# Robust self-position estimation algorithm against displacement of crater detection in the SLIM spacecraft


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## ABSTRACT

This paper proposes the robust spacecraft location estimation method against displacement of crater towards the SLIM (Smart Lander for Investigating Moon) mission proposed by JAXA (Japan Aerospace Exploration Agency), and investigates its estimation accuracy by using the crater detected from camera shot image.

In the conventional planetary landing, a spacecraft generally requires the large landing without obstacles t to land a safe area "where is easy to land". This means that the conventional approach is difficult to land at the area which is very close to an exploration target because of decreasing the safe area. To overcome this problem, JAXA focuses on the pinpoint landing on the moon and aims at establishing the method of landing at the pinpoint area "where is desired to land" in the SLIM mission [1]. To achieve this goal, the spacecraft needs to estimate the current its location by matching (a) the crater map created beforehand from the camera shot image taken from "KAGUYA" (SELENE) satellite launched by JAXA with; (b) the craters detected from the camera shot image over the moon from the spacecraft. For this purpose, our previous research proposed the ETSM (Evolutionary Triangle Similarity Matching) method [2] which searches the current location through match of the crater map with the craters on the camera shot image.

As a problem of craters matching, the SLIM spacecraft has to address the serious displacement of crater detection between the camera shot image and crater map, which causes when SLIM spacecraft altitude and posture are largely different from "KAGUYA" satellite which tool the pictures of the crater. In such a case, the shape of the triangle is largely distorted, which makes it difficult to match the triangle of the crater map with that of the camera shot image. To tackle this problem, our method introduces the ratios of the triangle side and the distance between centroid of the similar triangle for the ETSM method. By the ratios of triangle side, this method can evaluate from the viewpoint of the triangle size. By the distance between centroid of the similar triangles, this method also can evaluate from relationship of the distance between the similar triangles.

To investigate an effectiveness of the proposed method for the serious displacement of crate detection, we conducted the experiments by shifting the crater coordinate of the camera shot images according to the SLIM spacecraft altitude and posture. From the experimental results, we have revealed that the proposed method can achieve a high estimation accuracy while keeping the estimated time in comparison with the time without considering the serious displacement of the crater detection.


## 1 INTRODUCTION

JAXA is proposing SLIM mission for establish the pinpoint landing on the moon by small unmanned spacecraft. A purpose of this mission is establishment of pinpoint landing method "to landing at the point where the landing" rather than conventional landing method "to land to get off easy to point". In order to achieve the pinpoint landing, it is necessary for spacecraft to estimate its own position during descent. The self-position estimation is carried out in the crater verification by the crater map and the camera shot image.

As this self-position estimation method, the ETSM method has been proposed by Harada. This method can estimate the current spacecraft location by matching the craters detected from the camera shot image with those in the crater map. This method searches the current spacecraft location by evaluating from the viewpoint of the triangle similarity. By displacement of the crater detection between the crater map and the camera shot image, however, the ETSM method cannot search the similar triangles. This is because the position of craters in the camera shot image may have a little difference against that in the crater map. As the result, the sharp of triangle is largely distorted between the camera shot image and the crater map. Thus, it is sometimes difficult for this method to estimate the current spacecraft location.

To tackle this problem, in this paper, we propose that the ETSM method introduces the ratios of the triangle length and the distance between centroid of the similarity triangle. In particular, the ETSM method uses only the interior angles of the triangle to search the triangle similarity between the crater map and the camera shot image. However, the proposed method uses not only the interior angles of the triangle between the crater map and the camera shot image but also used the ratios of triangle length between the crater map and the camera shot image. Moreover, the proposed method compare the distances of between centroid of the similar triangles in the crater map and camera shot image and evaluate the relationship of the similar triangle pair.

In this paper experiments, we use the crater map and the five camera shot images that were taken at different 5th locations in the crater map. Further, we shifted all craters in camera shot image and prepared an environment in which all crater of the camera shot image is shifted against the crater map. From the experiments, we evaluate an effectiveness that the proposed method can estimate the current spacecraft location robustly. In particular, this method can search the similar triangle of the camera shot image in the crater map even if the triangle the shape of the triangle is largely distorted when the crater map and the camera shot image have the difference of altitude.

