COMPUTATIONAL TIME REDUCTION OF EVOLUTIONARY SPACECRAFT LOCATION ESTIMATION TOWARD SMART LANDER FOR INVESTIGATING MOON

Tomohiro Harada[1], Rie Usami[2], Keiki Takadama[2], Hiroyuki Kamata[3], Shinji Ozawa[4], Seisuke Fukuda[5], and Syujirou Sawai[5]

[1]*The University of Electro-Communications, Research Fellow of the Japan Society for the Promotion of Science DC, Japan*
[2]*The University of Electro-Communications, Japan*
[3]*Meiji University, Japan*
[4]*Aichi University of Technology, Japan*
[5]*Japan Aerospace Exploration Agency, Japan*

ABSTRACT

This paper proposes two methods to reduce a computational time of our evolutionary spacecraft location estimation method (namely, Evolutionary Triangle Similarity Matching (ETSM) method) which search a current spacecraft location by matching craters as a amera shot image with those in a crater map taken from "KAGUYA" satellite. However, the ETSM method required a huge computational time to estimate the current location due to the local search mechanism. To investigate the effectiveness of the proposed methods, this paper conducts computer simulation experiments based on several locations of craters as the camera shot image which is randomly selected from the crater map. Intensive experiments have revealed that (1) a one direction local search of the potential area reduces the calculation time without decreasing a success rate of the spacecraft location estimation; and (2) an integration of a continuous local search and a one direction local search can quickly estimate the spacecraft location.

Key words: location estimation; smart lander; crater matching; genetic algorithm.

1. INTRODUCTION

It is usual for a spacecraft to be planned to land a safe area "where is *easy* to land" in the conventional landing. However, this approach is hard to land an area where is close to an investigating target because of a small safe area. To tackle this issue, Japan Aerospace Exploration Agency (JAXA) proposed the SLIM (Smart Lander for Investigating Moon) mission which aims at establishing a method for landing an area "where is *desired* to land" [1]. To achieve this goal, it is indispensable for a spacecraft to estimate its current location by matching craters on a camera shot image over the moon from the spacecraft with those of a crater map created by the camera image taken from "KAGUYA" (SELENE) satellite launched by JAXA [2]. In this mission, the location estimation is required in any altitude of the satellite because SLIM satellite requires its current location during its descent, and such location estimation should be done in real time. From this fact, the location estimation of the SLIM mission requires (1) estimation any altitude of the spacecraft, and (2) short computational time which enable the spacecraft to estimate the location in real time.

Regarding this issue, the conventional location estimation approaches have been proposed, such as a star catalog matching with a star pattern given by a star sensor [5][7], and Fourier-Mellin invariant descriptor and symmetric phase-only matched filter [6]. These conventional approaches, however, do not satisfy the requirement of the SLIM mission. For example, [5] and [7] cannot cope with the change of an altitude of spacecraft because of using elongation of stars, while [6] requires huge computational cost to execute image processing.

Toward the location estimation for the SLIM mission, our previous research proposed the *Evolutionary Triangle Similarity Matching (ETSM)* method [8] which searches the current spacecraft location by matching the craters taken as the camera shot image with the crater map. In detail, the ETSM method firstly generates a lot of candidate locations of the spacecraft and secondly changes their locations by *Genetic Algorithm (GA)* [9] to search the current spacecraft location. As the feature of the ETSM method, it can estimate the location not depending on the altitude of the spacecraft because of the use of the triangle similarity and has robustness to the noisy camera shot image. However, the ETSM method requires a huge computational time to estimate the current location. To overcome this problem, this paper proposes the two methods which can reduce the computational time of the ETSM method by improving the local search mechanism in the GA process.

To investigate the effectiveness of the proposed methods, this paper conducts computer simulation experiments on matching craters as a camera shot image with those in the crater map taken by “KAGUYA” satellite. In the experiment, we compare the result of our conventional method with that of our improved method from the viewpoint of the success rate of the spacecraft location estimation and the actual calculation time.

