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Sampling and Surface Exploration Strategies in MUSES-C and Future Asteroid Missions

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Abstract

This paper presents sampling and surface exploration strategies in the future possible asteroid missions. As a pioneer of the asteroid sample-return missions, MUSES-C has been developed by Institute of Space and Astronautical Science, Japan, and will be launched in May, 2003. In the MUSES-C, various technologies are challenged and studied for future exploration of minor bodies in our solar system. One of the key technologies is sampling strategy. As the surface of an asteroid is very small, it is difficult for a spacecraft to land and stay, or support the reaction from the sampling action. We discussed a variety of sampling strategies and came up with the idea of touch-down sampling for MUSES-C. Efficiency of sample collection, and motion dynamics of the spacecraft during and after the sampling have been studied intensively. A micro-rover for surface locomotion was also developed to be deployed over the asteroid's surface. In the first half of the paper, the sampling and surface exploration technologies developed for MUSES-C are reviewed. By extending these technologies, the later half of the paper investigates possible mission scenarios that use a novel exploration rover to travel over a boulder of the asteroid's surface. In order to guarantee the arbitrary locomotion over the micro-gravity surface, a grabbing mechanism using micro-nails was studied. Micro-nails under the scale of the boulder's surface roughness would be advantageous, comparing to other methods for stick or walk. A prototype model is developed to confirm this basic idea Feasibility study of mass and power budget is also presented.

1 Introduction

Minor bodies, including a number of asteroids, comets and meteors, are attracting scientific interests as a means of not only delivering extraterrestrial materials to Earth, but deeply committing of the generation and extinction of lives on the Earth. A number of probes have been launched to explore some of those bodies, and revealing their interesting nature. Such probes include *GIOTTO* to comet *Halley, NEAR-Shoemaker* to asteroid *Eros,* which successfully brought a number of exciting pictures and scientific data. An emerging generation of the missions, such as *STARDUST* and *MUSES-C,* are for sample acquisition and return to Earth, which will enable us to analyze detailed mineralogic composition of specific comets and asteroids, and hence, enable us to identify the origin of meteorites collected on the Earth.

And in an upcoming generation of minor body exploration, *in-situ* analysis at arbitrary locations of the surface, such as on a boulder and in a groove, is expected. To make such exploration possible, robotics technology for surface locomotion will play an important role. As a breakthrough step to future robotic exploration, in the mission of MUSES-C (see Figure 1), currently under the development by Institute of Space and Astronautical Science, Japan (ISAS) and foreseeing the launch in May, 2003, a robotic device named *MINERVA* will be deployed on the target asteroid 1998SF36.

Unlike the surface of *Major* bodies, such as Earth, Moon, or Mars, the gravity level on the surface of a minor body is remarkably small, then a conventional lander cannot stay stably, or a robot cannot move on the surface with conventional locomotion strategies. Therefore the main body of MUSES-C will attempt dynamic *touch-and-go* for sample collection from the surface [1], and its tiny rover MINERVA will use an internal reaction wheel, or torquer, instead of conventional car-like wheels, to obtain the thrusting force on the surface [2].

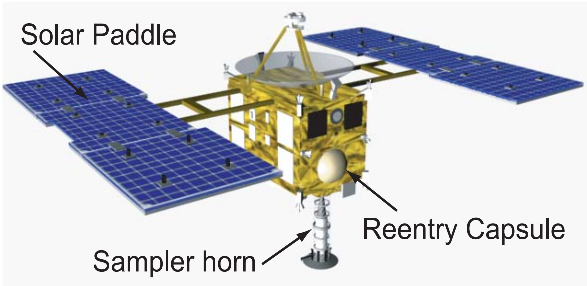


Figure 1: MUSES-C for an asteroid sample-return mission

Even with its genius idea, the motion of the MINERVA will be hopping and bouncing, then the location of the robot when the bounds are finally damped out is very opportunistic and difficult to predict or control. As an improved design of a rover for arbitrarily locomotion over the micro-gravity surface, this paper propose a robot named *"Cliff Hanger, Rock Climber Rover."*

The proposing rover uses multiple limbs with a sticker at the end. After a careful consideration of possible sticking forces, centimeter-long claws are concluded most effective to grab a boulder that may have millimeter-order roughness on its surface. The proposing rover is promising to move to a given location on a boulder or in a groove with minimum uncertainty.