This paper is organized as follow. Section 2 explains the algorithm of the ETSM method, and Section 3 explains the improvements for displacement of the crater detection and Section 4 explains the problem in terms of estimating the current spacecraft location.

## 2 Evolutional Triangle Similarity Matching : ETSM

### 2.1 Overview

The Evolutional Triangle similarity Matching (ETSM) method estimates the current spacecraft location by using Genetic Algorithm (GA) which is one of optimization technique. In particular, this method searches the similar triangle that formed by three craters in the moon camera shot image of SLIM spacecraft from the crater map that created based on the shot camera image by "KAGAYA" satellite. Figure 1 shows overview the ETSM method. The left Side in Figure 1 is the moon shot camera image of spacecraft and the right side in Figure 1 is the crater map and the middle in Figure 1 is one of the candidate regions of spacecraft. The ETSM method determines the candidate region containing the similar triangle.

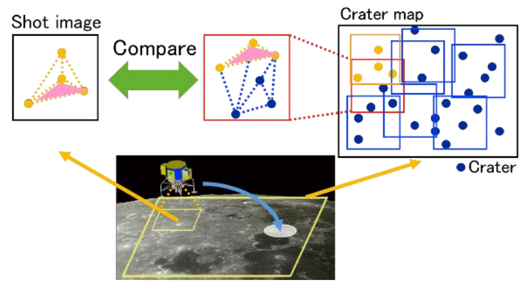


*Figure 1 : Image of the ETSM method*

### 2.2 The ETSM method algorithm

The ETSM method estimates the current spacecraft location by the following step (the following number is step number).

1. **The formation of triangle in the camera shot image:** As shown in Figure 1 (1), the triangles composed of three craters without containing other craters are detected from the camera shot image.

2. **Initialization of Genetic Algorithm:** As shown in Figure 1 (2), a lot of the candidate locations of the spacecraft represented by the squares are created. One square as the candidate location is described as (*x,y,l*), where the point (*x,y*) indicates the bottom left corner of the square and a length / indicates one side if the square. As the beginning of this method, the candidate locations are equally arranged on the crater map to cover a whole area, which number is initially configured. From the viewpoint of GA, one square corresponds to an *individual*, and the number of the candidate locations corresponds to *population size* ().

3. **The formation of triangle in candidate region on the crater map:** As shown in Figure 2 (3), four triangles in each candidate location is created from the top, left, bottom, and right sides.

4. **Evaluation of candidate locations:** To evaluate whether candidate location is close to the current location, the interior angles of the triangles in the camera shot image and those four triangles in the candidate location are calculated. If the difference of the interior angles between these triangles (*i.e.*, the triangle in the camera shot image and that in

the candidate location) becomes zero, then these triangles have a similarity feature. As an evaluation of the candidate location, the minimum difference value of the triangle among four triangles in the candidate location is employed. From viewpoint of GA, this minimum difference value corresponds to a fitness.

5. **Elite strategy:** number of candidate locations are selected by the elite selection using the fitness value, and those are taken over as candidate locations of the next generation. Note that the number of the remaining candidate locations is initially configured as a number of elites.

6. **Genetic operation:** To search another potential area, two candidate locations are selected by the tournament selection using the fitness value, and one of the following procedures is executed as shown in Figure 2.

   - **Crossover operation:** New candidate locations are generated through the crossover of two selected candidate locations.
   - **Movement operation:** The selected candidate location is moved a littles bit toward the triangle having a high fitness value, in order to enlarge a new area.
   - **No operation:** No operation is executed.

7. **Mutation operation:** If the target candidate locations do not have at least one triangle among four triangles, their location change at random.
8. **Local search operation:** This operation is the same as the Movement operation.

