MINERVA rover which became a small artificial solar satellite

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Abstract––Institute of Space and Astronautical Science (ISAS), JAXA of Japan is operating the deep space explorer "Hayabusa" which made a rendezvous with the target asteroid "Itokawa" in September 2005. Hayabusa precisely observed the asteroid from the vicinity of the target and then landed on the surface in order to get some fragments from the asteroid, which will be brought back to the Earth in 2010. The authors have installed an experimental small rover named "MINERVA" into the explorer. It was supposed to make a world first surface exploration after having been deployed onto the surface from the mother spacecraft. MINERVA was deployed on 12 November 2005. Unfortunately it could not reach at the asteroid because the deployment was not done at the good timing. Thus it became a smallest artificial planet. It survived more than 18 hours after the deployment, all the while the obtained data were transmitted to the Earth via the mother spacecraft. This paper describes the operation and the obtained data of MINERVA.

Key Words: MINERVA, Hayabusa, asteroid rover

INTRODUCTION

Small planetary bodies (asteroids, comets and meteorites) in our solar system have received worldwide attention in recent years. That is because these objects are considered to preserve some traces when the solar system was born. Thus many scientific explorers have been launched continuously heading for small bodies since the late 1990s[1]–[8].

Institute of Space and Astronautical Science (ISAS), JAXA of Japan has launched the spacecraft "Hayabusa" on 9 May 2003 (Fig.1). The target of the explorer is "Itokawa", one of the smallest asteroids. After more than two years' interplanetary cruise, Hayabusa was successful in the rendezvous with the asteroid in September 2005. The spacecraft precisely observed the asteroid from the vicinity of the asteroid for two months. Then it tried to land on the surface in order to get some fragments, which will be brought back to the Earth in 2010.

The authors have installed an experimental small rover named "MINERVA(MIcro/Nano Experimental Robot Vehicle for Asteroid)" into the explorer [10](Fig. 2). MINERVA was supposed to make a world first surface exploration after having been deployed onto the surface from the mother spacecraft. It is the smallest spacecraft with a weight of 591[g] and a dimension of about 10[cm] in size. In its small body, MINERVA is equipped with an autonomous moving ability over the micro-gravity environment on the asteroid and a few science instruments to characterize the surface.

MINERVA was deployed on 12 November 2005. Unfortunately it could not reach at the asteroid because the deployment was not done at the good timing. Thus it became an small artificial planet. It survived

Fig.1 Artist's computer graphics illustration of HAYABUSA and MINERVA on the asteroid surface (Courtesy of Ikeshita/MEF/ISAS[9])
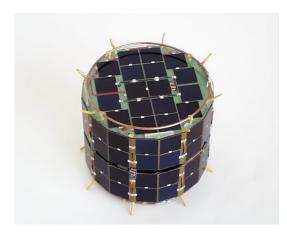

Fig.2 MINERVA

for more than 18 hours after the deployment, all the while the obtained data were transmitted to the Earth via the mother spacecraft.

This paper describes the operation and the aquired data of MINERVA. The reminder of the paper is as follows. In the next sections, MINERVA mission and its specifications are described. Then the deployment and operation conducted on 12 November 2005 are detailed. Last of all, the acquired data by MINERVA transmitted to the Earth are shown.

SUPPOSED MINERVA MISSION

MINERVA was installed in Hayabusa as an in-situ rover on the asteroid surface. It was supposed to be deployed onto the surface when the spacecraft was very near the asteroid on the way to the surface for acquiring some fragments. After the deployment, it was expected to move autonomously over the surface by hopping for a couple of days and the obtained data on multiple places were transmitted to the Earth via the mother spacecraft while Hayabusa remained near the asteroid before the departure for the Earth (Fig.3).

The major objectives of MINERVA were as follows.

(1) the establishment of the mobile system over the micro-gravity environment of small planetary bodies.
(2) the demonstration of the fully autonomous exploration equipped with the rover.

According to the precise observation by Hayabusa, the dimensions of the target asteroid Itokawa are 535 × 294 × 209[m][11]. The gravity on such a small body is on the order of 10 [μG], which is extremely weak compared with that on the Earth. The rover has a hopping mobile system fitted for the micro-gravity environment on the asteroid surface, which was supposed to be evaluated by the mission.

The acquired data by the rover is transmitted to the Earth via the mother spacecraft. The communication link was very narrow with a long time delay (about 30[min] of round trip) when the rover was on the asteroid. Additionally it was not always established between the rover and the Earth because the Earth-spacecraft communication link and the rover-spacecraft one could not be attained simultaneously. Thus, teleoperating the rover from the Earth was not practical and the rover needed the fully autonomous exploration capability, which was expected to be demonstrated by the mission.