In this paper, as an extension of MUSES-C technology, discussion is made on a feasible design of future asteroid mission with a dedicated exploration rover.

2 Sampling From a Minor Body

2.1 Candidate Strategies

Key consideration in the sampling on a minor body is versatility to micro-gravity and unknown hardness of the surface. As a general discussion, the following strategies are considered possible candidates (see Figure 2):

(a) Anchor and Drill: Drilling is a common idea to obtain core samples from surface to interior. However to achieve the drilling, the spacecraft must be anchored firmly on the surface to accommodate the reaction (see Figure 2 (a)). Both drilling and anchoring will be possible on soft surface, such as the surface of a comet. ROSETTA, an European comet probe takes this strategy [3].

(b) Harpoon and Penetrator: Figure 2 (b) describes an idea to penetrate a sampling probe into the target using its kinetic energy. If properly designed, samples will be packed in the penetrator, and if tethered they can be retrieved. In this strategy, the

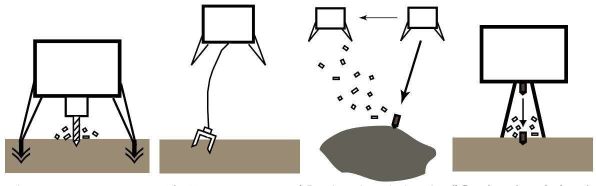


Figure 2: Variety of sampling strategies

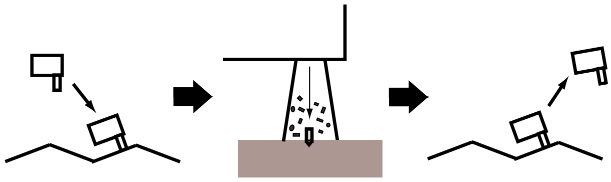


Figure 3: Sampling sequence of MUSES-C

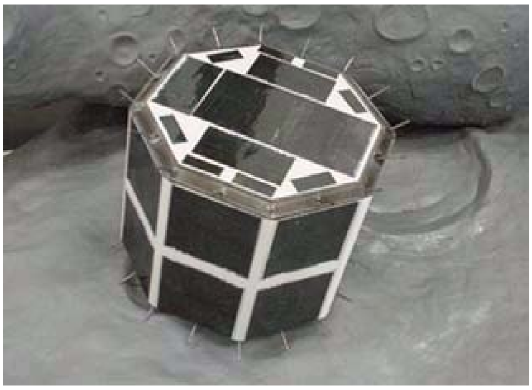
spacecraft needs hovering over the sampling site, but landing or touch-down is not needed. Hovering may be less critical than touch-down when without tether. But with tether, its deploy and retrieval becomes a challenging issue.

(c)(d) Crash Sampling: If a bullet-like projectile is projected with certain velocity, the surface will be crashed and fragments are ejected. Then, one idea is to collect such fragments in an orbit (see Figure 2 (c)). The dust collection technology used in STARDUST mission [4] will be applied here. But as the distance between the crash and sampling sites is far away, the sample acquisition becomes uncertain and, even if obtained, it is difficult to distinguish the point where each fragment comes from.

Another idea is to collect the crushed fragments on or at close vicinity of the surface, as shown in Figure 2 (d). In this option, the spacecraft is required to make physical contact with the surface although, if the projectile is projected inside a probe that has a conical shape, the ejected fragments will be deflected along the cone and concentrated at the top corner. With this strategy, samples are efficiently collected from a specific point of the surface. This strategy is applicable for a wide range of surface hardness from basalt, for example, to regolith. Also, since the sampling will be completed instantaneously, the time of the physical contact with the asteroid's surface can be short, then the sampling sequence will be like "touch-and-go."