This paper is organized as follow. Section 2 explains the overview of the SLIM mission, and Section 3 explains the algorithm of the ETSM method. Section 4 describes the problem of our conventional ETSM method, and proposes the methods to reduce the computational time. Section 5 conducts the computer simulation experiments and shows their results. Section 6 discusses the experimental results, and, Section 7 finally concludes this paper.

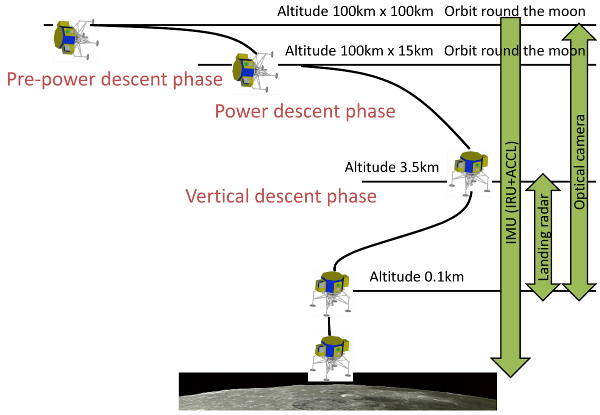


Figure 1. An image of landing sequence of SLIM

2. SLIM MISSION

2.1. Overview

The SLIM (Smart Lander for Investigating Moon) mission is proposed by Japan Aerospace Exploration Agency (JAXA) and aims at establishing a method of a *pinpoint landing* on the moon with a small spacecraft with launch weight 400kg (dry weight 100kg) [1]. The pinpoint landing achieves a method for landing an area “where is *desired* to land”, unlike it is usual for a spacecraft to be planned to land a safe area “where is *easy* to land” to avoid obstacles in the conventional landing. This method enables future landing exploration to land close to a investigating target area. The pinpoint landing method estimates a current location of a spacecraft by sensor data such as a camera shot image, and automatically navigates a spacecraft to a target area, and lands by avoiding obstacles. From this background, the SLIM mission aims at accomplishing the following three methods which are required for the pinpoint landing; (1) a surface topography matching with a camera shot image, (2) automatically obstacles detection and avoidance, and (3) a radio altitude and velocity meter, and additionally accomplishing the following two methods which are great relevant to a landing exploration; (4) reusable landing gear with a memory metal, and (5) a surface exploration rover. This paper particularly tackles (1) a surface topography matching with a camera shot image.

2.2. Spacecraft Location Estimation in SLIM

The landing sequence of SLIM is divided to two phases as shown in Figure 1; (1) the power descent phase and (2) the vertical descent phase, and the power descent phase is further divided to two phases; (i) the inertia guidance phase and (ii) the LOS (Line Of Sight) guidance phase. This paper focuses on a method of an estimation of current spacecraft location by matching an image of a surface of the moon, which is used during (i) the inertia guidance phase and (ii) the LOS guidance phase, and during the initial stage of (2) the vertical descent phase.

In space, it is difficult to localize the current area because localization systems such as GPS (Global Positioning System) are unavailable. Since the pinpoint landing of SLIM, however, requires estimating a spacecraft location above the moon, an estimation of a spacecraft location is necessary toward success of the SLIM mission.

3. EVOLUTIONARY TRIANGLE SIMILARITY MATCHING (ETSM)

3.1. Overview

Evolutionary Triangle Similarity Matching (ETSM) [8] method estimates a current spacecraft location by matching triangles which consist of craters in a camera shot image taken from the spacecraft with the crater map created by the camera image taken from “KAGUYA” satellite [2] by the triangle similarity. In detail, as shown in Figure 2, the ETSM method firstly generates a lot of candidate location in the crater map and changes their location by *Genetic Algorithm (GA)*[9] to search the current location. The use of the triangle similarity enables to estimate the location estimation any altitude or the rotation of the spacecraft, and employing GA enables to quickly search the potential location.

