Asteroid Exploration Using Plural Small Rovers and Relative Distance Estimation on Undulating Terrain

Masahiko Mikawa
University of Tsukuba
e-mail: mikawa@slis.tsukuba.ac.jp

Abstract

This paper describes a robot system consisting of plural small size rovers for an asteroid exploration. The rover equipped with sensors communicates each other with ZigBee and configures a wireless mesh sensor network on an asteroid surface. When the rovers communicate each other, received signal strength indicators (RSSIs) can be obtained. It is known that the antenna characteristics as internal factors, distance and terrain undulation among antennas as external factors have some influences on RSSI values. So, this paper presents a radio wave propagation model among the rovers and a relative position estimation method. Our proposed system has the following three advantages against a conventional exploration system using one or two rovers: (1) It is possible to explore a wider area efficiently. (2) The mesh network has redundant communication paths is more robust over troubles. (3) The estimated relative distances among plural rovers is useful for asteroid analyses. Our proposed estimation method is evaluated by simulation experiments.

1 Introduction

Planetary, asteroid and lunar explorations are one of the active research areas in aerospace fields. Hayabusa (MUSES-C), an unmanned asteroid explorer developed by the Japan Aerospace Exploration Agency (JAXA), returned samples of the asteroid “Itokawa” to Earth in 2010 [1]. The improved Hayabusa-2 [2] will be launch to the asteroid “1999 JU3” in 2014. The National Aeronautics and Space Administration (NASA) has also proposed that the OSIRIS-REx [3] will be launched to the asteroid “1999 RQ36” in 2016.

The sample return is the most important task for these projects. At the same time, Hayabusa-2 has several other missions too. One of them is to carry the improved MINERVA-II (the Micro/Nano Experimental Robot Vehicle for Asteroid) [4] to the asteroid. MINERVA-II will explore autonomously on the asteroid surface under a microgravity environment.

There are some research topics for a small planetary exploration rover like MINERVA-II. One is research and development for a movement mechanism that is suitable to explore under a microgravity environment. Several hopping mechanisms have been proposed in these papers [4][5][6][7]. The other is a self-localization estimation for a rover. Yan, et al. proposed the self-localization method using asteroid surface images captured by plural cameras mounted on the rover [8]. Kanata, et al. proposed the self-localization method based on round-trip propagation delays derived when a rover on a asteroid and a mother spacecraft communicate with radio waves [9].

So, we are studying both a new type of a robot system consisting of plural small size rovers for an asteroid exploration and a method for estimating relative distances among the plural rovers [10]. Our proposed rover can communicate with the others using radio, and a wireless mesh network is configured on an asteroid surface. When a rover communicates another ones, RSSI (Received Signal Strength Indicator) can be obtained at the same time. Since the RSSI value changes depending on a distance between two antennas, the relative distances among the rovers are estimated based on the RSSI values. Our proposed system has the following three advantages compared with a conventional exploration system using one or two rovers.

(1) It is possible to explore a wider area efficiently.
(2) Since the mesh network has redundant communication paths, it has more robustness against troubles.
(3) The relative distance estimation is useful for asteroid analyses using sensors that the rovers have.

Both our proposed relative distance estimation method based on using the genetic algorithm (GA) and the mathematical model that expresses the relations among the RSSI values and the distances worked well. When three rovers were used, the error rates of the estimated relative distance were less than 2.3 [%], and when five rovers were used, the error rates were less than 6.2 [%]. However, we assumed that a terrain between two rovers (antennas) was flat, the RSSI value is affected by the terrain actually.

So, we design a new propagation model with taking into consideration of an undulating terrain between two rovers (antennas) in this paper. However, since many parameters are required in order to express a complex undulating terrain, we use a knife-edge diffraction propagation model to express an undulating terrain between two...
rovers for simplicity. Even the propagation model using one knife-edge can express a convex or concave terrain depending on the height of the knife-edge. On the other hand, both the number of unknown parameters to be estimated and the search space for GA increase more than those of the previous paper. Lastly, we evaluate the proposed model and relative distance estimation method with simulation results.

2 Asteroid exploration system consisting of plural small size rovers

2.1 Concept

We have proposed the robotic system consisting of plural small size rovers for an asteroid exploration. Figure 1 shows our proposed exploration system. This system consists of the plural cubic type rovers whose dimension is about 30 [mm] on a side in our plan.