2.2 Sampling Sequence of MUSES-C

From the above four candidates, the last strategy was chosen for MUSES-C and a number of tests have been carried out to make a detailed design. In the flight model, the projectile of 5 [g] is projected at 300 [m/s]. The test results show that several hundred milligrams to several grams of fragmented target materials can be collected by a single sampling action [5].



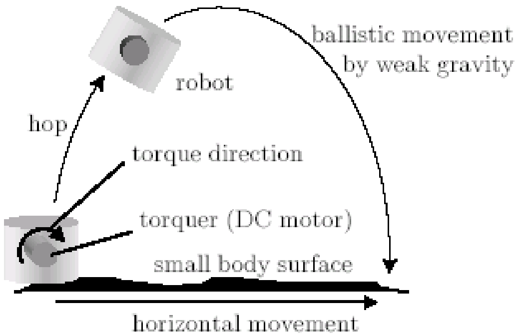


Figure 4: A picture of MINEVRA rover with a schematic of its hopping motion

Figure 3 illustrates the sampling sequence. The spacecraft descends toward a specific point of the asteroid using a vision-based autonomous guidance system, so that the contact velocity is controlled within 0.1 [m/s] vertically and 0.08 [m/s] horizontally.

The conical probe is supported by *Double-reverse Helical Spring (DHS)*, a dedicated deployable structure with compliance. This compliance is effective to absorb the remaining kinetic energy and ensure a certain period, 1-2 seconds based on our analysis, of contact time.

As soon as the contact is detected, the projectile is projected for crash sampling. Tumbling motion of the spacecraft can be caused by the contact reaction through the sampler horn, because the horn is mounted on the spacecraft with some offset from its centroid. After the sampling, gas-jet thrusters will be fired to lift the spacecraft off from the surface, and ensure the safety against any tumbling, or tip-over motion or uncertain behavior.

2.3 Deployment of MINERVA Rover

Before the MUSES-C will come to the contact with the asteroid, a small rover named *MINERVA* which stands for MIcro/Nano Experimental Robot Vehicle for Asteroid, will be deployed to the asteroid's surface.

Table 1: Possible strategies of locomotion on micro-G surface

Mode of Locomotion	Example	Feasibility	Location
Wheel Traction	Nano Rover (JPL)	Minor	Opportunistic
Hopping	MINERVA (MUSES-C)	Flight Model	Opportunistic
Holding ("Rock Climber")	This Study	Promising	Boulders and Grooves
Snake	Proposed by Mizuno et al. [4]	Promising	Grooves

The shape of MINERVA is hexadecagon-pole with diameter of 12 [cm] and height of 10 [cm], as shown in Figure 4. It weighs about 600 [g]. It is powered by solar energy.

The rover has a capability to hop over the surface. There is no apparent actuator outside the rover, but by rotating a torquer inside the rover, a reaction force against the surface makes the rover hop in the micro gravity field.

In spite of its small body, MINERVA equips three CCD cameras for scientific observation. It also has communication capability with the spacecraft MUSES-C. The communication bit rate is 9,600[bps] and the maximum communicable distance is 20[km].

MINERVA is expected to carry out the following scientific missions: (1) obtain images of the asteroid surface in visible wavelength, (2) construct a detailed surface model by comparing a pair of images which is taken by two cameras with short focal length, (3) directly measure the surface temperature, and (4) estimate the local gravitational direction and friction coefficient of the surface.

3 Design of Future Asteroid Exploration Rover

3.1 Possible Strategies for Locomotion on Micro-G Surface

Due to the luck of the forces to push a wheel, limb or body on the surface in the mirco-gravity environment, the design of a robot becomes completely different from the familiar designs that we usually see on the ground. Table 1 summarizes possible strategies for locomotion on micro-gravity surface.