MINERVA SPECIFICATIONS

The developed rover is shown in Fig.2 and the specifications are summarized in Table 1. It has the shape of hexadecagonal-pole (a pole with the base plane of hexadecagon, nearly a cylinder) with a diameter of 120[mm] and height of 100[mm]. Its weight is slightly less than 600[g].

CPU system

The CPU system has 512k[Byte] of ROM which preserves the program and 2M[Byte] of RAM as a
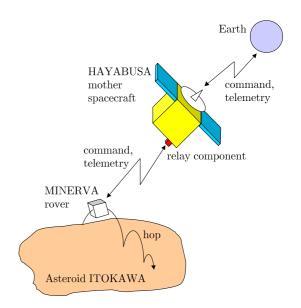

Fig.3 MINERVA mission

working area. Additionally it has a Flash ROM of 2M[Byte] in which the acquired data are once stored. The clock speed of the CPU is decreased to 10[MHz] in order to lessen the power consumption.

Power supply

The rover is powered by solar energy, supplemented by secondary batteries, which enable a few minutes activity with no help by the sun when the solar rays are blocked by shadows.

The solar cells are attached on each face of the rover. The generated power is dependent on the attitude of the rover, with a maximum power of 2[W] expected when the rover is at a distance of 1[Astronomical Unit] from the Sun.

The extra power is charged in the electric double layer capacitors. The onboard CPU works with the instantaneous solar power, but it is not sufficient for actuators and radio communication with the mother spacecraft. For such operations, additional power supply from the charged capacitors is necessary.

Actuators

MINERVA has a hopping ability with two actuators inside the body (Fig. 4). Both actuators are DC motors controlled by a PWM scheme. One motor is used as a torquer making the rover hop. By rotating a torquer inside the rover, a reaction force against the surface makes it hop (Fig.5)[12][13]. The other one rotates the table on which the torquer is placed. This turntable is rotated very slowly, which controls the hopping direction. The hop by rotating the turntable is also possible.

The hop speed is largely dependent on the actuated torque. So it can be roughly controlled onboard, but not so precisely because the hop speed is also affected by the friction between the rover and the surface which can not be predicted.

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Table 1 Specifications of MINERVA rover

size	hexa-decagonal-pole diameter ϕ: 120[mm], height: 100[mm]
mass	591[g]
CPU	Hitachi SH3 (32bit RISC CPU), clock: 10[MHz]
memory	ROM: 512[kB], RAM: 2[MB], Flash ROM: 2[MB]
temperature range	-50 $\sim$ +80[°C]
actuators	two DC motors (hop,turn)
hopping ability	9[cm/s](max)
power supply	solar cells: 2[W](max) @ 1[AU] from the Sun capacitors: 5[V], 20[F]
communication	9,600[bps]
sensor	three CCD cameras six photo diodes ten thermometers

Depending on the friction coefficient, a maximum speed of 9[cm/s] can be attained using the selected DC motor. The hop speed is controlled by changing the duty ratio of the PWM pulses in order not to exceed the velocity of escape from the small body surface.
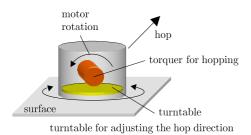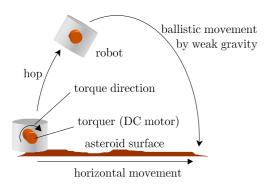

Fig.4 Turntable structure

Fig.5 Hopping mobile system by torquer

Thermal control

The surface of the asteroid is very cruel in the sense of temperature. The surface temperature will grow up above +160[°C] in the daytime but it will drop down below -100[°C] in the night semisphere. There is no device working all the time in such a wide thermal range. Thus some action is needed for severe thermal condition.

The operational temperature range of the onboard devices is from -50[°C] to +80[°C]. Beyond the range, the devices are saved but do not work well.

There is an automatic capability equipped with the rover to wake up and shutdown the onboard CPU depending on the surrounding temperature. When the temperature becomes more than +80[°C] or less than -50[°C], the power supply to the CPU is suspended.

The capacitors are not degraded even if it is very cold. But they gradually degrade themselves when the temperature goes higher than +130[°C]. After a couple of days on the asteroid surface, the capacitors can no longer be used because they have experienced a couple of overheated daytimes. Even so, as long as the solar energy is supplied, the CPU works, but the hop performance is degraded and the rover may not move.

The onboard software also monitors the internal temperature. If it comes toward the threshold of working temperature, the actions which consume much power are suspended and the data in RAM are transferred to the Flash ROM in order not to be disappeared by the sudden shutdown of the CPU system.