![Figure 1. Asteroid exploration system consisting of plural small rovers](image)

The rovers communicate with each other through a wireless network and establish a mesh-type network on the asteroid surface as shown in Figure 2. The wireless mesh network offers multiple redundant communication paths through the network. If the network link or the rover as the network node fails for any reason, the network automatically routes messages through alternate paths. This means that the exploration mission can have high robustness against several troubles such as failures of a part of plural rovers or missing them. Moreover, the rovers can explore a wider area of the asteroid surface efficiently while changing the network topology as shown in Figure 2 (b). These ideas are useful for an asteroid exploration.

2.2 Rover configuring mesh network using ZigBee

A rover equipped with a hopping mechanism [4][6] has a high mobility and it is effective to explore under a microgravity environment such as an asteroid surface. However, when this type of rover lands on an asteroid surface after hopping, it is difficult to control the orientation of the rover. If the antenna for communication is buried in the ground, or if the level of the antenna from the ground is too low, the rovers might have some troubles in communication. So we design a rover equipped with twelve antennas using a diversity scheme as shown in the left of Figure 3. The rover can always communicate with others under the good condition by selecting a pair of antennas shown in the same color on the top side, whenever the rover is in any orientation.

![Figure 3. Rover with twelve antennas and prototype with three antennas](image)

The right of Figure 3 shows prototypes equipped with three antennas. It is composed of an onboard microcomputer (AM-205, Air Micro, Inc.), three chip antennas (AH083F245001, Taiyo Yuden Co., Ltd) and a switch (MASW-008330, M/A-COM Technology Solutions Inc.) for switching the antenna. This microcomputer is small and has enough I/O ports. And since its electrical power consumption is low, it is suitable to control the rover totally. Moreover, it is compliant to 2.4GHz band ZigBee/IEEE802.15.4 MAC protocol stack, and it is easy to configure a mesh network.

3 Relative distances and terrain parameters estimation based on RSSIs

3.1 Basic idea and estimated parameters

When the rover as the communication node receives a packet from another one, RSSI can be obtained at the same time. Table 1 shows an example of the communication contents related to RSSIs. \( r_{ai,bj} \) means a RSSI value from an antenna \( a \) mounted on a rover \( i \) to an antenna \( b \) mounted on a rover \( j \), and NG means communication failure. Each rover transmits a beacon periodically to make
Table 1. Communication contents sent from rovers to Earth

<table>
<thead>
<tr>
<th>Rover ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna</td>
<td>a</td>
<td>b</td>
<td>a</td>
<td>b</td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td></td>
<td>a</td>
<td>b</td>
<td>r_{1a,2a}</td>
<td>r_{1a,2b}</td>
<td>r_{1a,3a}</td>
<td>r_{1a,3b}</td>
</tr>
<tr>
<td>b</td>
<td>r_{2a,2a}</td>
<td>r_{2a,2b}</td>
<td>r_{1b,2a}</td>
<td>r_{1b,2b}</td>
<td>r_{1b,3a}</td>
<td>r_{1b,3b}</td>
</tr>
<tr>
<td>a</td>
<td>r_{2a,1a}</td>
<td>r_{2a,1b}</td>
<td>r_{2b,2a}</td>
<td>r_{2b,2b}</td>
<td>r_{2b,3a}</td>
<td>r_{2b,3b}</td>
</tr>
<tr>
<td>b</td>
<td>r_{3a,1a}</td>
<td>r_{3a,1b}</td>
<td>r_{3a,2a}</td>
<td>r_{3a,2b}</td>
<td>r_{3b,2a}</td>
<td>r_{3b,2b}</td>
</tr>
</tbody>
</table>

... ... ...

this RSSI table. The RSSI table is transmitted from the rover to Earth through a mother spacecraft like Hayabusa.

Let the number of the rovers be \( n \). Since two antennas per the rover are used for communication as described in the previous section, the number of the RSSI values is \( 4n(n - 1) \) combinations. Let the data size of RSSI be 1 [byte] and the number of the rovers be \( n = 10 \), the data size of a set of the RSSI values is only 360 [byte]. Of course, since the rover transmits and receives observation data collected on board several sensors, an actual transmission data size increases.

Since the calculation of the location estimation is complex, it is not suitable for the low power consumption onboard microcomputer in the rover to calculate it. In our plan, all the RSSI values obtained from the rovers are transferred to Earth, complex calculations are executed on a more powerful computer on Earth.