The NANO Rover [6] was studied as a candidate for the rover to be carried in the MUSES-C asteroid mission. However, the cancellation was announced by NASA in November 2000. The NANO Rover has four wheels; each one is attached at the end of a swingable strut. The wheel itself will not work on micro-gravity surface because no traction force is generated without any normal force to push the wheel on the surface. However, the wheel may work with dynamic forces when it is swung down by the strut, and the rover will hop to a certain direction.

The hopping action can be generated by a simpler mechanism. The MINERVA uses a single reaction wheel (torquer) inside the robot to produce the inertial reaction. In both designs, however, the location of the robot when the bounds are finally damped out is very opportunistic and difficult to predict or control.

If the robot has limbs with a sticker, it can walk on the surface like a rock climber, or an insect, or a spider. This is a very promising idea, but the development of a reliable sticker becomes an issue.

Snake like articulated body that can tie around a rocky edge or push both lateral sides in a narrow ditch, is also an interesting idea [7].

3.2 The Cliff Hanger, Rock Climber Rover

A conceptual design of a newly proposing robot is depicted in Figure 5, with a photographs of a laboratory prototype.

The robot has multiple limbs with a dedicated sticker at the end, and walks over the surface using these limbs. The design of the limb can be like an articulated manipulator arm. But considering that it does not need to support gravitational load, and hence it should be light-weight, slim, and compact, the limb can be like a multi-DOF forceps that are used in laparoscopic surgery[8][9].

Like a laparoscopic forceps, the endtip of the limb has jaws to pick or pinch an object. The idea is to use the jaws to hold the surface of the asteroid. As discussed in the following section, claws in the scale of roughness of the surface will help to ensure the holding capability of the jaws.

In addition to the hold and legged locomotion, the limbs will be use to pick up rock fragments and to scoop soft regolith if it exists. The rover may need to row in a pond of regolith between boulders. As for the preparation of in-situ analysis, the limbs will be also useful to blush the surface of specimens.

The mission concept of the boulder exploration is depicted in Figure 6. The surface exposed boulders contain direct information of the asteroid's interior as deep as its size. The proposed rover can provide crawling capability over arbitrary boulders, cliffs, grooves and ponds. Specific scientific activities include:

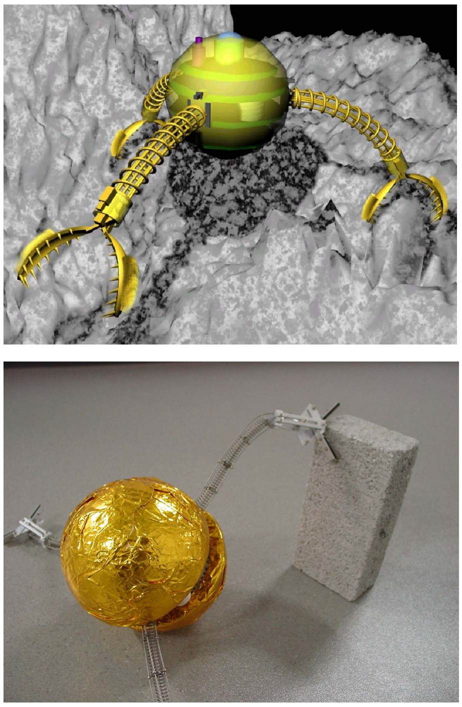


Figure 5: A conceptual drawing and a laboratory prototype of “Cliff Hanger, Rock Climber Rover”

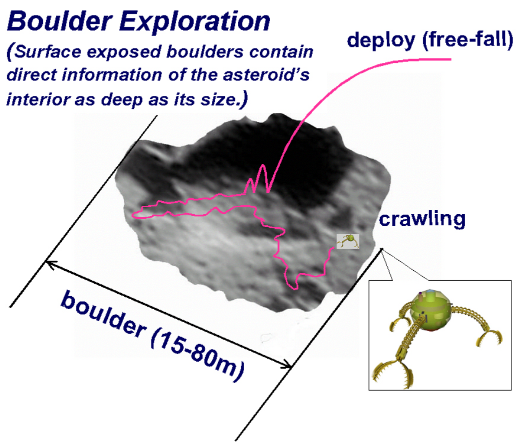


Figure 6: A mission concept for boulder exploration

- Image the stratigraphy exposed on a boulder or groove,
- Blush the surface regolith coating, then take images or conduct in-situ mineralogical and elemental analyses by mass spectrometry (e.g., NIR, APX, gamma-rays.)