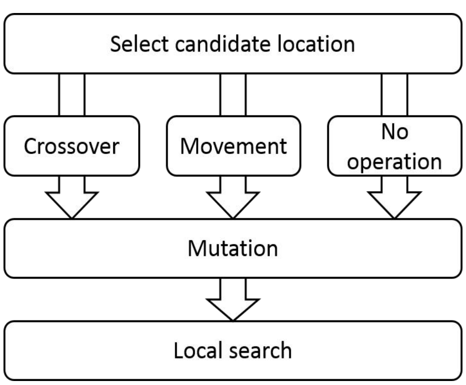


*Figure 2 : Algorithm from step 6 to step 8*

9. **Next candidate location generation:** After generating the number of the target candidate locations by the cycle from 6 to 8 steps, those candidate locations and those selected in step 5 are replaced with the old candidate locations.
10. Return from step 3 to step 9 until finding the location which has at least two similarity triangles among four triangles or exceeding the maximum generation. Note that the maximum generation is initially configuration.

## 3 Problem in order to self-position estimation

The ETSM method evaluates the relationship of the similar triangles by interior angles and estimates the current spacecraft location in short time. However, the ETSM method is difficult to estimate the current spacecraft location by displacement of crater detection between the crater map and the camera shot image. That is because the altitude and posture of the SLIM spacecraft are largely different from that of “KAGUYA” satellite. From this problem, the ETSM method has the following problems: (1) distortion of the triangle formed by the craters in the camera shot image against that formed by the craters in the crater map; (2) the ETSM method misjudges the triangle similar.

### 3.1 Distortion of the triangle formed by the craters

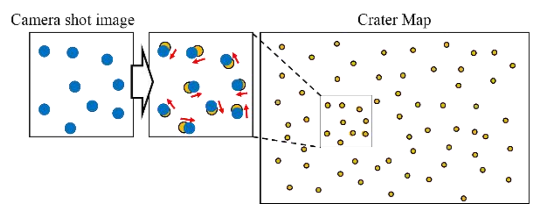


*Figure 3 : Displacement of crater detection between the crater map and the camera shot image*

Figure 3 shows the crater map and the camera shot image. In detail, the square is the camera shot image (as shown in the left side in Figure 3) and the square is the crater map (as shown in the right side in Figure 3). In addition, the yellow circles are craters in the crater map and the blue circle are craters in the camera shot image. Then, as shown in the middle in Figure 3, the position of craters in the camera shot image have the slightly against that of the crater map. As the result, the ETSM method is unable to judge the similarity when this method compares a triangle formed by craters in the crater map with that formed by craters which exist in the crater map in the shot camera image. The left side in Figure 4 is the middle in figure 3. As shown in the middle in Figure 4, the difference of interior angle between the triangle in the crater map and that in the shot camera image is not zero. Therefore, the ETSM method is difficult to accurately evaluate the relationship of the triangle similarity.

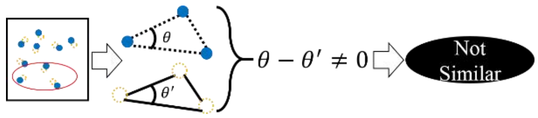


*Figure 4 : Distortion of the triangle formed by the craters*

## 3.2 The ETSM method misjudges the triangle similar

The ETSM method ends the search of estimating the current spacecraft location when this method find the least two similar triangle in the candidate location in the crater map. This method, however, does not consider that the relationship of distance between the similar triangles. Furthermore, this method has the possibility that this method recognizes an incorrect location as a current spacecraft location. This is because this method evaluates the similarity of the other triangles which are created in various locations in order to recognize as similar to the triangle in shot camera image and that in crater map even when displacement of crater detection.

# 4 The proposed method

To tackle problems of section 3, we propose (1) evaluation by the ratios of triangle; (2) evaluation of the positional relationship by the distance between centroid of triangle.

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## 4.1 (1) Evaluation by the ratios of triangle

As shown Figure 5, the ETSM method calculates not only the interior angles of triangle but also the length of that () in step 1 and step 4. In addition, this method calculates the ratios of the triangles length () in the crater map and the camera shot image. By introduce of this ratios, the ETSM methods can discriminate whether the triangle in the crater map is the same size as the triangle in the camera shot image. If the triangle in the crater map is the same size as that in the camera shot image, those ratios are 1. Thus, the difference ( equals 0.

