Attitude Estimation for Small Asteroid Exploration Rovers Equipped with Plural Antennae

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ABSTRACT

We are studying an exploration system consisting of plural small size rovers. Each rover equipped with plural wireless network antennas communicates each other, and configures a wireless mesh sensor network on an asteroid. Although a hopping mechanism is suitable for exploring a micro-gravity environment such as an asteroid surface, it is difficult to control a rover attitude during landing. Since our rover is equipped with twelve antennae on its cube body, good communication state can be established among plural rovers in any attitude after landing by selecting the antennae on the top surface. In order to achieve it, it is necessary to estimate which surface is top. So this paper presents an attitude estimation method based on received signal strength indicators (RSSIs) obtained when the rovers communicate each other.

1 INTRODUCTION

An asteroid exploration is one of the active research areas in aerospace fields in recent years. Hayabusa developed by the Japan Aerospace Exploration Agency (JAXA) had been launched in 2003 and returned samples of the asteroid Itokawa to Earth in 2010 [1]. Moreover, JAXA had launched Hayabusa 2 [2] in 2014, and it is currently traveling to the C-type asteroid “Ryugu” (formerly know as 1999 JU3). The National Aeronautics and Space Administration (NASA) is also going to launch OSIRIS-REx [3] to the B-type asteroid “Bennu” in 2016. One of the important tasks in these missions is, of course, to bring samples back to Earth. On the other hand, every spacecraft is going to carry one or more than two rovers for an exploration on the asteroid surface. Three small rovers, MINERVA-IIs (MINERVA-II-1A, -1B, and -2) [4] that are improved versions of MINERVA [5], are carried to Ryugu by Hayabusa 2.

We are studying a distributed robotic system consisting of plural small size rovers for an asteroid exploration [6]. Each rover can communicate with others using radio, and a wireless mesh network is configured on a surface of an asteroid. When the rovers communicate each other, received signal strength indicators (RSSIs) can be obtained. It is possible to estimate relative distances among the rovers based on RSSIs and our proposed radio wave propagation model [7]. Our proposed system has the following advantages compared with a conventional system using one or two rovers. (1) Since the mesh network built by plural rovers has redundant communication paths, the exploration system has more robustness against some troubles. (2) It is possible to estimate the relative distances among plural rovers, the estimated results are useful for asteroid analyses using sensors that the rovers are equipped with.

It is said that a hopping type [8][9] is one of suitable moving mechanisms under a micro-gravity environment such as an asteroid surface. On the other hand, a wheel or crawler moving mechanism is not suitable because of not enough friction between the moving mechanism and the ground surface. Therefore we are planning to use the hopping mechanism for our proposed rovers. However, it is difficult for a hopping type rover to control its attitude while attempting to land, it is not clear which surface of the rover is top after landing. So the conventional Then we designed the cube-shaped rover equipped with plural antennae. Since the arrangement of the antennae has rotational symmetry, the rovers can keep a good communication state regardless of their attitudes by selecting the proper antennae for communication.

This paper presents an attitude estimation method based on received signal strength indicators (RSSIs) obtained by transmitting among plural antennae arranged on the rover. An experimental result reveals the validity and effectiveness of our proposed attitude estimation method by using the prototype rovers.

2 EXPLORATION SYSTEM CONSISTING OF PLURAL ROVERS

2.1 Concept

We are developing the robotic system consisting of plural small size rovers for an asteroid exploration as shown in **Fig. 1** [6][7].

The rovers communicate with each other through a wireless network and establish a mesh-type network on the asteroid surface as shown in **Fig. 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 **Fig. 2** (b). These ideas are useful for an asteroid exploration.

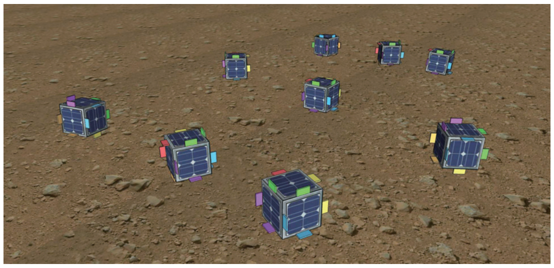

Figure 1 : Exploration system consisting of plural small rovers

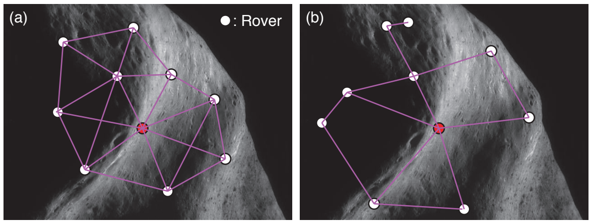

Figure 2 : Dynamic and redundant wireless mesh network configured by plural rovers

2.2 Small Rover Equipped With Plural Antennae

A rover equipped with a hopping mechanism [8][9] has a high mobility and it is effective to explore under a micro-gravity 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 attitude 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 **Fig. 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 attitude.

