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The robust spacecraft locaiton estimation algorithm toward the misdetection crater and the undetected crater in SLIM

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This paper proposes the self-position estimation method by the triangle composed of the craters called Triangle Similarity Matching (TSM) method for spacecraft landing in Smart Lander for Investigating Moon (SLIM) mission[?)] of JAXA. SLIM mission aims at establishing the method of landing at the pinpoint area "where is desired to land". This method compares the crater map on Moon with the shot image taken from the spacecraft to detect where position of the shot image are on the crater map. Concretely, TSM method finds the similarity triangle and *N* pairs of craters matching that triangle between crater map and shot image. To investigate the effectiveness of TSM, the experiment simulated self-position estimation is conducted. The three case are existed in this experiment: (i) the altitude of the crater map is different from that of the shot image; and (ii) the direction in which the shot image is taken is different from that of the crater map in terms of roll, pitch and yaw angles. This experiment has revealed that TSM method can (i) drives a high estimation accuracy; and (ii) estimate self-position and judge not being able to estimate within 3 second.

Key Words: Location Estimation, Small Spacecraft, SLIM, Moon Exploration

Nomenclature

x_i	:	triangle crater X coordicate in crater map
y_i	:	triangle crater Y coordicate in crater map
x_i'	:	triangle crater X coordicate in image
y_i'	:	triangle crater Y coordicate in image
x_g	:	GNC spacecraft position X coordicate
y_g	:	GNC spacecraft position Y coordicate
l_i	:	length of triangle in crater map
l_i'	:	length of triangle in image
θ_g	:	yaw angles of GNG information
$cos\theta$	:	angle of triangle in crater map
$cos\theta'$	:	angle of triangle in image
N	:	necessary points
n	:	matching crater count
Subscripts		
i	:	0〜2

1. Introduction

JAXA proposes the SLIM mission to establish the pinpoint landing method on the moon by small unmanned spacecraft.[1)] The conventional landing method is "to land at the point where is easy to land". However, establishment of pinpoint landing method "to land at the point where is the target point" is possible to land on planets with severe resouce limits than the moon. In order to achieve the pinpoint landing, it is necessary for spacecraft to estimate its own position during descent. The mechanism for the estimation of the current spacecraft location is that the system matches between the craters by crater map and camera shot image as shown in Fig 1.

As this conventional method, the Evolutionary Triangle Similarity Matching (ETSM) method has been proposed by Harada.[2)] The ETSM method searches the current spacecraft location by evaluating from the viewpoint of the triangle similarity. In particular, this method searches the similar triangles between crater map and camera shot image. After that, this method compares the relative relationship of the similar triangles between crater map and camera shot image. This method finishes searching spacecraft location when a certain number of pairs of similar triangles are detected. However, it is difficult for this method to search the spacecraft location under the condition that there are a lot undetected craters. The undetected craters mean the relationship between the crater detected on the crater map and undetected on the camera shot image or the relationship between the crater undetected on the crater map and detected on the camera shot image. Since the undetected craters, it is difficult form the common triangles between on the crater map and on the camera shot image. Besides, the number of the craters on the camera shot image are limited to save the computational time, which is bad effect on the performance of the estimation of the self-location. To tackle this problem, in this paper, we propose the Triangle Similarity Matching (TSM) method. In particular, the TSM method searches one similar triangle between crater map and camera shot image. After that, this method compares the relative relationship between the similar triangle and the surrounding craters of that triangle. This method finish searching spacecraft location when there are a certain number of pairs of the similar triangle and the surrounding crater. Moreover, this method uses Guidance Navigation & Control (GNC) information to search efficiently.