3.2. Algorithm

The ETSM method estimates the current location by the following seven steps;

Step 1 As shown in Figure 2(1), interior angles of the triangles which consist of three craters and do *not* contain other craters are calculated in the camera

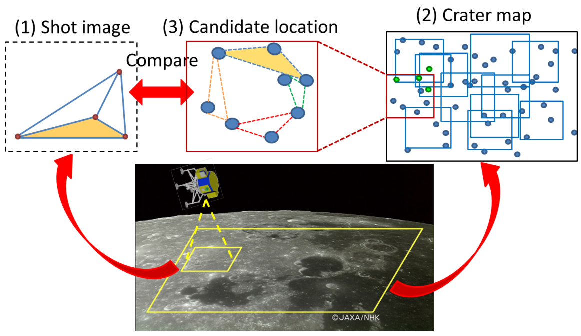


Figure 2. An image of the ETSM method

shot image. The ETSM method searches the triangle which is similar to these triangles from the crater map.

Step 2 A candidate location is indicated as a square on the crater map as shown in Figure 2(2) and consists of a point (x, y) at the lower left of the square and a length l on one side of the square. The square described as (x, y, l) is corresponding to an *individual* of GA, and firstly candidate locations are equally arranged on the crater map to cover all area, which number is initially configured and afterward this number is termed as *population size*.

Step 3 To evaluate whether a candidate location is close to the current location or not, the interior angles of four triangles in the candidate location are calculated. Here, four triangles respectively have the three largest x value, the three smallest x value, the three largest y value, and the three smallest y value as shown in Figure 2(3). Difference between the interior angles of these four triangles and the ones of the triangle in the camera shot image calculated in Step 1 is calculated, and the minimum difference becomes the evaluation of its location. From this evaluation, the location which difference is close to zero is evaluated better because it has the triangle which is similar to the one in the camera shot image.

Step 4 Randomly chosen two candidate locations are compared, and a smaller difference location is selected depending on the difference, and new candidate locations are generated based on selected two locations. Concretely, operations termed as *crossover*, *displacement* and *mutation* in GA are conducted with a certain probability (details are described in Section 3.3).

Step 5 A local search is executed after generating the new candidate location. The local search compares the new candidate location with its surrounding eight locations and selects the smallest difference location (details are described in Section 3.4).

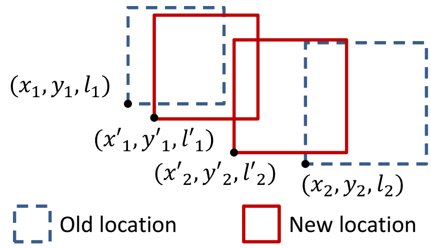


Figure 3. Crossover operator

Step 6 After generating new candidate locations with the same number of the population size, the number of the best old locations remains and the other old locations are replaced with the new ones. The number of the remaining locations is initially configured as a number of elites, *e.g.*, five locations.

Step 7 Steps 3 to 6 are repeated, and the estimation finishes when at least one candidate location which has three triangles that difference is zero is found or iterations are over the configured number.

3.3. Crossover, Displacement, and Mutation

Crossover and Displacement operators generate a new location close to selected locations which have small difference.

As shown in Figure 3, the crossover operator generates two new locations from two selected locations. Concretely, when two locations described as (x_1, y_1, l_1) and (x_2, y_2, l_2) are selected, two new locations described as (x'_1, y'_1, l'_1) and (x'_2, y'_2, l'_2) are generated depending on the following equation;

$$\begin{aligned}
x'_1 &= r_x \times x_1 + (1 - r_x) \times x_2 \\
y'_1 &= r_y \times y_1 + (1 - r_y) \times y_2 \\
l'_1 &= r_l \times l_1 + (1 - r_l) \times l_2 \\
x'_2 &= (1 - r_x) \times x_1 + r_x \times x_2 \\
y'_2 &= (1 - r_y) \times y_1 + r_y \times y_2 \\
l'_2 &= (1 - r_l) \times l_1 + r_l \times l_2
\end{aligned} \tag{1}$$

, where r_x, r_y, and r_l are uniform random numbers between 0 and 1.