Figure 4 shows estimated parameters. The coordinate system \( \Sigma_i \) is fixed at the center of the rover \( i \) \((i = 1, ..., n)\), and two antenna \( ia \) and \( ib \) are mounted on it. \( \Sigma_1 \) of the rover 1 is the reference coordinate system for the other rovers. \( ip_j \in \mathbb{R}^{3 \times 1} \) and \( IR_j \in \mathbb{R}^{3 \times 3} \) mean the position and the orientation of the rover \( i \) in \( \Sigma_i \) respectively.

Next, there are a knife-edge between two rovers, the knife-edge divides the line segment defined by two point \( ip_j \) and \( ip_j \) internally in the ratio \( r_{ij,ij} \): \((1 - r_{ij,ij}) \) \((0 < r_{ij,ij} < 1)\). And let the height of the knife-edge be \( h_{ij,ij} \).

These parameters related to the knife-edge such as \( r_{ij,ij} \) and \( h_{ij,ij} \) are also estimated. Although the knife-edge exists in Figure 4, when its height has a negative value, a concave terrain can be expressed.

The number of the rovers is \( n \). The known parameters are a set of the obtained RSSI values as shown in Table 1. Since \( r_{ia,ja} \) has the same value with \( r_{ja,ja} \), the number of this known parameters is \( 4n_1 C_2 = 2n(n - 1) \). Since \( \Sigma_1 \) of the rover 1 is the reference coordinate system, the number of the unknown parameters related to the rover’s position and orientation is \( 6(n - 1) \). The number of the unknown parameters related to the knife-edge’s height and position is \( 2n C_2 = n(n - 1) \). So then, the total number of the unknown parameters is \((n - 1)(n + 6)\). Therefore, \( n \geq 9 \) rovers are required to estimate these unknown parameters based on the known parameters, a set of RSSIs.

3.2 Radio wave propagation model

In this subsection, we describe the calculation of RSSI based on the geometric relationships between two rovers.

First of all, a received electrical field intensity \( E_f \) [V/m] in a free-space is given by

\[
E_f = \frac{\sqrt{30P_{t}f}}{d}
\]

(1)

where \( P_{t} [\text{W}] \) is a transmitted power, \( d [\text{m}] \) is a distance between transmitting and receiving antennas and the antennas are loss free.

Figure 5 shows a two-ray ground reflection propagation. A received power \( P_{r} [\text{dBW}] \) is given by

\[
P_{r} = 10 \log \left( \frac{E_f \lambda^2}{480 \pi^2} \right)
\]

(2)
where \( \lambda \) [m] is a wavelength. A received electric field intensity \( E_r \) [V/m] and a phase delay \( Ph_d \) are shown by the following equations respectively.

\[
E_r = 2E_f \left| \sin \left( \frac{Ph_d}{2} \right) \right| \quad (3)
\]

\[
Ph_d = 2\pi \sqrt{\frac{(h_1 + h_2) - \sqrt{d^2 + (h_1 + h_2)^2}}{\lambda}} \quad (4)
\]

\[ \text{Figure 6. Knife-edge diffraction propagation} \]

Thirdly, Figure 6 shows a knife-edge diffraction propagation. The Fresnel-Kirchhoff diffraction parameter \( v \) is given

\[
v = h_k \sqrt{\frac{2}{\lambda} \left( \frac{1}{r_k d_1} + \frac{1}{d_1 (1 - r_k) d_1} \right)} \quad (5)
\]

where \( 0 < r_k < 1 \) and \( h_k \) is a height of a knife-edge as shown in Figure 6. The knife-edge diffraction gain \( G_k(v) \) as the propagation model is given by the following equations using \( E_k(v) \) and a free-space electrical field intensity \( E_f \).

\[
G_k(v) = \frac{|E_k(v)|^2}{|E_f(v)|^2} = \frac{1}{2} \left( C(v) + \frac{1}{2} \right) + \left( S(v) + \frac{1}{2} \right) \quad (6)
\]

\[
S(v) = \int_0^\infty \sin \left( \frac{\pi t^2}{2} \right) dt, \quad C(v) = \int_0^\infty \cos \left( \frac{\pi t^2}{2} \right) dt \quad (7)
\]

\[
L_{kr} = -10 \log_{10} G_k(v) \quad (8)
\]

The variations of \( G_k(v) \) with \( v \) are shown in Figure 7. In short, this graph shows that the propagation loss increases when \( v \) is large (the knife-edge is high) and the propagation loss is little when the knife-edge height is low.

\[ \text{Figure 7. Relations between } G_k(v) \text{ and } v \]

The received power \( P_{ar} \) [dBW] is given by the following equation under the environment where there are both a two-ray ground reflection and a knife-edge.

\[
P_{ar} = P_{ir} - L_{kr} \quad (9)
\]

\( P_{ar} \) depends on the distance between two antenna \( d_1 \), the height of the knife-edge \( h_k \) and the ratio \( r_k \) in which the knife-edge divides the distance \( d_1 \). This propagation model is not perfect but approximate. However, we believe that this model is useful as a first step for evaluating the relative distance estimation method under the condition where the rovers are on the undulating terrain.