From this evaluation, the ETSM method evaluates not only shape of the triangle by the interior angles but also the size of the triangle by the length of that between the crater map and the camera shot image.

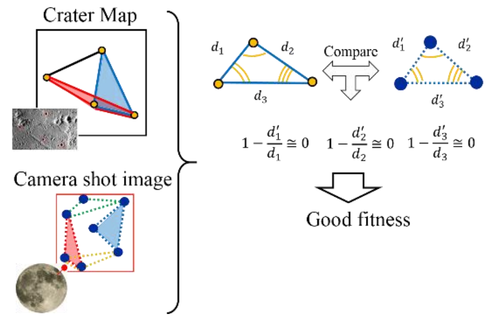


*Figure 5 : Evaluation of the ratios of the triangle*

## 4.2 (2) Evaluation of the positional relationship by the distance between centroid of triangle

As shown Figure 6, the proposed method evaluates the relationship of position between the similar triangles. In particular, when the proposed method finds the least two similarity triangles in the candidate location (as shown in the left side in Figure 6), this method calculates the distance between centroid of the similarity triangles () before exiting searching the current spacecraft location.

If the difference of the distance is nearly zero (i.e.,), the ETSM method recognize that the yellow triangle and the blue triangle are the correct pair. On the other hand, if the difference of the distance is large, this method recognize the incorrect pair. The ETSM method recognize the candidate location as the current spacecraft location when the count of the correct triangles similar pair has the least the number. The number is initially configured.

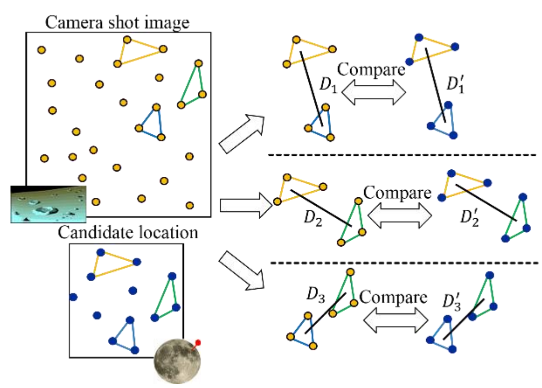


*Figure 6 : Evaluation of the positional relationship by the distance between centroid of triangle*

# 5 Experiment

## 5.1 Cases

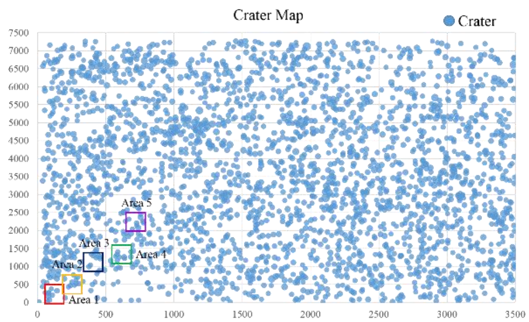


*Figure 7 : Crater map and five camera shot image*

To evaluate an effectiveness of the proposed the proposed method for the serious displacement of crater detection, we conduct the experiments based on the five locations in the crater map on the moon as shown Figure 7, which is taken from "KAGUYA" satellite at the altitude of 15km. In the experiment, the following cases are conducted to investigate the experiment the effectiveness of the following improvements: (1) There is a no altitude difference between the crater map and the shot camera image; (2) There is a no altitude difference (5%) between the crater map and the shot camera image. (Details are described in Section 5.2)

## 5.2 Altitude difference

In this paper, the ETSM method experiments estimation of the current spacecraft location by the crater map and the camera shot image that have the shot altitude. However, the crater map and the camera shot image is the same shot altitude. Accordingly, we shift all craters in the camera shot image when spacecraft shoots at the different altitude from the crater map. The experiment of this paper were conducted the following the camera shot image: (1) the altitude of the camera shot image is higher than that of the crater map; (2) the altitude of the camera shot image is lower than that of the crater map.