On the other hand, as shown in Figure 4, the displacement operator moves one selected location toward the minimum difference triangle in its location. Concretely, when a location described as (x_1, y_1, l_1) is selected, a new location described as (x'_1, y'_1, l'_1) is generated depending on the following equation;

$$\begin{aligned}
x'_1 &= r_x \times x_1 + (1 - r_x) \times x_d \\
y'_1 &= r_y \times y_1 + (1 - r_y) \times y_d \\
l'_1 &= l_1
\end{aligned} \tag{2}$$

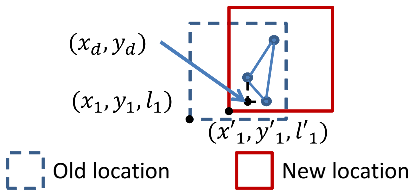


Figure 4. Displacement operator

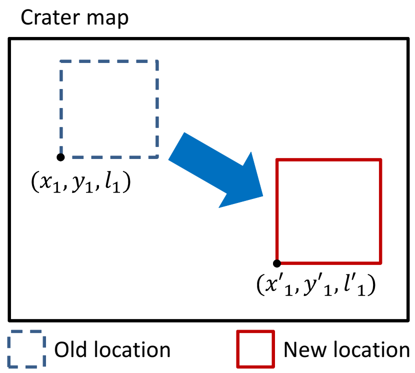


Figure 5. Mutation operator

, where r_x and r_y are uniform random numbers between 0 and 1. While, (x_d, y_d) is determined as a point at the lower left of the minimum difference triangle in the location. Concretely, when each point of the minimum difference triangle is described as (x_i, y_i), (x_d, y_d) is described as $(x_d, y_d) = (min(x_i), min(y_i))$.

As shown in Figure 5, the mutation operator randomly generates a new location in order to search location in which candidates are not and to get out of local optimal. Concretely, x, y, and l of a selected location are randomly changed to other values and a new location consists of their value is generated.

3.4. Local Search

After generating new locations as the same number of the population size, the local search is conducted to all generated location. The local search generates a new location which has smaller difference than the generated location by searching its surrounding locations. Concretely, as shown in Figure 6, eight new locations surrounding a generated location are evaluated and the location which has the smallest difference among the original location and the surrounding eight locations is chosen to the next step.

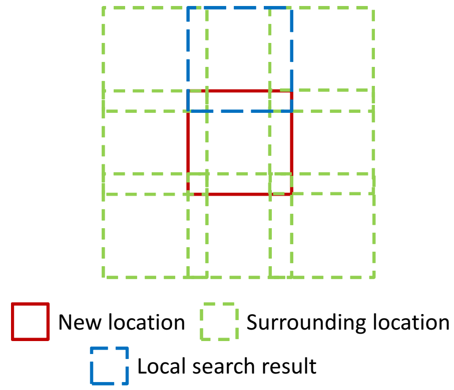


Figure 6. Local search

4. COMPUTATIONAL TIME REDUCTION OF ETSM METHOD

4.1. Problem of ETSM method

Although our previous research [8] revealed that the ETSM method can estimate the current location not depending on the spacecraft altitude and rotation and is robust to the noisy camera shot image. However, the conventional ETSM method required a huge computational time for the estimation. This is because the local search to all generated location requires a huge computational time. The local search compares the generated location with the surrounding eight locations, however, it executes inefficient comparisons because the surrounding eight locations contain locations which are far from the current location.

4.2. Computational Time Reduction Methods

To overcome this problem, this paper focuses on the local search of the ETSM method and proposes two methods which improve the local search and reduce the computational cost. Concretely, this paper proposes (1) a one direction local search of the potential area instead of searching surrounding areas of solution, and (2) a continuous local search to get out of local optimal area.

