HOPPING ROVER "MINERVA" FOR ASTEROID EXPLORATION

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ABSTRACT

The Institute of Space and Astronautical Science (ISAS) of Japan will launch an engineering test spacecraft, MUSES-C to a near Earth asteroid NEREUS (4660) in 2002. The MUSES-C spacecraft will perform the world first sample and return attempt from the asteroid NEREUS. A science-equipped robot which moves on the surface of the asteroid would provide an in-situ scientific observation. So the authors have proposed a small robotic lander for the MUSES-C mission. This robot is called "MINERVA" (MIcro/Nano Experimental Robot Vehicle for Asteroid), which has the mobility by hopping and can take images on the asteroid surface. Currently MINERVA remains in an optional payload of the MUSES-C spacecraft. The final decision will be made just before the launch of the spacecraft whether it is included in the spacecraft. So we are developing MINERVA according with the MUSES-C milestones. In this paper, the mission scenario, the mobility mechanism, the microgravity experiments by the test model and the prototype model of MINERVA are presented.

1 INTRODUCTION

In recent years, missions for exploring small bodies such as asteroids, comets, and meteorites have received significant attention across the world. It is believed that the earth-type planets (Mercury, Venus, Earth, Mars etc.) were formed by small bodies. Hence the studies on these small bodies would throw a light upon the origin and evolution of the earth-type planets. Rendezvous and sample return missions for asteroids, specially, would be expected to provide extensive rewards from both technological and scientific points of views. Especially, in-situ surface observations of an asteroid have been of great interest to planetary science.

The Institute of Space and Astronautical Science (ISAS) of Japan will launch an engineering test spacecraft, MUSES-C to a near Earth asteroid NEREUS (4660) in 2002[1][2]. The MUSES-C spacecraft will perform the world first sample and return attempt from the asteroid NEREUS.

A science-equipped robot which moves on the surface of the asteroid would provide an in-situ observation [3][4][5]. So the authors have proposed a small robotic lander for MUSES-C mission[6]. This robot is called "MINERVA" (MIcro/Nano Experimental Robot Vehicle for Asteroid), which has mobility system by hopping [7][8]. Currently MINERVA is an optional payload of the MUSES-C spacecraft. Its realization is dependent on the total mass of the MUSES-C spacecraft. The final decision will be made just before the launch of MUSES-C spacecraft whether it is included in the spacecraft. So we are developing the robot according with the MUSES-C milestones.

In section 2 of this paper, the mission scenario of MINERVA is presented. Section 3 describes the mobility system which is newly proposed for explorations on the surface of small planetary bodies. In section 4, the microgravity experiments by the test model is detailed. Section 5 shows the developing prototype model of MINERVA which is to be manufactured and tested in the near future.

2 MINERVA MISSION

2.1 ASTEROID ENVIRONMENT

The asteroid NEREUS or 1989ML are the candidate target for MUSES-C mission to explore. The orbit of these asteroids are known by the observation from the Earth. But the parameters of the asteroid itself (size, shape, density etc.) are not decided so far. TABLE 1 shows our estimation for the asteroids.

The gravity on the surface of the targeted asteroid is expected to be very weak from 1 to 100[μG] compared

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with the Earth. The robot on the asteroid has to be movable to any arbitrary direction in such a low gravity environment.

The traction force that drives the robot horizontally are obtained from the friction between the robot and the asteroid surface. Not-friction-based mobility, such as thrusting a gas backward, can not be used because of the contamination.

Another requirement for the robot comes from the payload weight and size. The robot has to be small and light-weighted. The allowed total mass is 1[kg] including the OME (on-board mount equipment). The simple mechanism is essential in order to meet this weight limitation.

We have developed a new mobile mechanism which is fitted in such low gravity environment and can meet the above requirements.

TABLE 1 : Estimated environment of the asteroid

diameter	a few 100[m]~ a few [km]
shape	ugly (major to minor axis length ratio :1 ~ 2.5)
density	1 ~ 4[g/cm^3]
rotation axis	unknown
rotation period	4 ~ 30[hours]
temperature	-100 ~ +140[°C]
material	unknown
surface gravity	10^{-5} ~ 10^{-3}[m/s^2] (1~100[μG])
escape velocity	0.02 ~ 2[m/s]

2.2 MISSION SCENARIO

The MUSES-C spacecraft remains at the distance of 20[km] away from the targeted asteroid when the parameters of the asteroid, such as its shape, its size and its rotating rate, are investigated by remote sensing. The parameters are initialized to the robot because they are required for autonomous navigation. Also the global path-planing or strategy will be made on the ground.