And as possible extensive options, the followings are expected:

- Place of seismometer network at specific locations,

- Collect and bring samples back to an ascending vehicle.

4 Grabbing Forces

4.1 Candidates for the Grabbing Sticker

The grabbing force is a key to achieve the surface locomotion. In this section four of fundamental forces are compared, and the feasibility of the claw-like mechanical sticker is discussed.

As candidates for sticking forces that may work on micro-G surface, we picked up Van Der Waals force, electrostatic force, and universal gravity to be compared with the holding force of mechanical claws.

The Van Der Waals force is known as the intermolecular force. Its attracting magnitude is in the inverse proportion to the sixth power of the distance in case of between two molecules. But as the summation of those forces, the force between two parallel surfaces becomes in the inverse proportion to the third power of the distance [10]:

$$F_v = \frac{A}{6\pi L^3} \quad \text{(per unit area)} \tag{1}$$

where L is a representative length on the distance of parallel surfaces, and A is known as the Hamaker constant.

Electrostatic force works if there is electrical charge, or its potential field. The magnitude of the force between two parallel surfaces is:

$$F_e = \frac{\epsilon_0 V^2}{2L^2} \quad \text{(per unit area)} \tag{2}$$

where V is voltage (electrical potential,) and ϵ_0 is known as the coefficient of dielectricity or permittivity of vacuum.

Universal gravity force between two bodies is well known as:

$$F_g = G\frac{Mm}{r^2} \tag{3}$$

where r is not the distance of the gap, but the distance of centroid of two bodies, and G is known as the gravity constant.

As for the clamping force of claws, the following model is considered:

$$F_c = W_{max}\mu \sin^2\theta \tag{4}$$

where μ is friction coefficient and θ is the inclination of the surface. W_{max} is the force when the claw has a maximum bending displacement, x_{max}. If the claw is modeled as a uniform cantilever, the relationship between the bending displacement and force is expressed as:

$$W_{max} = \frac{3EIx_{max}}{\ell^3} \tag{5}$$

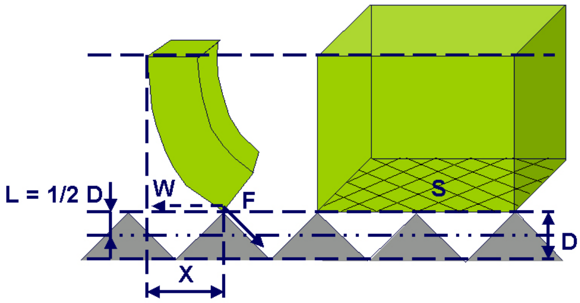


Figure 7: Contact model on a rough surface

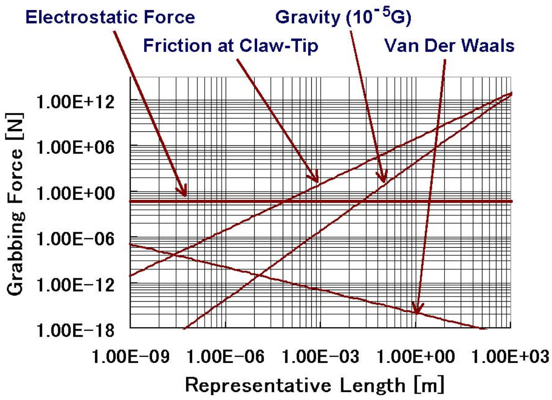


Figure 8: Scale Effect of Grabbing Forces

where E and I are Young's modulus and moment of inertia of area, respectively. ℓ is the length of the cantilever.

