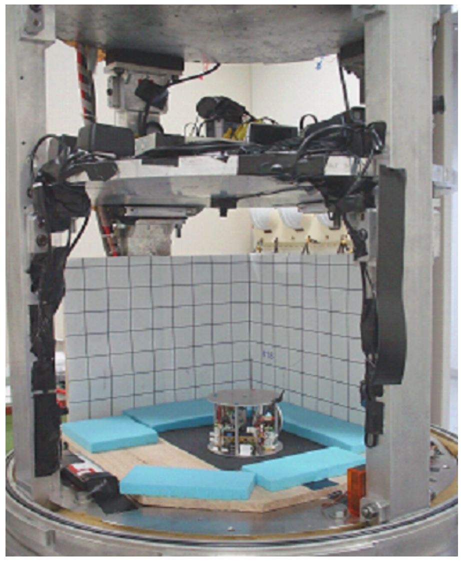


Fig.7 Microgravity experimental setup

3·2 Experimental Setup

The prototype rover was installed into the capsule (Fig.7). In the capsule, the rover was settled on the imitated terrain of asteroid surface. After the capsule have started its free fall along the tower, the rover starts its torquer and hops into the free space, which is recorded by the video cameras.

3·3 Experimental Results

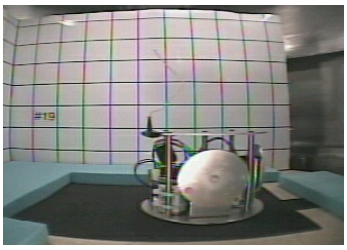
Nine experiments were conducted with the different pair of PWM duty ratios. Fig.8 shows one of the rover movement during the fall. The experiments show that

- the azimuth of the hopping direction is controlled by the proportion of the two PWM duty ratio.
- the elevation of the hopping direction is totally dominated by the friction coefficient between the rover and the surface.
- the hopping speed is controlled by the magnitude of the PWM duty ratio.

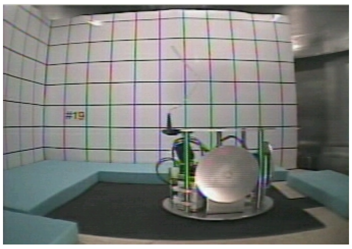
Thus the landing point of the rover is roughly controlled by the combination of two torquers when the rover has a good posture on the surface.

4. Conclusion

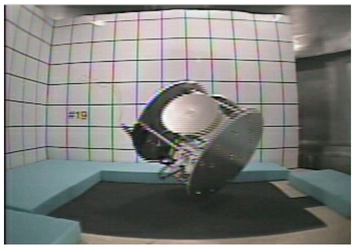
In this paper, the hopping mobile system with two torquers for the upcoming rover payload of Hayabusa-2 asteroid explorer is described. Microgravity experiments using a drop tower were made using the prototype rover. By simultaneously rotating the torquers with the PWM duty ratios adequately designated, both the hopping speed and direction are controlled, which shows the effectiveness of the mobile system.



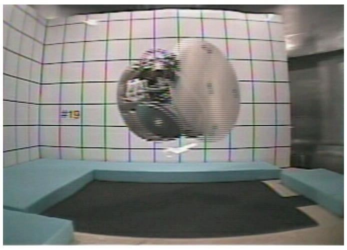
(a) start of free fall (t=0)



(b) start of torquer (t=1 [sec])

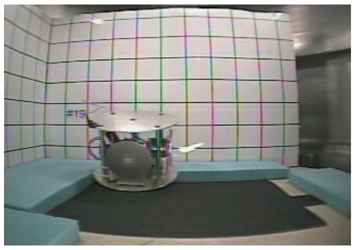


(c) t=2 [sec]



(d) t=3 [sec]

(e) t=4 [sec]



(f) after free fall (t=5 [sec])

Fig.8 Microgravity experiment

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