### 3.3 RSSI values between two rovers

Two antennas fixed on the surface of the rover are used to communicate another rover as shown in Figure 3, and \( n \) rovers are used in this paper. The coordinate system \( \Sigma_i \) is fixed in the center of the rover \( i \), the rover \( i \) is equipped with two antennas \( a_{ia} \) and \( a_{ib} \). When two rovers communicate each other, four RSSIs, \( r_{ia_{ia}}, r_{ia_{ib}}, r_{ib_{ia}} \) and \( r_{ib_{ib}} \), are obtained. Figure 8 shows these geometric relationships.

\[ \text{Figure 8. Geometric relations among two rovers, four antennas and knife-edge} \]

In this subsection, we describe how to calculate these four RSSIs based on the geometric relationships among two rovers, four antennas and the knife-edge. As described in the previous subsection, the heights of two antennas, the height of the knife-edge, the distance from one antenna to the knife-edge and the distance from the other antenna to the knife-edge are used to calculate one RSSI.

The knife-edge plane \( pl_e \) passes through the point \( e \) that divides the line \( ij \) internally in the ratio \( r_k : (1 - r_k) \), and let the line \( ij \) be at right angle to the knife-edge plane \( pl_e \). The points \( k_{ia_{ia}} \) and \( k_{ia_{ib}} \) are intersections of the lines \( a_{ia_{ia}} \) and \( a_{ia_{ib}} \) and the plane \( pl_e \) respectively.

The plane \( pl_b \) is the reference plane for calculating the heights of four antennas and the knife-edge, and defined by the following two conditions. First, the height \( h_b \) between the point \( e \) and the plane \( pl_b \) is a constant value and determined based on the dimensions of the rover. Second, the normal vector of \( pl_b \) is vertical to both the directional vector of line \( ij \) and the vector \( \overrightarrow{ka_{ia_{ia}}ka_{ia_{ib}}} \).

The points \( k'_{ia_{ia}} \) and \( k'_{ia_{ib}} \) are the points for defining the top of the knife-edge. The point \( k'_{ia_{ia}} \) is at the distance \( h_k \) from the point \( k_{ia_{ia}} \) in the direction of the vector that is vertical to both the normal vector of \( pl_e \) and the vector \( \overrightarrow{ka_{ia_{ia}}ka_{ia_{ib}}} \). When \( h_k \) is positive, the knife-edge hides the paths among all the antennas. When \( h_k \) is negative, although the path between two antennas is clear, the knife-
edge have some effects on the Fresnel zone. The point $k'_{ia_{ib}}$ can be determined using $k_{ia_{ib}}$ in the same manner. As a result, the knife-edge line $k'_{ia_{ib}}$ that is parallel to the line $k_{ia_{ib}}$ is determined. Therefore, $h_k$ is the height of the knife-edge related to the both of the communication between two antennas $a_{ia}$ and $a_{ib}$ and the communication between two antennas $a_{ja}$ and $a_{jb}$.

Next, the intersections $k_{ib_{ja}}$ and $k_{ib_{ja}}$ of the lines $a_{ia}a_{ja}$ and $a_{ib}a_{jb}$ and the plane $p_{le}$ are calculated respectively. Let the foots of a perpendicular from the points $k_{ia_{ja}}$ and $k_{ia_{ja}}$ to the line $k'_{ia_{ja}}$ be $k'_{ia_{ja}}$ and $k'_{ia_{ja}}$ respectively, the height of the knife-edge related to the communication between two antennas $a_{ib}$ and $a_{ja}$ is determined by the length of the line segment $k_{ib_{ja}}k_{ib_{ja}}$. Likewise, the height of the knife-edge related to the communication between two antennas $a_{ib}$ and $a_{jb}$ is determined by the length of $k_{ib_{ja}}k_{ib_{ja}}$.