4.2 Scale Effect Analysis

For a fair comparison of above four possible grabbing forces, a contact surface model, with normalization by a representative length, is introduced. The magnitude of the forces are evaluated according to the representative length.

As shown in Figure 7, the roughness of the asteroid surface is modeled by uniform ridges (or notches) with the height (or depth) of D and the width of $2D$. For the evaluation of the Van Der Waals, electrostatic, and gravitational forces, the robot is assumed to be laid down on the ridges. The covering area S is grater than a single ridge. In such a case, the mean distance between the asteroid and the robot is $D/2$.

Set the representative length $L = D/2$, and the size of robot is assumed a cube with $100L$ each, then $S = L^2 \times 10^4$.

As for the claw force, the maximum deformation of the claw is assumed by $x_{max} = D = 2L$. Eventually, if the deformation is grater than this, the claw will loose contact with a current ridge and slip to a neighbor ridge. Here, the claw's length and moment of inertia of area are assumed $\ell = 10L$ and $I = D^4/12 = 4L^4/3$. Then, Equation (4) becomes:

$$F_c = 8\mu E L^2 \sin^2\theta \times 10^{-3} \tag{6}$$

Here, the constants are listed as:

$$\begin{aligned}
A &= 10^{-19} \ \text{[J]} \\
\epsilon_0 &= 8.85 \times 10^{-12} \ \text{[F/m]} \\
V &= 10^3 \ \text{[volt]} \\
G &= 6.67 \times 10^{-11} \ [\text{m}^3/\text{kgs}] \\
R &= 1.0 \times 10^3 \ \text{[m]} \\
M &= 5.0 \times 10^{12} \ \text{[kg]} \\
\rho &= 10^3 \ [\text{kg/m}^3] \quad = 1 \ [\text{g/cm}^3] \\
\mu &= 0.5 \\
\theta &= 45 \ \text{[deg]} \\
E &= 6.9 \times 10^{10} \ [\text{N/m}^2]
\end{aligned}$$

Figure 8 shows the result of comparison of four forces for the scale L from 10^{-9} to 10^3 [m]. The figure clearly describe the scale effect of the forces.

Van Der Waals force is always smaller than others in all scales. Electrostatic force is dominant in the scale of $L < 10^{-5}$ [m]. The claw force is then dominant in the scale of $10^{-5} < L < 10^3$ [m], that is a very wide range covering from 10 microns to 1 kilometer. Finally the gravitational force dominates in the scale of $L > 10^3$ [m], i.e. the robot is in an equivalent size, or larger than the asteroid.

As a feasible size in a practical mission, this paper assumes the robot in the order of 0.1 [m] (10 cm) cube or sphere, mass of 1-10 [kg], having claws of 0.01 [m] (1 cm) long and 0.001 [m] (1 mm) thick, which can grip the surface with the roughness of ± 0.001 [m] (1 mm).

4.3 Claw prototype

Figure 9 depicts a prototype of a claw in the above dimension. A miniature servo motor for a model plane was used as an actuator. The developed claw works to hold on the surface of a natural stone, even in 1G environment.