In this paper, we conduct experiments of 3 cases. From the experiments, we evaluate an effectiveness that the proposed method can estimate the current spacecraft location robustly. In

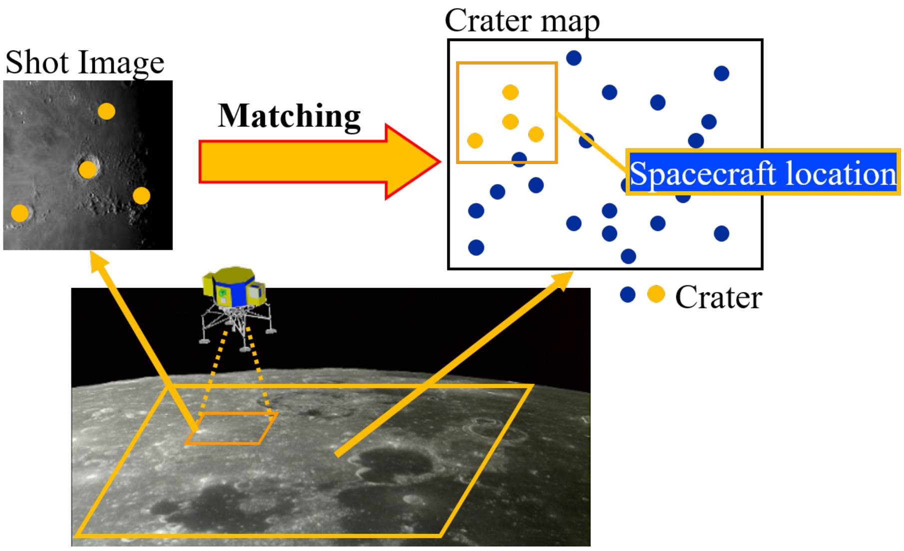

Fig. 1. approach

particular, this method can search the spacecraft current location even if the proportion of undetected crater is large (about 70 %).

The rest of this paper is organized as follows. Section 2 gives the explanation of the ETSM method as one number of the previous algorithm, Section 3 explains TSM method as proposed method, Section 4 conducts the experiments to investigate the effectiveness of the proposed method and discuss the results. Finally, we summarize the contribution of this paper and show the future works in Section 5

2. Previous Study

2.1. Evolutionary Triangle Similarity Matching method

Evolutionary Triangle Similarity Matching (ETSM) method searches the spacecraft current location using Genetic Algorithm (GA).[3] As shown in Fig 2, the ETSM method creates candidate regions (blue square) in the crater map and forms triangles from craters in each candidate region. This method forms triangles using craters in each candidate regions and compares these triangle and triangles in camera shot image. The more similar triangles are in the candidate region, the better this candidate region is evaluated. After all candidate regions are evaluated, low evalutation candidate regions are deleted and new candidate regions are created near high evaluation candidate region evaluated. This method repeatd that cycle and when there are some similar triangles that match relative relationship in one candidate region, this method estimated the place as spacecraft current location.

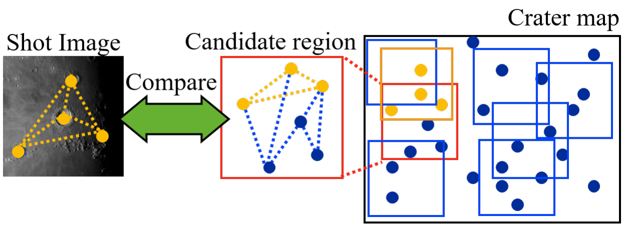

Fig. 2. ETSM

3. Triangle Similarity Matching

3.1. Overview

This method searches the spacecraft current location with GNC information. In particular, this method determines the search range in crater map and searches the similar triangle from that search range. This method compares the relative relationship between that triangle and the surrounding craters. This method finishes the search when there are more than N pairs whose relative relationships match.

3.2. Algorithm

This method searches by the following procedure.

1. **Formation of triangle in the camera shot image**: As shown in Fig.4, the triangles composed of three craters are formed in the camera shot image. Interior angles lengths of triangle in shot image are sorted in ascending square. Crater coordinates is sorted with these interior angles.

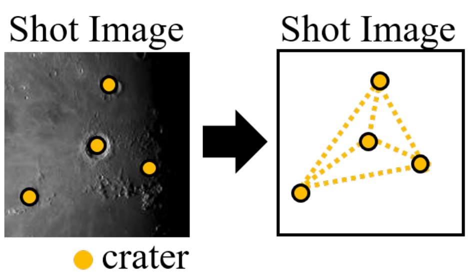

Fig. 4. Form triangles using crater in camera shot image

2. **Determination of search range**: Search range on the crater map is determined by Guidance, Navigation and Control (GNC) information of spacecraft. As shown in Fig.5, when GNC information of the coordinates of the spacecraft location is (x_g, y_g), the search range is generated based on centering on the coordinates. After that, the triangles composed of three craters are formed in the search range and the interior angles, length and crater coordinates of triangle are sort like triangles of shot image.