When the MUSES-C spacecraft descends to the asteroid for acquiring the surface fragments, MINERVA is released from the OME(on-board mount equipment) which keeps the robot to the spacecraft. Then MINERVA falls onto the asteroid surface and starts the exploration. Small cameras and a sun sensor are used for the autonomous navigation.

The mobile robot provides an in-situ observation of the asteroid surface. The science mission candidates are shown below.

(1) view the asteroid surface crossly by small cameras (including the observation of the MUSES-C sampling point)

(2) measure the surface gravity.

(3) measure the surface temperature.

Tiny instruments that enable the above missions are now under developing. Because the allowed total mass for MINERVA is limited in 1[kg], not all the listed instruments are possible. For reducing the mass, the installed navigation cameras are also used as the scientific observation.

3 PROPOSED MOBILITY SYSTEM

It is necessary to develop a high-mobility robot configuration which can meet the mission and science requirements. Under the micro gravity environment on the surface of small planetary bodies, robots with traditional wheeled mechanism would not work well because of two reasons stated below.

(1) The contact force between the robot and the surface is very week and so the robot-surface friction is very low. If the traction is larger than the maximum friction, the robot slips. So the traction has to be so small, which makes the horizontal speed extremely slow.

(2) Small disturbance on the surface of rough terrain makes the robot away from the surface, which robs of the traction.

For the above latter reason, we have concluded that the mobility which is specialized in hop has the advantage for the surface of the asteroid. If the robot hops with horizontal force, it can move with no contact with the surface.

There are several ways that make the robot hop, but our proposed hopping mechanism is an innovative one that the robot includes a torquer inside. By rotating the torquer, a reaction force against the surface makes the robot hop at a significant horizontal velocity. After hopping into the air, the robot moves ballistically (FIG. 1).

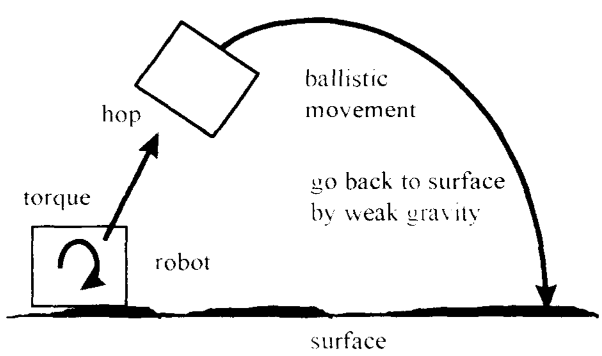


FIG. 1 : Proposed hopping robot

The proposed mechanism has several significant advantages

(1) No actuators, which have direct interactions with the asteroid surface, are necessary outside the robot body. Actually the torquers inside the body can even be sealed to prevent contamination by dusts.

(2) The torquer can also be used for attitude control during hopping.

(3) The contact force between the surface and the body is increased with the help of the artificial pushing force made by the torquer, which makes the friction larger and provides the mobility at larger horizontal speed.

(4) DC motors can be used as a torquer, the control of which is easy. The imposed torque has to be adjustable in order to move in any situations of the gravity from 1 to 100 μG. A DC motor driven by PWM is used to provide the torque adjustability.

(5) On the microgravity environment of the asteroid surface, the required torque is as small as the small DC motors, which makes the robot light-weighted.

4 EXPERIMENTAL TEST MODEL

The test model for the experiments was developed to confirm the proposed mobility. The configurations of the test robot are shown in TABLE 2(a). A DC motor is used as the torquer whose specification is shown in TABLE 2(b). The motor is driven by PWM of 8.1[V] pulses, the pattern of which can be programmed on the following two modes.

(a) step drive: the constant duty ratio pulses are imposed on the DC motor. The duty ratio d_m can be programmed to an arbitrary value.

(b) ramp drive: At $t = 0$, the duty ratio of the pulse is 0%, increased proportionally to the passed time, consequently comes to 100%. Time t_m when the duty ratio arrives at 100% can be programmed to an arbitrary value.