4.2.1. One Direction Local Search

Although the conventional local search searches surrounding eight locations of the generated location, they include locations which are far from the current location. To reduce the computational time of the local search, it is effective to reduce the searched locations only potential locations. The interiors of four triangles which are lower, upper, right and left side in the location are calculated to evaluate candidate location. In these four triangles, the direction of the smallest difference triangle is assumed

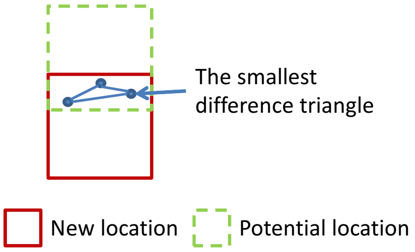


Figure 7. One direction local search

that a direction of the triangle is close to the current location. From this fact, this paper proposes a one direction local search which compares the original location with only one location where is assumed to be close to the current location because of the smallest different triangle.

Concretely, as shown in Figure 7, when the local search is conducted, only one potential location is compared with the original location, unlike the conventional local search compares the original one with the surrounding eight locations. Since the one direction local search compares only two locations, it can reduces the computational time of the comparison.

4.2.2. Continuous Local Search

The conventional local search compares the original location and the surrounding locations, and the surrounding location is chosen only if its evaluation is better than the original one, and otherwise the original location remains. However, although this method can maintain a better evaluated location, it has possibility to fall into a local optimal because the locations do not move to other area. To overcome this problem, this paper proposes a continuous local search which chooses from only the surrounding locations without comparison, but does not choose the original one. The continuous local search does not contribute to get out of the local optimal because it forces the original location to move to other area, but also reduces the computational time of the comparison.

5. EXPERIMENTS

5.1. Settings

To investigate the effectiveness of the proposed methods, this paper conducts computer simulation experiments based on several locations of craters as the camera shot image which is randomly selected from the crater map. The conventional ETSM method is compared with the proposed methods, and four experimental cases are conducted as shown in Table 1. In each case, this paper considers the crater map as shown in Figure 8, which is taken at an altitude of 15km and 3.5km where the SLIM

Table 1. Experimental cases

	Eight locations (conventional)	One direction (proposed)
Comparison (conventional)	Case 1 [Okamura et al., 2011]	Case 2
Continuous (proposed)	Case 3	Case 4

Table 2. Experimental parameters

Num. of candidate areas	25
Crossover rate	45%
Displacement rate	45%
Mutation rate	50%
Num. of elites	5

mission assumes the spacecraft to estimate the current location. In Figure 8, points indicate craters, a square in the left figure indicates an example of the selected camera shot image, and the right figure indicates the camera shot image where is the same area of the square in the left figure. 1228 craters are in Figure 8(a), while 361 craters are in Figure 8(b).

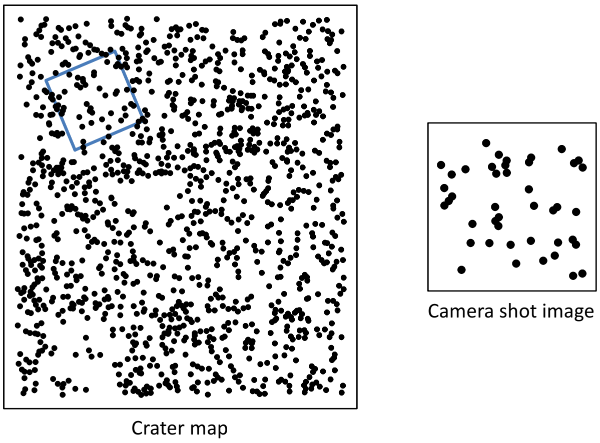
Parameters are set as shown in Table 2. 25 candidate locations are generated. The crossover and the displacement are respectively executed with 45%, while the mutation is executed with 50%. When the old locations are replaced with the new ones, five best old locations remain.

To evaluate the effectiveness of the proposed methods, (1) a success rate in 100 trials and (2) an average actual estimation time in 100 trials are compared among four cases. Note that the same 100 camera shot images are used in all cases. In this experiment, the estimation finishes when the ETSM method finds the location where contains at least three minimum difference triangles, *i.e.*, three triangles which have similar triangles in the camera shot image.