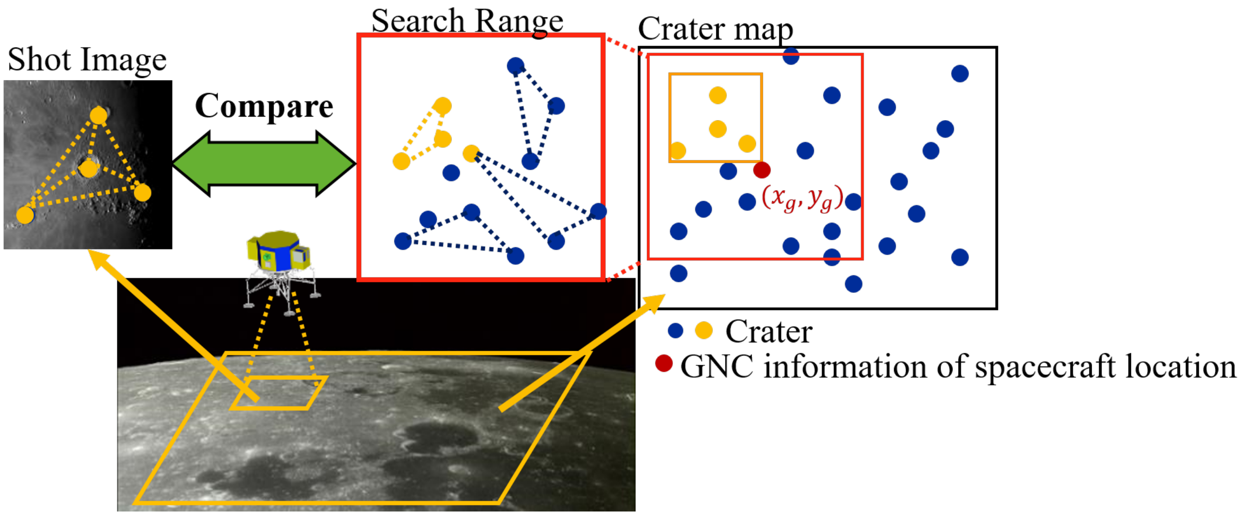

Fig. 3. TSM

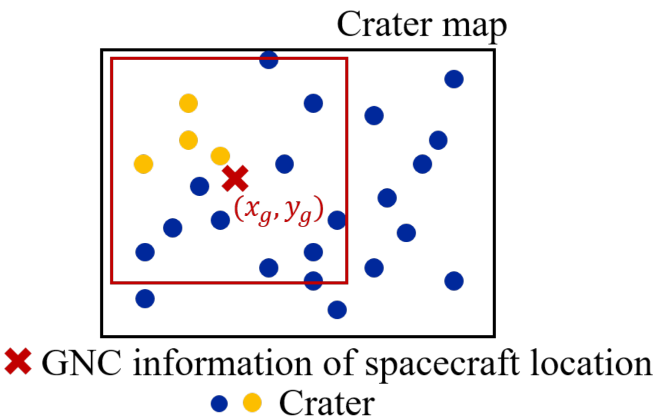

Fig. 5. Determination of search range

3. **Comparison of the cross product of triangle of the crater map and that of the camera shot image**: The cross product of triangle selected in camera shot image is compared that in crater map. As shown Fig.6, the orthogonal vector is calculated by the cross product of $\vec{AB}$ (second length vector of triangle) and $\vec{AC}$ (third length vector of triangle).