A 30[g] aluminum flywheel is attached to the rotor of the DC motor for increasing the inertia of the rotor.

The micro gravity of 10[sec] is obtained by the free fall of 490[m] with help of jets thrusting upward in order to compensate for the resistance of the air. With this facility, three experiments were conducted under the microgravity environment. The conditions in three experiments varied in (1) the friction between the robot and the surface and (2) the motor driver method. TABLE 2(c) shows the simulation conditions in each experiment.

In experiment #2 and #3, the surface is made up of a flat piece of wood, where the coefficient of static friction is 1.0. In experiment #1, a board is inserted between the robot and the surface. Also a needle sticks out from the bottom of the robot. With these items, the robot never slides leftward, making the friction ∞.

The video images during the experiment #1 are shown in FIG. 2. These figures show the validity of the proposed mechanism visibly because the robot hops with a significant horizontal velocity.

All the experiments are summarized in TABLE 3. The hop time in TABLE 3 shows the passed time since the DC motor started. The hop velocity v_x and v_y denote the horizontal and vertical speed at the instant of hop. The hop speed is calculated by $v = \sqrt{v_x^2 + v_y^2}$. The hop angle θ is measured from the normal line to the flat surface which is calculated by $\theta = tan^{-1} v_x / v_y$.

The numerical simulations under the zero gravity are also conducted, which are summarized in TABLE 4. The simulation results and the experimental results are consistent except for the hop angle and hop time of the first experiment.

The hop angle and hop time of the first experiment have differences from those in the simulation. In the first experiment, compared with the corresponding simulation, the contact duration time between the robot and the surface in the experiment(0.53[sec]) is longer than in the simulation(0.26[sec]). This makes the actual robot's hop angle larger. In experiment #1, to prevent the robot slide leftward making the friction ∞, a board is inserted. There should be no force from outside after the ascending speed of the robot surpasses the descending speed of the contact point with the surface. But in the case of experiment #1, the needle of the robot contacts the side of the inserted board after the detachment from the surface. This contact force from the side of the board increases the robot's horizontal speed and makes the contact duration time longer and the hop angle larger.

With these experiments, the proposed hopping mechanism has been verified to work well through the experiments. Also the simulations reflect the actual movement. In the future design of MINERVA, we are able to make the most use of the simulations.

TABLE 2 : Parameters in microgravity experiments

(a) robot testbed spec.

shape	120 × 96.5 × 61 [mm]
total mass	0.55 [kg]
robot inertia	1.0×10^{-3} [kg m^2]
DC motor rotor inertia	2.3×10^{-5} [kg m^2]

(b) DC motor spec. (in 9[V] measuring voltage)

Stall torque	500 [gf cm]
No-load speed	7650 [rpm]
Torque constant	11.2 [mNm/A]