Figure 7 shows the craters in two types of the camera shot image. The craters of yellow are shot at the higher altitude than the craters of blue. As shown in Figure 7, all craters in the camera shot image are shifted radially toward the center of the camera shot image.

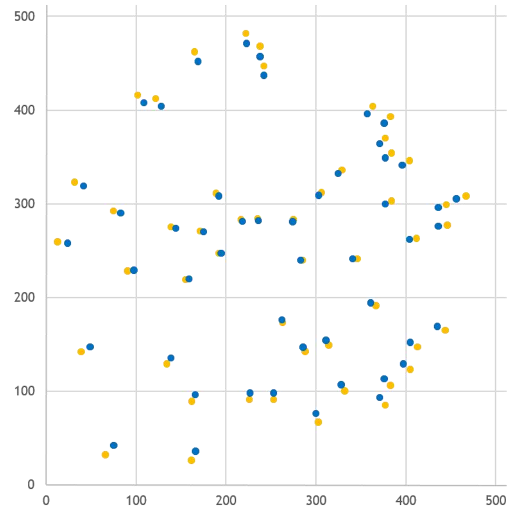

*Figure 8 : the craters of the camera shot image 1 at the difference altitude (1)*

On the other hand, figure 8 shows the craters in two types of the camera shot image. The craters of yellow are shot at the higher altitude than the craters of blue. As shown in Figure 8, they are shifted radially from the center of that toward the outside if the SLIM spacecraft is 5% lower than "KAGUYA" satellite.

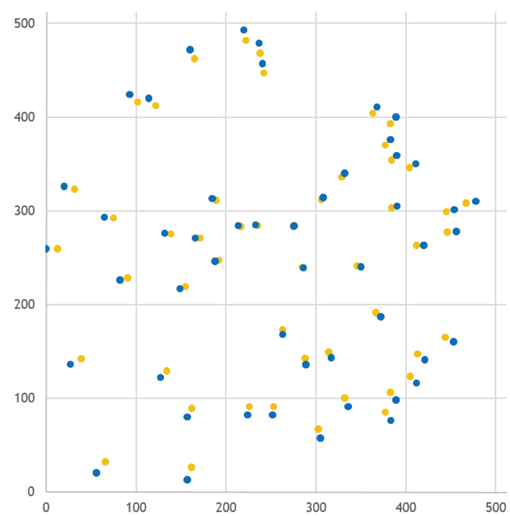

*Figure 9 : the craters of the camera shot image 1 at the difference altitude (2)*

## 5.3 Evaluation criteria

The following evaluation criteria are employed: (1) a success rate in 100 trials and (2) an average estimated time for finding the correct location in 100 trials. To calculate the estimated time for finding the correct location, we convert the time that expected to take at FPGA.

The parameters are set as shown in Table 1. Concretely, 25 () candidate locations are initially generated to cover a whole area. When the old candidate locations are replaced with the new ones, the five best old candidate locations remain at the elite selection. The count of the triangle pair is 5 when the altitude of the crater map is no difference against that of the camera shot image, while the count of the triangle pair is 12 when the altitude of the crater map is difference against that of the camera shot image. The maximum generation is set as 100.

*Table 1 : Experimental parameters*

| | |
|---|---|
| Num. of candidate location () | 25 |
| Num. of elites () | 5 |
| Num. of the triangle pair () | 5 or 12 |
| Num. of maximum generation | 100 |

## 5.4 Experimental results

Figure 10 shows the experimental result of case 1 that the ETSM method estimates the current spacecraft location when the SLIM spacecraft and the "KAGUYA" satellite have no difference of shot altitude, where the horizontal axis indicate the five areas while the left vertical axis indicates the success rate in 100 trials and the right vertical axis indicates the average estimated time in 100 trials. The blue and red bars respectively indicates the success rates of the ETSM method and the proposed method, while the blue and red lines respectively indicate their average estimated time. Figure 11, on the other hand, shows the experimental result of case 2 that the ETSM method estimates the current spacecraft location when SLIM spacecraft and the "KAGUYA" satellite have a difference () altitude, the two vertical axis and the horizontal axis have the same meaning. The bars and lines also have the same meaning.