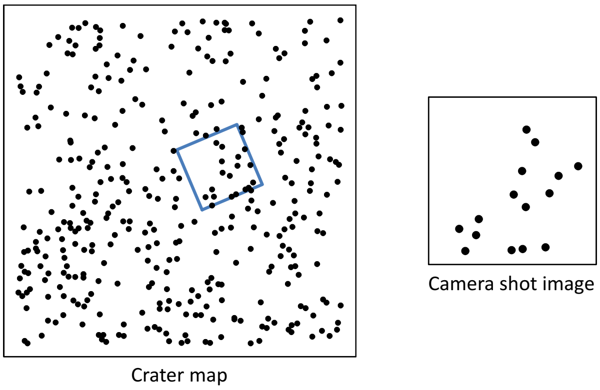
5.2. Results

Figure 9 shows the result of the experiments. Figure 9(a) shows the result with the crater map taken at the altitude of 15km, while Figure 9(b) show the result with the crater map taken at the altitude 3.5km. The horizontal axis indicates each case, the left vertical axis indicates the success rate in 100 trials, and the right vertical axis indicates the average estimation time in 100 trials. Lines indicate the success rate, while bars indicate the average estimation time.

This result indicates that all cases completely achieve the estimation in both altitude situations. Particularly, Cases



(a) Crater map at an altitude of 15km



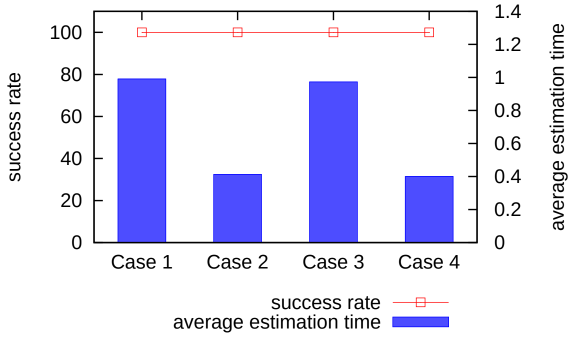
(b) Crater map at an altitude of 3.5km

Figure 8. Crater maps used in the experiments

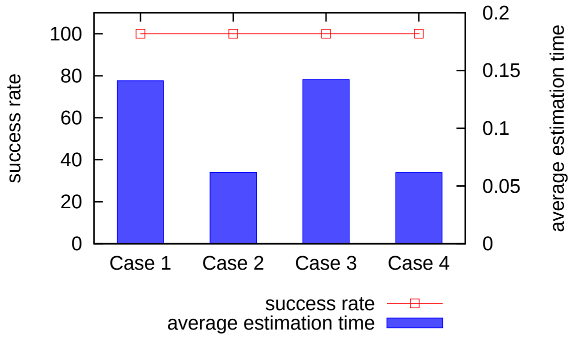
2 and 4 can estimate the location in all cases even if they reduce the local search area. From this fact, it is revealed that it is enough to search only one direction derived from the smallest difference triangle in the current area to estimate the location.

Focusing on the average estimation time, most cases which employ the proposed methods can estimate faster than the previous method. Concretely, employing the one direction local search in Case 2 considerably reduces the estimation time, and Case 2 is almost twice faster than Case 1 which is the previous method. On the other hand, although Case 3 which employs the continuous local search hardly reduces the estimation time, the integration of the continuous local search and the one direction local search further reduces the estimation time, which is faster than only employing the one direction local search in both altitude cases. This result indicates that the one direction search contributes to reduce the estimation time and the integration of the one direction search and the continuous local search accomplishes the fastest estimation.

This result reveals that (1) the one direction local search of the potential area reduces the calculation time without decreasing the success rate of the spacecraft location estimation, and (2) the integration of the continuous local search and the one direction local search can most quickly estimate the spacecraft location.