On the other hand, it is simple to determine the distance from one antenna to the knife-edge and the distance from the other antenna to the knife-edge. Since the points $k_{ia_{ja}}$, $k_{ia_{ja}}$, $k_{ib_{ja}}$, and $k_{ib_{ja}}$ on the knife-edge plane $p_{le}$ divide the lines $a_{ia}a_{ja}$, $a_{ib}a_{jb}$, $a_{ia}a_{ja}$, and $a_{ib}a_{jb}$ respectively, for example, the distance between two points $a_{ia}$ and $k_{ia_{ja}}$ and the distance between $a_{jb}$ and $k_{ia_{ja}}$ are used for calculating the RSSI value between two antennas $a_{ia}$ and $a_{ja}$.

Finally, the height of each antenna is determined based on the foot of the perpendicular from each antenna to the plane $p_{le}$.

To wrap up, the RSSI value can be calculated by these parameters and Eq. (9).

Although there are the following arrangement patterns of the antennas and the knife-edge, their explanations are omitted here. For example, all or three antenna positions are on one line, or the terrain is concave when $h_k$ has a large negative value.

### 3.4 Actual measured RSSI values

The actual RSSI values were measured on the wide and flat field in order to clarify the relation among the RSSIs and distances as shown in Figure 9. A pair of AM-205 ZigBee modules were placed opposite each other, and the distances and RSSI values were measured while changing the distance between two ZigBee modules.

The measurement results are shown in Figure 10. It is known that a relation between a RSSI value and a distance is nonlinear because of the multipath propagation when a pair of two antennas have a certain degree of height. However, when the antenna level is lower than the wave length (125 [mm] for 2.4 [GHz]), the influence of the multipath propagation disappears. So, we could get the linear characteristics of RSSI as shown in Figure 10. On the other hand, the theoretical received power (RSSI) calculated based on Eq. (2) is shown in Figure 11. Since this theoretical RSSI is similar to the actual measured value, we use the theoretical RSSI based on Eq. (2) in simulation experiments described in the following section.

**Figure 10.** Relation among RSSI values and distances

**Figure 11.** Theoretical value of received power

**Figure 12.** Antenna Characteristics

Next, we measured antenna characteristics related to its orientation in the situation where one of the pair of the AM-205 modules was fixed and the other was rotated. So we could get the approximate model related to the antenna orientation as shown in Figure 12. When the RSSI values are calculated based on Eq. (2), this model also factors in the calculation.

### 3.5 Relative distance estimation using genetic algorithm

As described in the subsection 3.1, the unknown parameters are the positions and orientations of all the rovers.
and the knife-edge parameters between all combinations of the rovers, the known parameters are the measured RSSI values. It is necessary to solve the nonlinear simultaneous equations that are expressed based on the relations among these known and unknown parameters in order to estimate the positions and orientations of all the rovers and the knife-edge parameters. However, the number of the simultaneous equations and the unknown parameters is large, it is impossible to solve analytically. Moreover, the search space for numerical analysis is large. So, in this paper, we use the genetic algorithm (GA) to solve this problem. Let the measured and estimated RSSI values \((i = 1, \cdots, n)\) be \(r_{ia_{ij}}\) and \(\hat{r}_{ia_{ij}}\) respectively. In this paper, the evaluation function \(f(r)\) for the GA was designed as shown in the following equation.

\[
f(r) = \sum_{i=1}^{n} \sum_{j=2}^{n} ((r_{ia_{ij}} - \hat{r}_{ia_{ij}})^2 + (r_{ia_{ij}} - \hat{r}_{ia_{ij}})^2 + (r_{ib_{ia}} - \hat{r}_{ib_{ia}})^2 + (r_{ib_{ia}} - \hat{r}_{ib_{ia}})^2) \tag{10}
\]

### 4 Experimental Results

#### 4.1 Conditions of genetic algorithm

GAlib [11], the C++ library of genetic algorithm components, was used to implement the GA. The number of the generation was 10000, the number of the population was 200, the crossover rate was 0.9, and the mutation rate was 0.05 in this paper. Each search range for the rover position \((x, y, z)\) was \(\pm 10\) [m] respectively, ones for the rover orientation (roll, pitch, yaw) were \(\pm \pi/4, \pm \pi/4\) and \(\pm \pi\) respectively, and ones for the knife-edge height and ratio were \(\pm 0.5\) [m] and \(0.2 \sim 0.8\) respectively.

Currently, it is not enough to adjust these parameters, estimated values are always different depending on initial values. So the estimation is repeated again and again, the best result that minimizes \(f(r)\) is chosen as a final result.