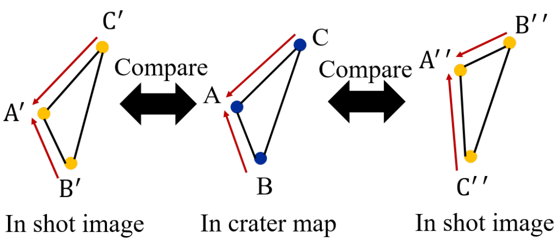

Fig. 6. Comparison of the cross product of triangle

As shown Eq. 1, if the direction of the orthogonal vector of triangle in crater map and that in camera shot image are the same direction, product of the orthogonal vector of triangle in crater map and that in camera shot image is a positive value. While, if the direction of the orthogonal vector of triangle in crater map and that in camera shot image are the different direction, product of the orthogonal vector of triangle in crater map and that in camera shot image is a nagative value. When product of the orthogonal vector of triangle in crater map and that in camera shot image is a positive value, this method moves in step 4. Otherwise, this method do step **??** using different triangle in crater map.

$$(\vec{BA} \times \vec{CA}) * (\vec{B'A'} \times \vec{C'A'}) > 0 \tag{1}$$

4. **Comparison of the rotation relationship of triangle of the crater map and that of the camera shot image**: Rotation relationship of triangle between crater map and camera shot image is compared using yaw (θ_g) of GNC information, the triangle length in crater map and that in camera shot image. As shown Eq. 2, if angle θ between the longest length of triangle in crater map and that in camera shot image is between $(-15+\theta_g)$ and $(15+\theta_g)$ degree , the rotation relationship of these triangle is judged matching.

$$-15 + \theta_g < \theta < 15 + \theta_g \tag{2}$$

When that angle implements Eq. 2, this method moves in step 4. Otherwise, this method do step **??** using different triangle in crater map.

5. **Calculation of triangle similarity between the crater map and the camera shot image**: To evaluate whether triangle in crater map is similar with that in camera shot image, the corresponding interior angles of triangles in camera shot image and the crater map are calculated. This method selects one triangle from those in camera shot image and evaluates with all triangles in search range of crater map by the following Eq. 3.

$$\sum_{i=1}^{3} |cos\theta_i - cos\theta_i^{'}| < DIFF \tag{3}$$

These difference of interior angles between these triangles becomes small if these triangles have a similarity feature. Therefore, if the sum of difference of these internal angles becomes less than $DIFF$, these triangles are similar. This method go to step 6.

6. **Pairing Matching**: Relative relation between triangle and its surrounding craters are compared with the crater map and the camera shot image as shown in Fig. 7.

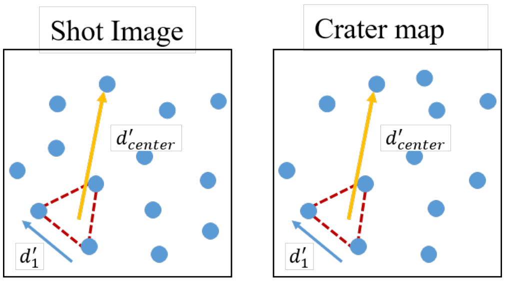

Fig. 7. pairing

This method compares the craters around the triangle of crater map with that of shot image in terms of inner and cross products. The inner product is calculated by Eq. 4. Concretely, the longest length vector of triangle and the vector to the crate around triangle form centroid of the triangle are used to calculate the inner product. Relative direction of triangle and the crater around that triangle are compare between crater map and shot image by the inner product. If difference of these inner product between crater map and shot image becomes less than $MIND2$, these relative directions are matched. While, the cross product is calculated using the same vectors as shown in Eq. 5 and compares relative distance of triangle and the crater around that triangle in crater map with that in shot image. If difference of these cross product between crater map and shot image becomes less than $MIND2$, these relative distances are matched. Relative relationship of these triangles and the crater around that triangles are judges matching when the inner and cross products are meet requirement. As well, Eq. 6 calculates scale of triangle of crater map and that of shot image using the longest triangle length. When this method finds N pairs of craters which meet requirement of these relationship, this method judges that craters of these triangles and that around these triangles between crater map and shot image are matched and goes to the step 7.