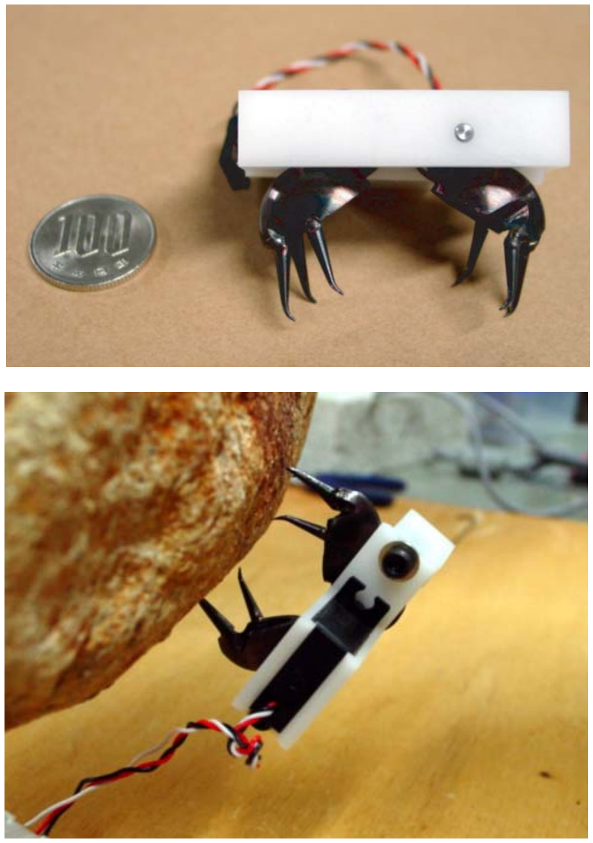


Figure 9: Photo of a claw prototype

5 Mission Scenarios and System Design

5.1 Baseline Scenarios

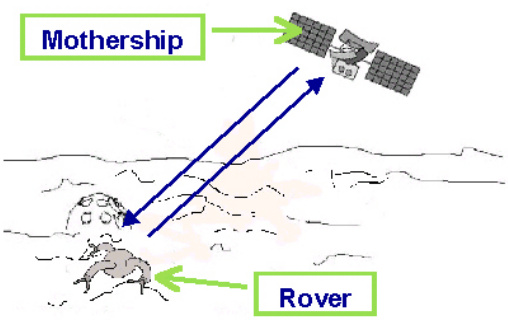
Here, two options of baseline mission scenarios are discussed. Scenario A is an option consisting of Orbiter (Mothership) and Rover (see Figure 10a.) On the other hand, Scenario B is an option consisting of Orbiter (Mothership), Lander, and Rover (see Figure 10b.)

In Scenario A, the rover will be deployed from the mothership to touch down on a boulder. For soft touch-down, the deploy should be done not from a high altitude of orbit, but from the mothership hovering at the height about 10-100 meters. The specific values are depend on the gravity of the target asteroid although, if the size of target is equivalent to the target of MUSES-C (several hundreds meters in a mean diameter,) the touch-down velocity will be 1-10 cm/s after the free fall from the height of 10-100 m. In this scenario, power, communication, and other house-keeping functions must be all contained within the rover. If the mothership goes back to the orbit after the deployment of the rover, it will be helpful to relay the communication from/to Earth.

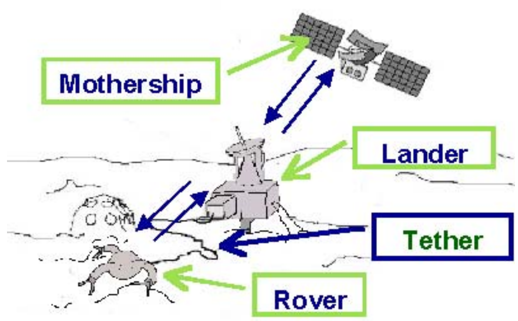
In Scenario B, a lander will be separated from the orbiter to touch down and anchored on a boulder. Then, the rover is deployed from the lander. If the lander and rover are connected by a tether for communication and power supply, the function of the rover can be focused on mobility and scientific activities. Or even the scientific instruments can be separately mounted on the lander and rover.

Table 2: System level trade-offs on two baseline scenarios

Baseline scenarios:	A. Orbiter + Rover	B. Orbiter + Lander + Rover
Landing	Effective shock absorber is required on Rover for shock protection and quick stabilization.	Anchor is required on Lander
Power	Power generator must be carried on Rover. Solar generation may have difficulty under the shade.	Power generator will be located on Lander that can stay under the sun.
Communication	Communication devices, including antenna, must be carried on the Rover. Data relay by Orbiter will be necessary.	Communication devices can be placed at Lander. Pointing of a high-gain antenna will be possible if Lander is firmly anchored.
Lander-Rover connection	not applicable	Power and Communication are supplied through the tether. Weight of tether is not negligible. Tether is sometimes difficult to handle.
Locomotion of Rover	Self-contained rover is more massive and bulky than Rover in B. Rover operation is subject to the communication window supported by Orbiter.	Distance from Lander is limited by the length of tether. Lander-based power supply and communication can offer wider window of operation.