The 2.4 GHz ZigBee module (AM-205, Air Micro, Inc.) integrating the CPU and the chip antenna was used as shown in **Fig. 3**.

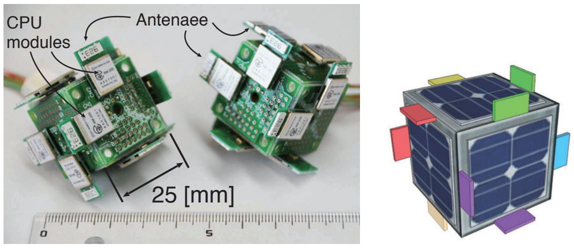

Figure 3 : Prototype of our proposed rover equipped with 12 antennae that can keep better communication

2.3 Maintenance Of Good Communication State

When a pair of the rovers communicate each other, the rovers can keep a better communication by selecting a proper pair of antennae from twelve ones. The higher the antenna level is, the longer the communication distance is. This means that it is necessary to select the pair of the antennae mounted on the top surface of the rover after landing. So, in this paper, we propose a method for estimating the attitude of the rover on the ground, specifically which surface is top.

In order to reduce the complexity of the communication sequences among the plural rovers, their communication traffic and electricity power consumption, RSSI values obtained by communicating among twelve antennae mounted on one rover are used to estimate its own attitude. This means that the rover attitude can be estimated by itself based on 132 RSSI values obtained by communicating among twelve antennae. In other words, it is unnecessary to communicate among the rovers.

3 ATTITUDE ESTIMATION BASED ON RSSIs

3.1 Collection Of RSSI values

Figure 4 shows the positions of twelve antennae mounted on the rover. Let the surface on which the antennae 0 and 1 are mounted be A, the surface with the antennae 2 and 3 be B, the surface with 4 and 5 be C, the surface with 6 and 7 be D, the surface with 9 and 9 be E, and the surface with 10 and 11 be F. RSSI values were measured from 100 to 200 times in the condition that each surface was placed upward. However, our prototype needs an external power supply, the supply cable is connected to the surface F. This means that the RSSI values cannot be measured in the condition that A is the top surface. Therefore, in this paper, we estimate which surface except A is the top surface.

The actual RSSI values were measured on the wide and flat field as shown in **Fig. 5**. The averages of the RSSI values measured among each twelve antennae are

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shown in Tables 1 ~ 5. Table 1 shows the RSSI values when B is the top surface, and Table 2 shows the RSSIs when C is the top surface. It is not easy, at first glance, to estimate the top surface from these tables. For example, when B is the top surface, the levels of the antennae 00 and 08 attached on B are the highest, and they are the best pair for communication. And the levels of the the antennae 04 and 10 attached on the bottom surface D are the lowest, and they are the worst pair. Contrary to our expectation, there were no obvious difference depending on which is the top face as shown in Tables 1 ~ 5. So we tried some classifiers based on machine learning methods as described in the next subsection.

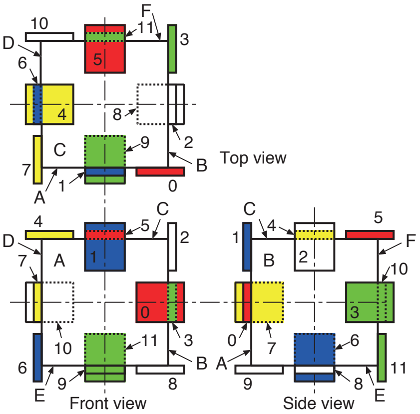

Figure 4 : Positions of antennae

Table 1 : Average values of RSSIs (Top surface is B)