$$\left| x_c \cdot x_p - \frac{x_c' \cdot x_p'}{\gamma^2} \right| < MIND2 \quad (4)$$

$$\left| x_c \times x_p - \frac{x_c' \times x_p'}{\gamma^2} \right| < MIND2 \quad (5)$$

$$\gamma = \frac{l_{max}}{l'_{max}} \quad (6)$$

7. **Point group matching**: After this method finds one similar triangle and N pairs of crater which match relative relationship with that triangle between crater map and camera shot image, this method calculates the spacecraft coordinates on the crater map using those craters. Blue circles of figure 8 shows craters which match between crater map and camera shot image. C shows positional vector of crater group in camera shot image while C' shows that in crater map. q_i and q_i' are positional vector from centroid position of crater group. Q_i of formula 7 shows position vector of each crater in crater map while Q_i' shows that in camera shot image. C, θ and s of formula 7 show spacecraft coordinate, yaw different between crater map and camera shot image and scale different between crater map and camera shot image. This method calculates the minimum value of C, θ and s.

$$Q_i = C + sR_\theta q_i \quad (7)$$

$$f(C, \theta, s) = \sum_{i=0}^{m} ||Q_i - Q_i'|| \quad (8)$$

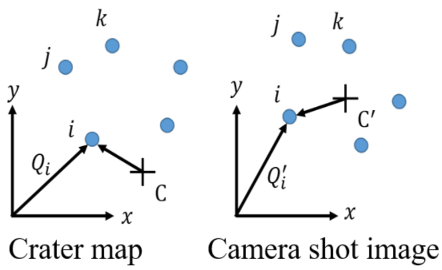

Fig. 8. Point group matching

4. Experiment

4.1. Cases

To evaluate an effectiveness of the TSM method, we conduct the experiments based on the 1,000 locations in the crater map on the moon, which is taken from "KAGUYA" satellite. In the experiment, three cases are conducted to investigate the experiments: (1) There is an altitude difference between the crater map and the shot camera image; (2) There is a roll and pitch difference between the crater map and the shot camera image; (3) There is a yaw difference between the crater map and the shot camera image.

4.1.1. altitude

In case1, we conducted experiments in the experiment that altitude of spacecraft camera shot image is a difference with that of crater map. The differences of altitude are the following seven types: (1) -15 % difference between altitude of spacecraft camera shot image and that of crater map; (2) -10 % difference between altitude of spacecraft camera shot image and that of crate rmap; (3) -5 % difference between altitude of spacecraft camera shot image and that of crater map; (4) ± 0% difference between altitude of spacecraft camera shot image and that of crater map; (5) +5 % difference between altitude of spacecraft camera shot image and that of crater map; (6) +10 % difference between altitude of spacecraft camera shot image and that of crater map; (7) +15 % difference between altitude of spacecraft camera shot image and that of crater map.

4.1.2. roll and pitch

In case2, we conduct experiments in the experiment that roll and pitch of spacecraft camera shot image is a difference with that of crater map. The differences of roll and pitch are the following three types: (1) -5 degree difference between roll and pitch of spacecraft camera shot image and that of crater map; (2) ± 0 degree difference between roll and pitch of spacecraft camera shot image and that of crater map; (3) +5 degree difference between roll and pitch of spacecraft camera shot image and that of crater map.

4.1.3. yaw

In case3, we conduct experiments in the experiment that yaw of spacecraft camera shot image is a difference with that of crater map. The differences of yaw are the following seven types: (1) -45 % difference between yaw of spacecraft camera shot image and that of crater map; (2) -30 % difference between yaw of spacecraft camera shot image and that of crater map; (3) -15 % difference between yaw of spacecraft camera shot image and that of crater map; (4) ± 0% difference between yaw of spacecraft camera shot image and that of crater map; (5) +15 % difference between yaw of spacecraft camera shot image and that of crater map; (6) +30 % difference between yaw of spacecraft camera shot image and that of crater map; (7) +45 % difference between yaw of spacecraft camera shot image and that of crater map.

4.2. Evaluation Criteria

The following evaluation criteria are employed: (1) a success frequency in each case (1000 camera shot images), (2) an average estimated time for finding the correct location in each case, (3) a max estimated time for finding the correct location in each case and (4) a worst estimated time in each case.

To calculate the estimated time for finding the correct location, we convert the time that expected to take at FPGA. The parameters are set at shown in table 1.