(c) different parameters in each experiment

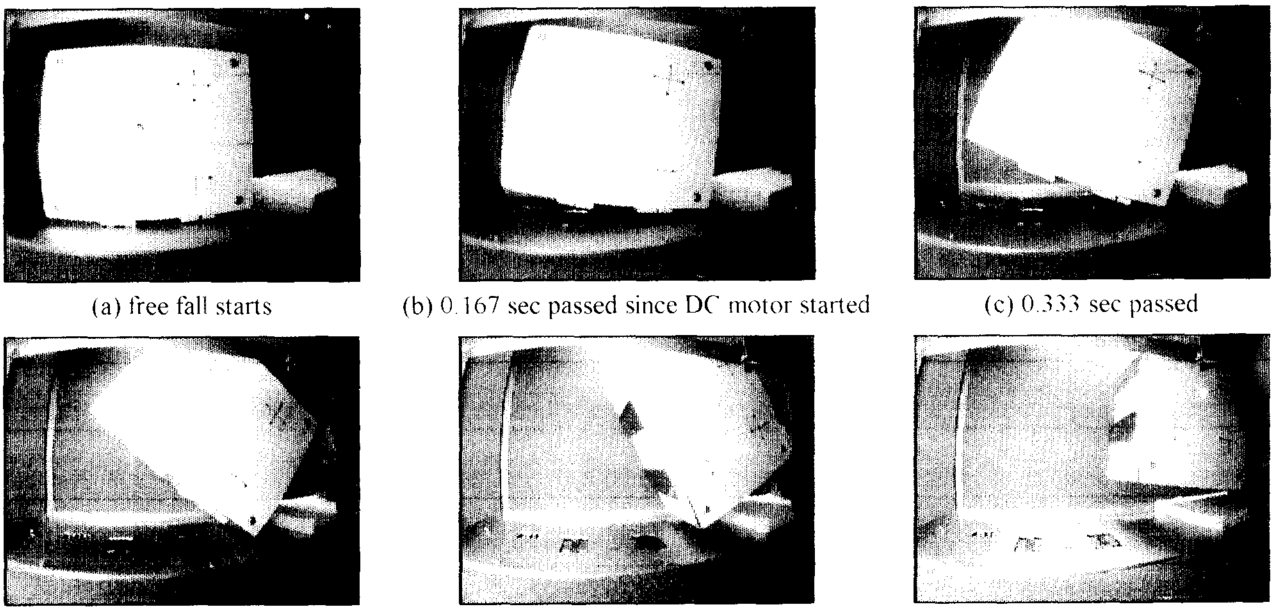
experiment	friction	motor drive method
#1	$\mu = \infty$	step
#2	$\mu = 1$	step
#3	$\mu = 1$	ramp(max at 1.71[sec])

TABLE 3 : Hop angle, speed and time of three experiments

experiment	hop angle [deg]	hop speed [mm/s] $v_\perp$	$v_{//}$	v	hop time [sec]
#1	73	144	44	151	0.53
#2	43	83	91	123	0.43
#3	46	57	58	82	1.10

TABLE 4 : Simulation result (hop angle, speed and time)

experiment	hop angle [deg]	hop speed [mm/s] $v_\perp$	$v_{//}$	v	hop time [sec]
#1	55	120	86	148	0.26
#2	40	90	109	141	0.30
#3	39	48	59	76	0.87



(a) free fall starts

(b) 0.167 sec passed since DC motor started

(c) 0.333 sec passed

(d) 0.500 sec passed

(e) 0.667 sec passed

(f) 0.833 sec passed

FIG. 2 : Video images of the experiment #1

5 PROTOTYPE MODEL

We are now developing the prototype model (PM) of MINERVA according with the MUSES-C milestones. The prototype model will be in the process of mechanical and thermal test in the near future.

The concept of PM is shown in FIG. 3. It has a cylindrical shape with two actuators. It includes a big turn table rotator on which is placed a torquer for hop. The adopted mobility is the hopping mechanism proposed in section 3, but has the ability to control the hop direction. It turns the table to set the torquer for an arbitrary direction, which decides the hop direction.

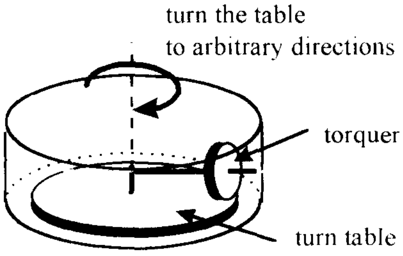


FIG. 3 : MINERVA PM concept

The precise design figure at present is shown in FIG. 4 and the specifications are summarized in TABLE 5. The height and the diameter are 100[mm] and 120[mm] respectively. But the actual shape is an octangle pole, all faces of which are put many solar panels on.

The prototype model has two condensers, where the generated solar energy is charged. The maximum generated power is estimated to be 2.2[W]. The required power of the selected torquer is 2.5[W], which is supplied from the charged condenser. Two flywheels are attached to the torquer for extending the accelerating duration of the torquer.

