A NOVEL STRATEGY FOR ASTEROID EXPLORATION WITH A SURFACE ROBOT

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ABSTRACT

A novel strategy of asteroid exploration is studied that enables in-situ analysis of a minor body at specific locations. As a first step for rover exploration of minor bodies, Japan’s asteroid sample/return probe MUSES-C, to be launched in May 2003, will deploy a robotic device Minerva over the surface of the target asteroid. Due to micro-gravity on minor bodies, the locomotion technology becomes completely different from the one on Earth, Moon, or Mars. The Minerva hops over the surface using inertial reaction, but its navigation is opportunistic. As a potential candidate for a coming generation of minor body rovers, this paper proposes a novel robot that could stick on the surface and move to desired directions on boulders and in grooves. The conceptual design is named “Cliff Hanger, Rock Climber” robot. Its design requirement, technology to stick and hold on boulders, and a feasible mission scenario and system design are addressed.

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 GIOOTTO 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, 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].

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

<table>
<thead>
<tr>
<th>Mode of Locomotion</th>
<th>Example</th>
<th>Feasibility</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel Traction</td>
<td>Nano Rover (JPL)</td>
<td>Minor</td>
<td>Opportunistic</td>
</tr>
<tr>
<td>Hopping</td>
<td>Minerva (MUSES-C)</td>
<td>Flight Model</td>
<td>Opportunistic</td>
</tr>
<tr>
<td>Holding (“Rock Climber”)</td>
<td>This Study</td>
<td>Promising</td>
<td>Boulders and Grooves</td>
</tr>
<tr>
<td>Snake</td>
<td>Proposed by Mizuno et al. [4]</td>
<td>Promising</td>
<td>Grooves</td>
</tr>
</tbody>
</table>

named “Cliff Hanger, Rock Climber Rover” (see Figure 1.)

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, the discussion is made on a feasible design of the asteroid exploration rover with the assessment of sticking forces, dimension and power budget, and feasible mission scenarios.

DESIGN OF AN ASTEROID EXPLORATION ROVER

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 micro-gravity environment, the design of a robot becomes completely different from the familiar designs that we usually see on the ground. Table I summarizes possible strategies for locomotion on micro-gravity surface.

The NANO Rover [3] was studied as a candidate to the rover to be deployed 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 [4].

In this paper, the discussion and analysis are made on the rock climber concept.

The Cliff Hanger, Rock Climber Rover: Its Design Concept and Prospecting Mission

A conceptual design of the proposing robot is depicted in Figure 1 and the photographs of a laboratory prototype are in Figure 2.

The robot has at least three sets of 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[5][6].

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 used 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 brush the surface of specimens.

The mission concept of the boulder exploration is depicted in Figure 3. 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 are

- Images interior of cracks and stratigraphy exposed on groove walls,
- Brush the surface regolith coating, then image and conduct in-situ mineralogical and elemental analyses, including mass spectrometry (e.g., NIR, APX, gamma-rays.)

And as possible options,

- Place seismometer network at specific locations,
- Collect and bring samples back to an ascending vehicle.

THE GRABBING FORCES

Candidates for the Grabbing Sticker

The grabbing force is a key to achieve the surface locomotion. In this section four of fundamental forces are
Figure 2: A Prototype model for “Cliff Hanger, Rock Climber Rover”

Boulder Exploration
(Surface exposed boulders contain direct information of the asteroid’s interior as deep as its size.)

crawling
deploy (free-fall)
boulder (15-80m)

Figure 3: A mission concept for boulder exploration 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 \[ F_v = \frac{A}{6\pi L^3} \text{ (per unit area)} \] (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:

\[ F_e = \frac{\varepsilon_0 V^2}{2L^2} \text{ (per unit area)} \] (2)

where \( V \) is voltage (electrical potential,) and \( \varepsilon_0 \) is known as the coefficient of dielectricity or permittivity of vacuum.

Universal gravity force between two bodies is well known as:

\[ F_g = \frac{GMm}{r^2} \] (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:

\[ F_c = W_{\text{max}} \mu \sin^2 \theta \] (4)

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

\[ W_{\text{max}} = \frac{3EIx_{\text{max}}}{\ell^3} \] (5)

where \( E \) and \( I \) are Young’s modulus and moment of inertia of area, respectively. \( \ell \) is the length of the cantilever.