	00	01	02	03	04	05	06	07	08	09	10	11
00	—	-11	-12	-11	-12	-13	-14	-10	-11	-11	-26	-32
01	-10	—	-11	-17	-17	-10	-14	-19	-17	-11	-13	-15
02	-11	-11	—	-12	-10	-11	-15	-15	-10	-17	-33	-20
03	-10	-15	-11	—	-19	-12	-23	-16	-12	-17	-11	-13
04	-12	-17	-10	-20	—	-11	-10	-27	-13	-18	-11	-19
05	-12	-10	-11	-12	-10	—	-17	-11	-20	-17	-13	-11
06	-13	-14	-15	-26	-10	-18	—	-11	-10	-12	-14	-11
07	-11	-20	-15	-18	-27	-12	-11	—	-18	-13	-12	-20
08	-10	-17	-10	-13	-12	-20	-10	-17	—	-13	-16	-13
09	-10	-11	-17	-18	-17	-17	-12	-12	-12	—	-17	-10
10	-25	-13	-32	-12	-10	-13	-14	-11	-16	-17	—	-13
11	-31	-15	-20	-14	-18	-11	-10	-19	-12	-10	-13	—

Table 2 : Average values of RSSIs (Top surface is C)

	00	01	02	03	04	05	06	07	08	09	10	11
00	—	-11	-11	-11	-12	-14	-14	-10	-11	-12	-17	-41
01	-10	—	-11	-17	-15	-10	-15	-20	-14	-11	-16	-22
02	-11	-11	—	-13	-10	-12	-16	-16	-11	-19	-19	-22
03	-10	-16	-12	—	-20	-11	-21	-17	-12	-21	-10	-14
04	-12	-16	-10	-21	—	-12	-10	-27	-13	-18	-10	-20
05	-13	-10	-11	-12	-11	—	-18	-10	-28	-18	-15	-12
06	-13	-15	-15	-22	-10	-19	—	-11	-11	-12	-12	-11
07	-10	-20	-17	-19	-26	-12	-12	—	-18	-12	-10	-18
08	-10	-14	-11	-13	-13	-27	-11	-18	—	-12	-19	-12
09	-11	-11	-18	-22	-17	-18	-12	-11	-12	—	-17	-11
10	-16	-16	-19	-11	-10	-15	-12	-10	-19	-18	—	-13
11	-40	-21	-22	-15	-18	-12	-10	-17	-12	-11	-13	—

Table 3 : Average values of RSSIs (Top surface is D)

	00	01	02	03	04	05	06	07	08	09	10	11
00	—	-11	-12	-11	-12	-18	-15	-11	-11	-11	-21	-23
01	-11	—	-11	-20	-15	-10	-16	-20	-14	-11	-13	-16
02	-12	-11	—	-13	-10	-11	-16	-14	-10	-15	-23	-25
03	-10	-19	-12	—	-20	-11	-26	-18	-12	-24	-11	-15
04	-12	-16	-10	-21	—	-11	-10	-29	-14	-18	-11	-22
05	-17	-10	-11	-12	-11	—	-16	-11	-27	-20	-11	-11
06	-15	-16	-17	-26	-10	-17	—	-10	-11	-12	-13	-11
07	-11	-21	-15	-20	-29	-12	-11	—	-19	-12	-10	-19
08	-10	-14	-11	-13	-13	-27	-10	-18	—	-12	-17	-13
09	-10	-11	-14	-24	-17	-20	-11	-10	-12	—	-20	-11
10	-21	-13	-23	-12	-10	-11	-13	-10	-18	-20	—	-14
11	-22	-16	-25	-16	-21	-11	-10	-18	-13	-11	-14	—

Table 4 : Average values of RSSIs (Top surface is E)

	00	01	02	03	04	05	06	07	08	09	10	11
00	—	-11	-12	-11	-12	-15	-13	-10	-11	-11	-21	-25
01	-10	—	-11	-18	-18	-11	-16	-22	-17	-11	-15	-18
02	-11	-11	—	-13	-10	-11	-18	-14	-10	-19	-19	-20
03	-10	-17	-12	—	-18	-12	-31	-18	-12	-23	-11	-13
04	-11	-18	-11	-20	—	-12	-10	-19	-14	-15	-11	-21
05	-14	-11	-11	-12	-11	—	-20	-11	-27	-18	-13	-12
06	-13	-16	-18	-35	-10	-21	—	-11	-11	-12	-13	-11
07	-11	-23	-15	-19	-19	-12	-12	—	-20	-12	-10	-20
08	-10	-17	-11	-14	-13	-27	-10	-19	—	-12	-17	-13
09	-10	-11	-18	-25	-14	-18	-12	-11	-11	—	-19	-11
10	-20	-16	-19	-12	-10	-14	-13	-10	-17	-19	—	-13
11	-24	-18	-20	-14	-21	-12	-10	-19	-13	-11	-13	—