The onboard devices are covered by a heat insulation material (MLI). The heat capacity of the rover is very small and the temperature of the onboard devices is very easy to synchronize with the surrounding asteroid temperature. During the night semisphere, the asteroid will fall in temperature below -100[°C], but the temperature on the onboard devices is not quickly dropped down because the heat transfer is blocked. This makes the quick wakeup of the rover at the sunrise because the device temperature is not so low. Toward the noon, the temperature may become higher than +80[°C] and the rover will take a nap for a while just like the people who live on the hotter region.

Onboard sensors

CCD cameras, photo diodes (PDs) and thermometers are installed in the rover for navigation and observation.

The rover has three identical CCD cameras mounted on the turntable. The camera sight direction can be controlled by rotating the turntable. There are camera windows at the center of the side faces of

Table 2 Deployment sequence of the rover

time (UT)	time offset [sec]]	event
12/Nov 06:07:38		transmission of command to deploy the rover on the ground
06:24	0	rover deployed
06:24:20		first real HK packet generation after the deployment
	+120	orbital maneuver of 30[cm/s] to get away from the asteroid by Hayabusa spacecraft
	+212	first shoot by the camera onboard Hayabusa
	+250	second shoot by the camera onboard Hayabusa
	+300	third shoot by the camera onboard Hayabusa
	+480	fourth shoot by the camera onboard Hayabusa
06:40		confirmation on the ground about the deployment by the telemetry-generated after the deployment
13/Nov 00:32:20		last telemetry tranmitted from the rover

the rover, through which the cameras view the outside. The focal length can not be adjusted onboard. So two of the cameras are set to observe the nearby scene and the last one is for more distant views.

The rover has six photo diodes (PDs). Every PD points to a different direction, and they are allocated at all the faces of the cube. A single PD senses the intensity of the incoming light. The rover always monitors the values of PDs and judges whether it moves or not. When the rover moves by hopping, it may slightly tumble and the incoming intensity into a PD varies with time. If the values do not change, the rover may be on the surface, not moving.

There are pins sticking out from the body to protect the solar cells. Six of the pins are also used as thermal probes, by which the temperature of the surface is measured.

OPERATION

Deployment plan

MINERVA was to be deployed from the mother spacecraft on 12 November 2006 when Hayabusa rehearsed the descent to the surface. During the operation at that day, Hayabusa was to be controlled very near the asteroid but did not touch onto the surface. The supposed closest distance was 70[m] with a relative velocity of 5[cm/s].

The approach operation of Hayabusa was controlled manually by the commands transmitted from the Earth. The trigger of the deployment of MINERVA was also manual, which was supposed to be conducted when Hayabusa was closest to the asteroid.

The one-way time delay between the Earth and Hayabusa was about 16[min] on 12 November 2006. Thus the deployment operation of MINERVA was a time-delayed teleoperation by estimating the world after 32[min]. The deployment command will reach at the spacecraft after 16[min] have passed since the departure from the Earth. The result of the deployment will be known to us after 16[min] have passed.

Actual deployment

According to the analysis after the operation, the distance of Hayabusa and Itokawa when MINERVA was deployed was 200[m], which is of course much longer than we had expected. Moreover Hayabusa was getting away from the surface with a relative speed of 15[cm/s]. Thus MINERVA did not reach at the asteroid surface. It became a solar orbiting satellite. The deployment of MINERVA was a complete failure.

After the deployment, Hayabusa made an orbital maneuver quitting away from the asteroid as soon as possible and conducted four photographings using the onboard camera in order to capture the deployed MINERVA. The sequences of events conducted and occurred during the deployment operation are listed in Table 2.

If the rover was on the surface, because the asteroid is rotating with the period of 12[hour], it went to the night semisphere with no light after 3[hour] had passed. The communication link should have been lost shortly after the deployment.

The communication link between MINERVA and Hayabusa was continuously established after the deployment. The last telemetry data from the rover was generated at 00:32:20(UT) on 13 November when 18[hour] has passed since the deployment. It proved that the rover was not on the surface but floating in the space.

There was nothing wrong in the last telemetry. The reason why the communication link was eventually lost after 18[hour] is that the rover went out of the coverage of the antenna onboard Hayabusa. The rover perfectly worked after the deployment.

CONFIRMATION OF DEPLOYMENT

We confirmed the deployment of MINERVA by a telemetry data reached at the Earth after 16[min].

MINERVA telemetry

- The working mode of the rover
  Immediately before the deployment, the rover was notified the upcoming deployment from Hayabusa. When the rover receives the notification, it automatically shifts the working mode from "manually controlled mode" to "autonomous exploration." The first telemetry

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data after the deployment said that the shift of the mode had been conducted to start the autonomous exploration.