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 4, 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 greater 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 $S = L^2 \times 10^4$.

From Equations (1) and (2), the Van Der Walls and electrostatic forces over the surface $S$ are expressed by $L$, as follows:

$$F_v = \frac{AS}{6\pi L^3} = \frac{A}{6\pi L} \times 10^4$$

Equation (6)

$$F_e = \frac{\epsilon_0 V^2 S}{2L^2} = \epsilon_0 V^2 \times 10^4$$

Equation (7)

As for the gravitational force, the mass of the robot is modeled as $\rho L^3 \times 10^6$. The centroid distance $r$ becomes $R + L$ where $R$ is a mean radius of the asteroid. Now, Equation (3) becomes:

$$F_g = G \frac{\rho M L^3}{(R + L)^2} \times 10^6$$

Equation (8)

As for the claw force, the maximum deformation of the claw is assumed by $x_{\text{max}} = D = 2L$. Eventually, if the deformation is greater than this, the claw will lose 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:

$$F_c = 8\mu EL^2 \sin^2 \theta \times 10^{-3}$$

Equation (9)

Here, the constants are listed as:

$$A = 10^{-19} \text{ [J]}$$
$$\epsilon_0 = 8.85 \times 10^{-12} \text{ [F/m]}$$
$$V = 10^9 \text{ [volt]}$$
$$G = 6.67 \times 10^{-11} \text{ [m}^3]/\text{kg}$$
$$R = 1.0 \times 10^{3} \text{ [m]}$$
$$M = 5.0 \times 10^{12} \text{ [kg]}$$
$$\rho = 10^3 \text{ [kg/m}^3]\] = 1 \text{ [g/cm}^3]\]$$
$$\mu = 0.5$$
$$\theta = 45 \text{ [deg]}$$
$$E = 6.9 \times 10^{10} \text{ [N/m}^2]\]$$

Figure 5 shows the result of comparison of four forces for the scale $L$ from $10^{-9}$ to $10^{7}$ [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 $L > 10^{6}$ [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 $\pm0.001$ [m] (1 mm).

**MISSION SCENARIOS AND SYSTEM DESIGN**

**Baseline Mission Scenarios**

Here, two options of baseline mission scenarios are discussed. Scenario A is the option consisting of Orbiter (Mothership) and Rover (see Figure 6a.) On the other hand, Scenario B is the option consisting of Orbiter (Mothership), Lander, and Rover (see Figure 6b.)

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

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

**Figure 6: Baseline mission scenarios**

Scenario A: Orbiter (Mothership)+Rover

Scenario B: Orbiter (Mothership)+Lander+Rover

 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.

**Landing Technology**

On 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 [8] can be applied. The bead absorption has been proved 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 [9] and Deep Space 2 [10] 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 [11]. However, the harpoons may not work for the surface of asteroid.

**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.

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 the case to sleep and charge the battery for \(n - 1\) rotations and become active in the \(n\)-th rotation. This option helps to make the array smaller, but the increment of battery size yields 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

<table>
<thead>
<tr>
<th>Mission per rotation</th>
<th>Peak power generation [W]</th>
<th>Max. battery charge [Wh]</th>
<th>Solar array area [m²]</th>
<th>Array size (if square) [m]</th>
<th>Array radius (if circular) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.0</td>
<td>1.2</td>
<td>0.17</td>
<td>0.41</td>
<td>0.23</td>
</tr>
<tr>
<td>1/2</td>
<td>9.5</td>
<td>2.3</td>
<td>0.09</td>
<td>0.31</td>
<td>0.17</td>
</tr>
<tr>
<td>1/3</td>
<td>6.9</td>
<td>3.6</td>
<td>0.07</td>
<td>0.26</td>
<td>0.15</td>
</tr>
</tbody>
</table>

CONCLUSIONS

In this paper, 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.

Feasible size of the rover was discussed and the following dimensions were suggested as one of reasonable designs:

- Number of limbs: more than 3
- Sticker mechanism: frictional contact by 1 cm long claws
- Surface roughness: order of 1 mm
- Size of solar array: 30 cm by 30 cm, typically
- Power in activity: 5W
- Power in sleep: 0.5W
- Rover mass: between 1 and 10 kg

REFERENCES