Scenario A: Orbiter (Mothership)+Rover



Scenario B: Orbiter (Mothership)+Lander+Rover

Figure 10: Baseline mission scenarios

5.2 Landing Technology

For the rover in Scenario A, effective shock absorber is required for the shock protection and quick stabilization. For this purpose, *bead absorption* technology developed for MUSES-C Target Markers [11] can be applied. The bead absorption has been proven highly effective to have smaller value of coefficient of restitution against landing impact. The rover can be covered by an insulator filled with a number of tiny beads.

For the Scenario B, the lander must be anchored. As for anchoring technology, penetration using the kinetic energy of hard landing can be applied. Technology for penetrators has been developed for *LUNAR-A* [12] and *DEEP SPACE 2* [13] missions. Very high-G impact will be a critical point in the design. On the other hand, technology for harpoon legs will be used for soft landing on a comet in *ROSETTA* mission [3]. However, the harpoons may not work for the surface of asteroid with hard surface.

5.3 System Level Trade-Off

System level trade-offs in various aspects are summarized in Table 2. Scenario B is more dedicated to higher quality of science though, there are a number of challenges in the landing and anchoring of Lander, and in the deployment and handling of the tether that connects Rover with Lander.

On the other hand, for Scenario A, all the technologies that are currently developed and will be demonstrated in MUSES-C, will be directly applied. Such technologies include free-fall deployment, shock absorption and quick stabilization using beads, and operation of Rover and data collection from Rover via Orbiter. Therefore, this option seems more promising for immediate future.

5.4 Sizing of a Scenario A Rover

Here, the size of Rover is discussed from the sizing of power sources. Table 3 shows the size of the solar array and battery, if required power in active mission is 5 [W] and required house-keeping power in sleep is 0.5 [W]. Mission per rotation, $1/n$, means a case in which the rover sleeps for battery charging for $n-1$ rotations and becomes active in the n-th rotation. Such option helps to make the array smaller, but increase the battery size then the robot heavier. The results on the array size are in the order of 10 centimeters, which fits our previous assumption made in force estimation.

Target asteroid:	
- distance from Sun:	1.4 [AU]
- rotation period:	3 [hrs]
Rover activity	
- time of enough light:	1 [hrs]
- power in active:	5 [W]
- power in sleep:	0.5 [W]

Table 3: Sizing of solar array and battery

Mission per rotation	Peak power generation [W]	Max. battery charge [Wh]	Solar array area [m^2]	Array size (if square) [m]	Array radius (if circular) [m]
1	17.0	1.2	0.17	0.41	0.23
1/2	9.5	2.3	0.09	0.31	0.17
1/3	6.9	3.6	0.07	0.26	0.15

6 Conclusions

In this paper, sampling and surface exploration strategies were discussed for the future possible asteroid missions.

After reviewing possible sampling strategy from an asteroid, which was characterized as a micro-gravity field, MUSES-C mission was introduced as a pioneer of asteroid sample-return missions. Its unique rover, MINERVA, was also highlighted.

Then a novel robot that could stick on the surface and move to desired directions on boulders and in grooves was discussed as a potential candidate for a coming generation of minor body exploration. The conceptual design was named "Cliff Hanger, Rock Climber" robot, and its laboratory prototype was developed.

The forces to stick on the asteroid's surface was discussed, and a mechanical gripper that uses claws was concluded advantageous than a sticker that uses electrostatic, or other forces.

Possible mission scenarios were discussed, and the mission composed by Orbiter and Rover was pointed out on the direct extension of MUSES-C technology.

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