Table 5 : Average values of RSSIs (Top surface is F)

	00	01	02	03	04	05	06	07	08	09	10	11
00	—	-11	-12	-11	-12	-17	-13	-11	-11	-13	-19	-19
01	-10	—	-11	-20	-15	-10	-14	-21	-15	-12	-14	-20
02	-11	-11	—	-13	-10	-11	-19	-15	-10	-15	-28	-22
03	-10	-19	-12	—	-29	-11	-25	-19	-12	-21	-11	-15
04	-12	-15	-10	-30	—	-11	-10	-20	-13	-20	-11	-19
05	-16	-10	-11	-11	-10	—	-16	-11	-34	-18	-12	-11
06	-12	-14	-18	-29	-10	-17	—	-12	-10	-12	-11	-11
07	-12	-22	-16	-21	-20	-12	-13	—	-16	-12	-10	-17
08	-10	-15	-10	-13	-12	-36	-10	-16	—	-12	-17	-12
09	-11	-12	-15	-21	-19	-17	-11	-11	-11	—	-22	-11
10	-19	-14	-27	-12	-10	-12	-11	-10	-18	-23	—	-12
11	-19	-20	-22	-16	-18	-11	-10	-16	-12	-11	-12	—

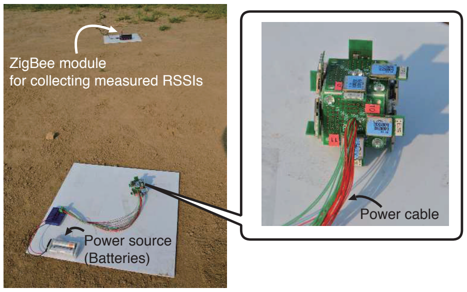

Figure 5 : Collection of RSSIs

3.2 Classifiers Based On Decision Tree

The decision tree C4.5 and the random tree were chosen to estimate which surface is the top of the rover as the classification method using machine learning

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technique. Weka [10], the data mining software, was used to design these decision trees and evaluate the estimation accuracy. The 10-fold cross-validation was carried out to train the classifier and test the data for C4.5 and the random tree respectively. The corrected RSSI values described in the previous subsection were used.

As the results of the evaluation experiments, both of the precision and recall were 100 [%] as shown in Table 6 in all the experiments. The good estimation results were got in the both C4.5 and the randome tree methods. The decision trees generated by C4.5 and the random tree are shown in **Fig. 6** and **7** respectively.

Although we could not evaluate in the case where A is the top surface, we believe that the estimation method will work well when the external power source and the power cable are removed. Moreover, since the structures of two decision trees designed in this paper were not the same, and the experimental situation where the RSSIs were collected was simple, we must proceed our investigation.

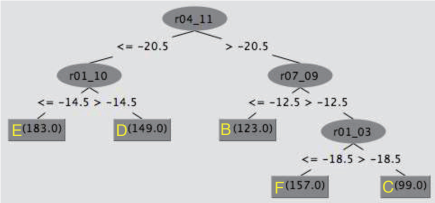

Figure 6 : Decision tree generated by C4.5

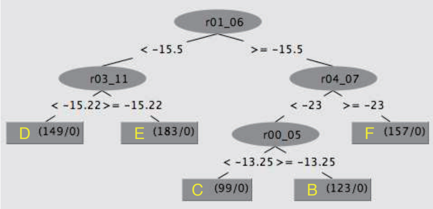

Figure 7 : Decision tree generated by random tree

Table 6 : Estimation results

	B	C	D	E	F
B	123	0	0	0	0
C	0	99	0	0	0
D	0	0	149	0	0
E	0	0	0	183	0
F	0	0	0	0	157

4 CONCLUSION

We are developing a robotic asteroid exploration system consisting of plural small size rovers, that configures a wireless network. Since the rover is going to be equipped with a hopping mechanism for moving, and its attitude is not always the same after landing. Therefore, the rover has plural antennae for communications on its surfaces. In order to maintain good communication states among the rovers, it is necessary to estimate which is the top surface of the cube body. So we proposed an attitude estimation method based on RSSIs obtained by transmitting among plural antennae arranged on the rover in this paper. The decision trees were designed by learning using the collected RSSIs, and the accuracy rate of the attitude estimation was 100 [%].

The experimental situation was simple in this paper. We will collect lots of RSSI values in several environments, and undertake several estimation experiments under more complex conditions in our future work.

Acknowledgments

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