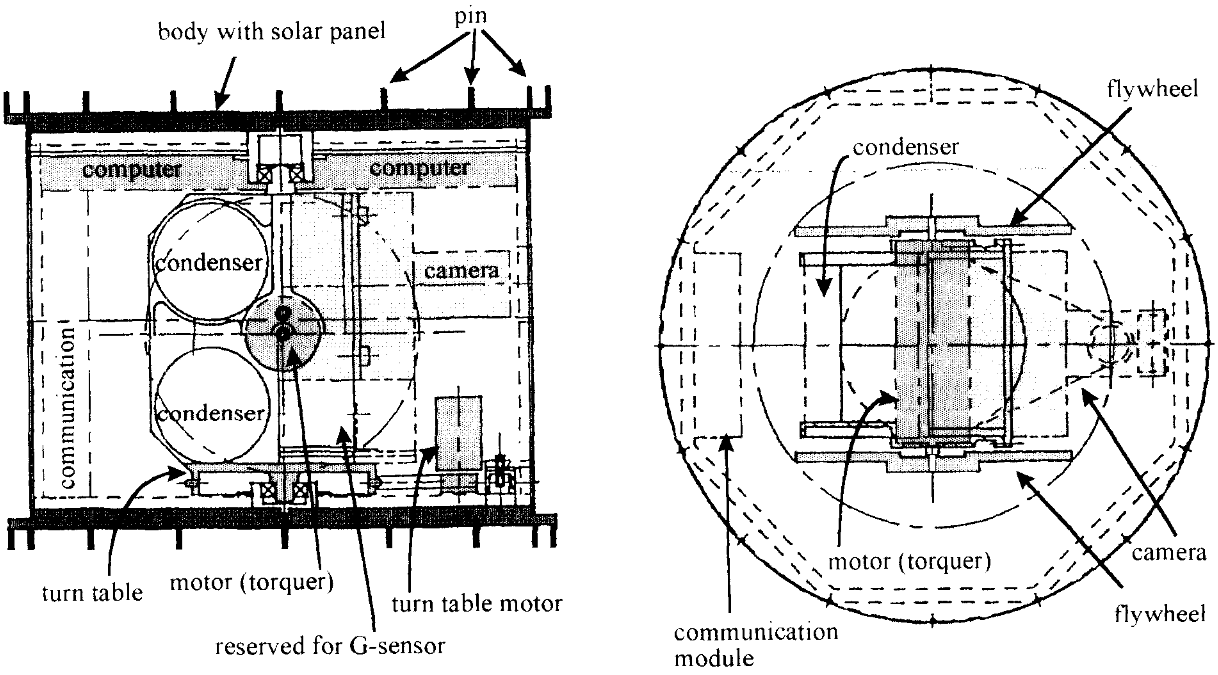
The possible payloads of the robot are a camera, a sun sensor, a G-sensor and so on. The camera is placed on the turn table so as to change pointed direction by rotating the table.

There are at least 16 pins sticking out from the vertices of the robotic lander. The purposes of pins are (1) to protect the solar panels from contacting against the asteroid surface and (2) to make intentional hooks to increase the friction.

The mass of the robotic lander is 550[g]. The on-board mount equipment (OME) will be made in 450[g], which keeps the robotic lander while the spacecraft cruises to the asteroid and releases it to the asteroid surface. The total mass of MINERVA and OME is 1[kg] and the requirement for the mass will be satisfied.

TABLE 5 : MINERVA PM specification

Body Size	ϕ : 120[mm], height: 100[mm]
Weight	550[g]
Mobility system	turn table type (two actuators) two flywheels (15[g] each)
Power Supply	solar panels : 2.2[W] (peak) condenser: 5V 50F
On-board computer	32bit CPU
Communication	RF link with MUSES-C S/C (max range : 20[km])
Payload	Camera (CMOS or CCD) Sun sensor G sensor (if possible)
Power consumption	2.5[W] for actuators 1.0[W] for telecommunication 0.5[W] for on-board computer 0.5[W] for camera
OME	450[g]



(a) side view (b) top view

FIG. 4 : MINERVA PM layout

6 CONCLUSIONS AND FUTURE WORKS

This paper describes the proposed MINERVA asteroid surface exploration project for the MUSES-C mission. The scenario, the proposed mobility system, the microgravity experiments by the test model and the development of the prototype model are presented.

A novel mechanism that drives a robot by hopping was proposed for the asteroid exploration. The validity and effectiveness of the proposed mobility system have been verified by microgravity experiments, which is consistent with the numerical simulations. With these validations, the prototype model of MINERVA is being designed using the proposed mobility system. The prototype model will be tested mechanically and thermally. We are also planning to do another microgravity experiments using the developed prototype model.

For robust asteroid explorations, the navigation strategy is also needed to be established. Also the tiny scientific instruments for MINERVA have to be developed.

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