#### 4.2 Estimation results using nine rovers

Nine rovers were placed on the \(x\)-\(y\) plane as shown in Figure 13. Table 2 shows the true distances, the estimated distances and the error rate. The distances \(d_{ij}\) are estimated at the error rate of \(0.7 \sim 41.7\) [%] (the average error rate 20.2 [%]).

<table>
<thead>
<tr>
<th>Table 2. Estimated relative distances</th>
</tr>
</thead>
<tbody>
<tr>
<td>True value [mm]</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>d12 6000.0</td>
</tr>
<tr>
<td>d13 8485.3</td>
</tr>
<tr>
<td>d14 6000.0</td>
</tr>
<tr>
<td>d15 4242.6</td>
</tr>
<tr>
<td>d16 3000.0</td>
</tr>
<tr>
<td>d17 6708.2</td>
</tr>
<tr>
<td>d18 3000.0</td>
</tr>
<tr>
<td>d19 6708.2</td>
</tr>
<tr>
<td>d20 6000.0</td>
</tr>
<tr>
<td>d21 8485.3</td>
</tr>
<tr>
<td>d22 4242.6</td>
</tr>
<tr>
<td>d23 3000.0</td>
</tr>
<tr>
<td>d24 6708.2</td>
</tr>
<tr>
<td>d25 8134.0</td>
</tr>
<tr>
<td>d26 3000.0</td>
</tr>
<tr>
<td>d27 6000.0</td>
</tr>
<tr>
<td>d28 4242.6</td>
</tr>
<tr>
<td>d29 6708.2</td>
</tr>
<tr>
<td>d30 3000.0</td>
</tr>
<tr>
<td>d31 6708.2</td>
</tr>
<tr>
<td>d32 3000.0</td>
</tr>
<tr>
<td>d33 4242.6</td>
</tr>
<tr>
<td>d34 6708.2</td>
</tr>
<tr>
<td>d35 3000.0</td>
</tr>
<tr>
<td>d36 3000.0</td>
</tr>
<tr>
<td>d37 6708.2</td>
</tr>
<tr>
<td>d38 3000.0</td>
</tr>
<tr>
<td>d39 3000.0</td>
</tr>
<tr>
<td>d40 3000.0</td>
</tr>
<tr>
<td>d41 3000.0</td>
</tr>
<tr>
<td>d42 6000.0</td>
</tr>
<tr>
<td>d43 4242.6</td>
</tr>
<tr>
<td>d44 4242.6</td>
</tr>
<tr>
<td>d45 4242.6</td>
</tr>
<tr>
<td>d46 4242.6</td>
</tr>
<tr>
<td>d47 6000.0</td>
</tr>
</tbody>
</table>

Average error rate 20.2

#### 4.3 Discussion and future works

When three rovers were used in previous work [12], the error rates of the estimated relative distance were less than 2.3 [%] (the average error rate 1.2 [%]). On the other hand, the estimation result is not good at present. When
a search space for one of the unknown parameters was confined, accuracy of the estimated results became better. This means that there is a room for improvement of the estimation method.

In the next step, we will aim to improve the relative distance estimation method. At the same time, it is necessary to make the target value of the estimation clear through consultation with experts at asteroid analyses. Especially in recent years, not only a surface exploration of an asteroid or planet but a underground exploration such as [13][14][15] are started to attract attention. If the accuracy of the estimated relative distance can be improved, our technique will be able to be used efficiently for surface or underground analyses using a surface-wave method.

5 Conclusion

We have proposed a relative distance estimation method using the genetic algorithm for a robotic asteroid exploration system consisting of plural small size rovers. Our proposed method can estimate not only relative distances among the rovers, but also parameters related to undulations of a terrain. Although the average error rate of the estimated relative distance is about 20 [%], we are going to improve the estimation method in the future work.

Our proposed system can be utilized to a sensor network for and analyzing an asteroid, and also explore a wider range on an asteroid surface efficiently and execute tasks robustly against troubles.

Acknowledgments

This research is partially supported by Project No. 24500195, Grand-in-Aid for Scientific Research (C), Japan Society for the Promotion of Science.

We would like to express our gratitude to Professor Takashi Kubota, Japan Aerospace eXploration Agency (JAXA), Professor Kazuya Yoshida, Tohoku University, Japan, Associate Professor Tetsuo Yoshimitsu, JAXA, Professor Masamitsu Kurisu, Tokyo Denki University, Japan, Assistant Professor Kenji Nagaoka, Tohoku University, Japan and Professor Koichi Osuka, Osaka University, Japan, who give us constructive comments and suggestions in the “the MINERVA-II consortium.”

References