(a) The result with the crater map taken at the altitude 15km



(b) The result with the crater map taken at the altitude 3.5km

Figure 9. The success rate and the average estimation time in each case

6. DISCUSSION

This experimental result reveals that the reduction of the direction of the local search from eight directions to one contributes to reduce the estimation time. This is because the one direction local search greatly reduces the number of the evaluations, *i.e.*, the calculation of the difference of the interior between four triangles in the location and all triangles in the camera shot image. Since the eight direction local search compares the original location with the surrounding eight locations, nine evaluations are required to every location. On the other hand, since one direction local search only compares the original location with the potential one location, only two evaluations are required, which is simply two-ninth evaluation of the conventional local search. Table 3 shows an average number of the GA generations, *i.e.*, an average number of replacements of the old candidates and the new ones. As shown in Table 3, despite of the average number of GA generations of the one direction local search is more than one of the eight direction local search, the one direction local search reduces the estimation time. This result indicates

Table 3. Average number of the GA generations

	Case 1	Case 2	Case 3	Case 4
15km	3.06	5.60	3.04	5.2
3.5km	3.18	5.39	3.26	5.15

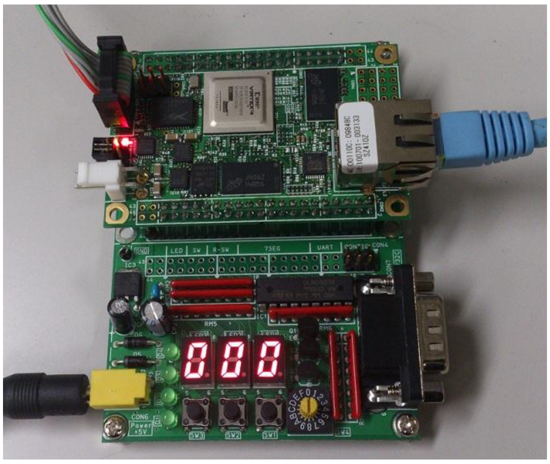


Figure 10. An image of SUZAKU-V

that reducing the number of evaluations contributes to the computational time reduction in the ETSM method, and the one direction local search accomplishes to reduce the evaluations by limiting the compared location to the potential area.

The experimental result also reveals that the continuous local search reduces the estimation time by integrating it in the one direction local search. The first reason of this reduction is that comparing time to decide the next location is not required in the continuous local search, unlike the comparison local search always compares the original location with the surrounding (or one) locations. Moreover, the continuous local search can get out of a local optimal area because it forces the location to change.

Finally, although the experiments in this paper are conducted in the computer simulation, we also conduct a part of the experiments on on-board computer. Concretely, we employs *SUZAKU-V* [10] developed by Atmark Techno, Inc. as shown in Figure 10. SUZAKU-V is CPU board which employs PowerPC405 as CPU core on Virtex-4 FX FPGA developed by Xlinx, which spec is as shown in Table 4. As the result on SUZAKU-V, the same tendency of the experiments in this paper is observed, and it is indicated that the integration of the one direction local search and the continuous local search has potential for the real time estimation. In near future, we will address more experiments on SUZAKU-V, and investigate the feasibility of the ETSM method on on-board computer.

Table 4. Spec of SUZAKU-V [10]

FPGA	Xlinx Vertex-4 FX
CPU core	PowerPC405
CPU clock	350Mhz
DRAM	32MB $\times$ 2
Flash memory	8MB (SPI)
Standard OS	Linux

7. CONCLUSION

To reduce a huge computational time of the ETSM method, this paper proposed two methods for the ETSM method by improving its local search mechanism in GA process. Concretely, this paper proposed (1) the one direction local search of the potential area instead of searching surrounding eight areas of the current location, (2) the continuous local search that can get out of the local optimal area. To investigate the effectiveness of the proposed methods for the ETSM method, this paper conducted the computer simulation experiments based on several locations of craters as the camera shot image which is randomly selected from the crater map. The experimental result revealed that (1) the one direction local search of the potential area reduces the calculation time without decreasing the success rate of the spacecraft location estimation, and (2) the integration of the continuous local search and the one direction local search can quickly estimate the spacecraft location.

The following issues should be addressed in the near future: (1) an experiment on an on-board computer assumed to be used on the SLIM satellite using both actual camera shot image and an actual crater map; (2) an analysis of the spacecraft location estimation using the camera shot image which includes the wrong crater detection; and (3) an exploration of a method which considers a crater size to further reduce the computational time.

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