- The estimated status of the rover
The onboard CPU of the rover is always estimating the own status by the values of the photo diodes (PDs) whether it is still on the asteroid surface or during the ballistic orbit after the hop. Before the deployment, the rover was attached to the mother spacecraft by the cover and no sunlight was shining on the rover. Thus the estimated status was always the former ("still") because there was no changes on the values of PDs. The estimated status changed to the latter ("during hopping") after the deployment. That meant the deployment was successfully conducted and the sunlight was filling the tumbling rover.

- Cover sensor
The cover has two metals inside and two hole elements sense the existence of metals. After the deployment, both hole elements showed that there were no metals in the vicinity, which meant that the rover and the cover were no longer there.

Images by Hayabusa camera

Four pictures were shot by the onboard camera of Hayabusa. Fig.6 shows the obtained images after 212, 250, 300[sec] have passed since the deployment respectively. There are somethings in two circles of the each image. The object in the circle is possibly the rover and the other object in the dotted circle may be the cover.

ACQUIRED DATA

In this section, the acquired data by the rover are described.
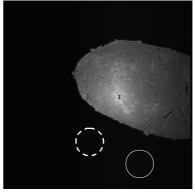
Obtained image

MINERVA captured an image of Hayabusa immediately after the deployment. Fig.7 shows the image. That is the first picture which photographed the spacecraft in the deep space from outside. Note that it is the only image that the rover transmitted to Hayabusa.
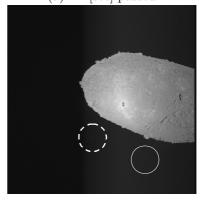
The image size is 160×80[pixel]. The original image size is 160×120[pixel] at this phase, which is larger than the actual transmitted image. One third of the image downside was not transmitted due to the autonomous evaluation function about the captured images equipped with the rover[14].

The rover evaluates the captured image. Partial areas with no scenes are trashed and not stored. This function was equipped with the rover for increasing the data transmission efficiency by the surface exploration of MINERVA. The rover captures the images very randomly with no attitude control during hopping over the asteroid surface, which stochastically prevents one-half of the images from begin included with scenes.
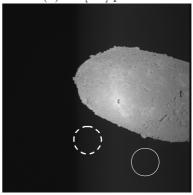
The reason why the only one image was transmitted will also come from the autonomous image evalua-

(a) 212[sec] passed

(b) 250[sec] passed

(c) 300[sec] passed
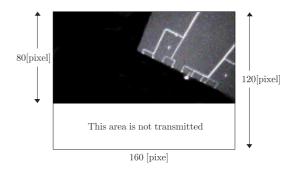
Fig.6 Picture taken by the Hayabusa camera

Fig.7 The only picture that MINERVA took after the deployment (size: 160 × 80 [pixel])

tion function. During the autonomous mode after the deployment, the rover certainly captures the images periodically, but almost all the images are not stored because Hayabusa and Itokawa are too small in the image if they existed.

Telemetry history

The status data of MINERVA such as temperatures, the voltage of the battery, and the incoming light sensed by the photo diodes were periodically measured and transmitted to the Hayabusa spacecraft for 18[hours].

Fig.8 ∼ 10 show the history of some status data. The horizontal line denotes the date and time in UTC. The rover was turned on four hours before the deployment and the figures show the trend before and after the deployment.

Fig.8 shows the voltage of the power supply system of the rover. Before the deployment, the power was supplied from Hayabusa spacecraft. After the deployment, it came from the solar cells, which dropped the voltage to some extent.

Fig.9 shows the history of incoming light sensed by one of the photo diodes. Because the rover was tumbling, the value was changing drastically.

Fig.10 shows the history of the temperature measured at the tip of the pin of the rover. After the deployment, the temperature was very stable by the influence from the Sun and Itokawa. Detailed analysis about the thermal radiance from Itokawa is needed which may derive the hint of the thermal structure of the asteroid.
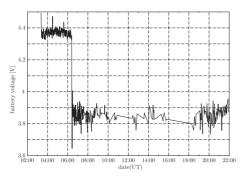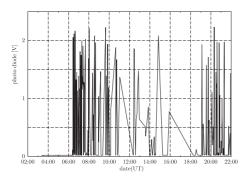

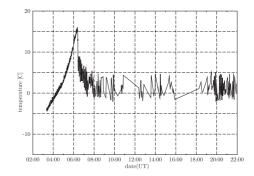**Fig.**8 Voltage history

Fig.9 PD history

Fig.10 Temperature outside history

Conclusions

This paper describes the operation and obtained data of MINERVA rover which was installed in the Japanese asteroid explorer "Hayabusa" and became the smallest artificial planet orbiting around the Sun.

MINERVA rover did not go to the target asteroid surface but it worked perfectly after the deployment. The technical experiments are partially conducted and the scientific knowledge may be derived by the future analysis of the obtained data.

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