Table 1. parameters

DIFF	0.08
MIND2	700
N	7

5. Result

Table 2 shows the result that experiment of estimating the spacecraft location when the altitude of camera shot images is different from that of crater map. Horizontal axis is the percentage of altitude difference between crater map and camera shot images and vertical axis is success frequency, mismatching frequency, not found frequency, max error, average time, max time and worst time from top to bottom. Success frequency means times when the error between estimated coordinates and answer coordinates is less than or equal 35pixels. Mismatching frequency means times when the error between estimated coordinates and answer coordinates is more than equal 35pixels. Not found frequency means times when TSM method cannot estimate spacecraft location. Max error means maximum error between estimated coordinates and answer coordinates within 35 pixels in each case. Ave time means the average estimated time for finding the correct location in each case. Max time means the maximum estimated time for finding the correct location in each case. Worst time means the maximum estimated time in each case. From table 2, this method can estimate 90% spacecraft current location when the spacecraft altitude is higher or equal than crater map. However, estimation accuracy decrease as the spacecraft altitude becomes lower than crater map. This is caused by that the lower the spacecraft altitude is, the narrower the range in which the camera shot image area.

Table 3 shows the result that experiment of estimating the spacecraft location when the roll and pitch of camera shot images is different from that of crater map. Horizontal axis and vertical axis have the same meaning as the table 2. From the table 3, this method can also estimate 90% spacecraft current location when the spacecraft roll and pitch are different from crater map. Max error of table 3 is larger than max error of table 2 and 4. That reason is because all craters are shifted in one direction.

Table 4 shows the result that experiment of estimating the spacecraft location when the yaw of camera shot images is different from that of crater map. Horizontal axis and vertical axis have the same meaning as the table 2 and 3. From the table 4, this method can also estimate 90% spacecraft current location when the spacecraft yaw is different from crater map.

From worst and max time of all results, this method can estimate spacecraft current location within 3 seconds. It can be said that this method not only estimates the spacecraft location but also judges that this method cannot estimate within 3 seconds. This method can estimate the spacecraft location with high accuracy but there are a few mismatching times.

6. Conclusion

To tackle the self-position estimation, this paper proposed the TSM method under the condition that there are a lot of undetected craters. In particular, this method searches one similar triangle and some craters that match relative relationship with that triangle. To investigate an effectiveness of this method, we conducted the simulation under the 1,000 locations in the crater map on moon taken by “ KAGUYA ” satellite and found that the proposed method could estimate the current spacecraft location robustly. In paritcular, ETSM method has to find a number of similar triangles, however, TSM method can estimate self-position by finding only one similar triangle. In the near future, we must pursued the following future research: (1) improvement of the success rate when the crater map and the camera shot image have the difference altitude. Specifically, the altitude of spacecraft is lower than that crater map ; (2)the difference between estimated position and the true position should be reduced within 3pix.

Acknowledgments

The editorial office appreciates authors’ efforts to fully follow this template style because a manuscript for this special issue must be made camera-ready for themselves.

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Table 2. result of case 1

altitude	-15 %	-10 %	-5 %	0 %	+5 %	+10 %	+15 %
success(<=35pix)	710	856	944	976	979	984	983
mismatching(>35pix)	4	2	1	0	1	3	0
not found	286	142	55	24	20	13	17
max error [pix]	3.78	3.45	4.31	3.57	4.55	4.71	5.54
ave time [ms]	628	497	417	378	357	350	359
max time [ms]	2700	2115	2282	1559	1559	2282	1976
worst time [ms]	2700	2227	2282	1612	1614	2282	1976

Table 3. result of case 2

roll and pitch	-5 degree	0 degree	+5degree
success(<=35pix)	948	976	965
mismatching(>35pix)	2	0	2
not found	50	24	33
max error[pix]	31.90	3.57	27.12
ave time[ms]	432	377	418
max time[ms]	2115	1531	2255
worst time[ms]	2115	1670	2255

Table 4. result of case 3

yaw	-45 %	-30 %	-15 %	0 %	+15 %	+30 %	+45%
success (<=35pix)	961	973	973	976	978	979	970
mismatching(>35pix)	1	0	2	0	1	1	0
not found	39	27	25	24	21	20	30
max error[pix]	6.15	5.99	4.43	3.57	3.20	3.07	2.86
ave time[ms]	389	385	381	385	398	371	390
max time[ms]	1921	1921	1837	1614	2533	2088	2032
worst time[ms]	1921	1921	1837	1642	2533	2088	2171