The result shown in Figure 10 indicates that the success rates of the proposed method mostly achieve 100% in all areas, while that of the ETSM method achieve 100% in area 4 and almost 70% in area 3. In the other areas, however, this method achieve 0%. This means that the proposed method estimates robustly the current spacecraft location to displacement of crater detection. The average estimated time of the proposed method is less than 2 seconds. In area 3, the time of the proposed method is shorter than the time of the ETSM method. This means that the proposed method estimates the spacecraft location in a less number of generation than the ETSM method.

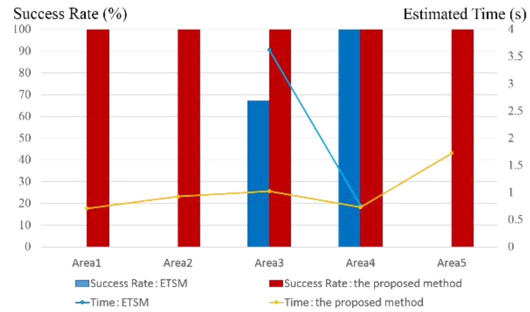


*Figure 10 : Result of the proposed method and the ETSM method*

The result shown in Figure 11 indicates that the proposed method mostly achieve 100% in area 1 from area 4 when the spacecraft altitude has the difference () to "KAGUYA" satellite altitude, while this method achieve 80% in 5 area. In all area, the average estimated time when the spacecraft altitude has the difference to "KAGUYA" satellite are longer than that when the spacecraft altitude has no difference to "KAGUYA" satellite. This means that the more the altitude of the camera shot image and the altitude of crater map have the difference, the longer the proposed method estimates the current spacecraft location.

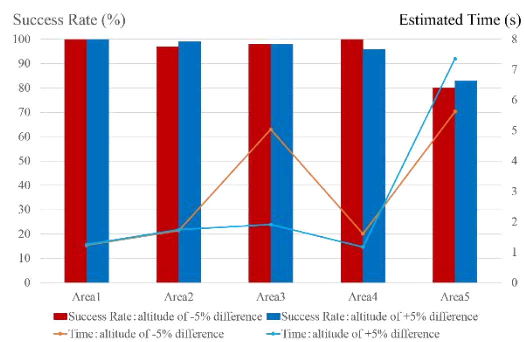


*Figure 11 : Result of the proposed method in case 2*

The above result reveals that the proposed method improved in order to estimation robustly for displacement of the crater detection can mostly achieve 100% in all areas when not only the crater map and the camera shot image have no difference of altitude but also the crater map and the camera shot image have the difference of altitude by employing (1 ) introduce the ratios of triangle side of the corresponding the crater map and the camera shot image; (2) the relationship of distance between centroid of the similarity triangles between the crater map and the camera shot image.

# 6 CONCLUSION

This paper proposed the robust spacecraft estimation method against displacement of the crater detection by using the ratios of triangle side and the distance between centroid of the similarity triangles. To investigate an effectiveness of the robustly estimation, the experiments were conducted under the five locations in the crater map on moon taken by "KAGUYA" satellite. Furthermore, assumed the spacecraft and "KAGEYA" satellite have the difference altitude, all craters in the camera shot images of those locations were shifted and we experimented. From the experiments, we have revealed the following implications: (1) the proposed method can estimate the current spacecraft location robustly than the ETSM method in terms of the distortion of the shape of the triangle by displacement of the crater between the crater map and the camera shot image; (2) the proposed method can estimate the current spacecraft location when the crater map and the camera shot image have the difference ().

What should be noticed here is that these results have only been obtained from the five locations in the crater map. In the near future, we must pursued the following future research: (1) improved success rate when the crater map and the camera shot image have the difference altitude and the more difference altitude; (2) this method should estimate the current spacecraft location accurately when the camera shot image is rotated from the crater map.

## Acknowledgement

Location Estimation, Small Spacecraft, SLIM, Moon Exploration

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