How to Detect Essential Craters in Camera Shot Image for Increasing the Number of Spacecraft Location Candidates while Improving Its Estimation Accuracy?

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ABSTRACT

This paper addresses the spacecraft location estimation by matching the craters (*i.e.*, one similar triangle composed of the three craters, and the craters around the triangle) between the camera shot image and the crater database stored in a spacecraft, and improves our proposed method (called as Triangle Similarity Matching (TSM) method) in terms of the location estimation accuracy by detecting the "essential" craters in the camera shot image. For this purpose, our improved method increases the number of the spacecraft location candidates while limiting the condition for matching the craters. To investigate the effectiveness of our improved method, we created 1,000 camera shot image taken at different locations with photographical noises and conducted the simulation experiments in the planned landing course of the SLIM (Smart Lander for Investigating Moon) mission proposed by JAXA (Japan Aerospace Exploration Agency). The intensive simulation has revealed that the improved TSM method can improve the location estimation accuracy while reducing the computational time in comparison with the original TSM method and the JAXA's method.

1. Introduction

Japan Aerospace Exploration Agency (JAXA) is planning Smart Lander for Investigating Moon (SLIM) mission which aims at establishing the pin-point landing technology of a spacecraft for landing in the near scientifically interesting terrain [1]. Concretely, the purpose of this mission is to achieve the landing technology for the pinpoint area "where is *desired* to land" [8] in comparison with the conventional landing technology for the safe area "where is *easy* to land". For the pinpoint landing, it is necessary for a spacecraft to estimate the current location.

Towards this goal, our previous research proposed the Triangle Similarity Matching (TSM) method [2]. The TSM method extracts the triangles of the craters detected from the camera shot image and those in the crater database, and searches the former triangle which is matched with the latter triangle (Note that the employed crater database includes the crater coordinates on the moon obtained by KAGUYA satellite). After finding the matched triangle of craters, the TSM method checks whether the craters around the matched triangle in the camera shot image match those in the crater database, and calculates the coordinate (*i.e.*, the current location) of the spacecraft from the crater database by the multiple point matching. Concretely, the TSM method matches one similar triangle and more than *N* craters around the triangle between the camera shot image and crater database.

The difficult issues of the current location estimation of the spacecraft by matching the craters in the camera shot image with those in the craters database are summarized as follows: (1) some craters in the camera shot image are wrongly detected (*i.e.*, the detected craters in the camera shot image are not included in the crater database); (2) some craters in the crater database cannot be detected from the camera shot image; and (3) the location of most craters in the camera shot image are slightly different from that in the crater database. Two difficult issues (1) and (2) increase the number of the wrong spacecraft location estimation in the case of the *weak* crater matching condition (*e.g.*, its location is calculated with the small number of the matched craters) or increase the number of the location-not-found cases where the spacecraft location cannot be estimated in the case of the *strong* crater matching condition (*e.g.*, its location is calculated with the large number of the matched craters). The difficult issue (3), on the other hand, decreases the accuracy of the spacecraft location estimation.

To overcome these problems (*i.e.*, to improve the location estimation accuracy by increasing the number of the spacecraft location candidates while limiting the condition for matching the craters), this paper improves the TSM method to detect the "essential" craters in the camera shot image. Here, the "essential" craters in this paper correspond to the "correct" or "mostly correct" craters in the camera shot image which contribute to calculating the accurate spacecraft location by matching those in the crater database. However, it goes without saying that we cannot know which craters are correct. For this issue, the improved TMS method tries to detect the craters which seems to be correct as much as possible.

This paper is organized as follow: Section 2 starts by introducing the algorithm of the TSM method and its problems, and Section 3 improves the TSM method. Section 4 conducts the experiment and Section 5 discusses the experimental results. Finally, our conclusion is given in Section 6

2. Triangle Similarity Method

2.1 Algorithm

Fig. 1 shows the brief algorithm of the TSM method, which is proceeded as follows:

1. The triangles composed of the three craters are created from the craters in the camera shot image.
2. One triangle is selected from the crater map (as the crater database), while one triangle is selected from the camera shot image. Note that many triangles in the crater map are created beforehand.
3. Two selected triangles are compared to determine whether they are similar or not. If they are similar, then go to the step 4; otherwise retune to the step 2.
4. The craters around the matched triangle in the camera shot image are checked to be matched with those in the crater database. If the N or more number of the craters is matched, then larger than is under a threshold, then go to the step 5; otherwise retune to the step 2.
5. The coordinate (*i.e.*, the current location) of the spacecraft are calculated from the matched craters (*i.e.*, one matched triangle composed of the three craters, and the matched craters around the matched triangle) by the multiple point matching.

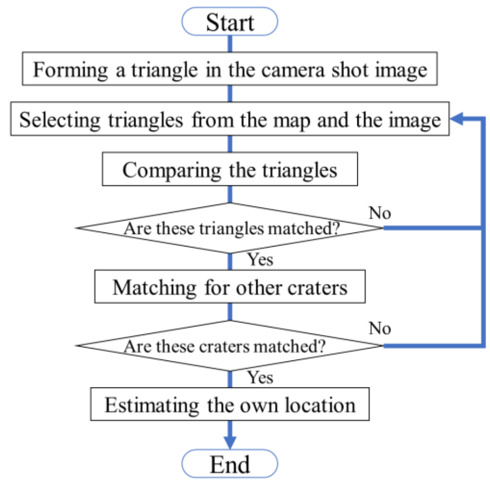

Figure 1: *Brief Algorithm of the TSM method*

2.2 Pairing mechanism

The essential mechanism of the TSM method is to determine whether the matched craters are correct or not. For this issue, the process (called "pairing process" in this paper) in the TSM method calculates the inner and cross products of two vectors such as d_1 and d_{center} (described below) as shown in Fig. 2, which respectively indicates the camera shot image in the left side while the crater map in the right side. In this figure, one triangle composed of the three craters, two craters around the triangle, and two arrows (vectors) are shown in each side. Note that the circle in the center of the triangle indicates the center of gravity of the triangle. As the arrows, one is the vector along to the long side of the triangle, the other is the vector between one crater around the triangle and the center of gravity of the triangle.

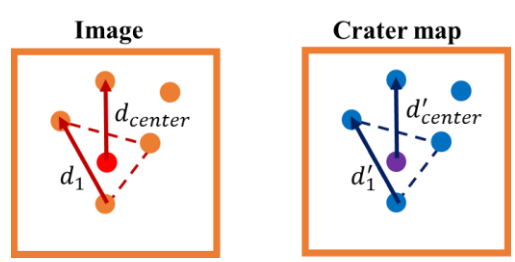

Figure 2: *Matching craters*

Concretely, the TSM method determines whether the matched craters are correct or not according to the following in Eq. 1 and 2 which are based on the inner and the cross products of the two vectors. In these inequalities, (i) MIND2 is a threshold which indicates the allowable amount of the difference of the location of the craters, and (ii) $\boldsymbol{\gamma}$ in both inequalities is a ratio of two sides of the triangle in the camera shot image and crater map as shown in Eq. 3.

$$\left| \boldsymbol{d_1} \cdot \boldsymbol{d_{center}} - \frac{\boldsymbol{d'_1} \cdot \boldsymbol{d'_{center}}}{\boldsymbol{\gamma^2}} \right| < \boldsymbol{MIND2} \quad (1)$$

$$\left| \boldsymbol{d_1} \times \boldsymbol{d_{center}} - \frac{\boldsymbol{d'_1} \times \boldsymbol{d'_{center}}}{\boldsymbol{\gamma^2}} \right| < \boldsymbol{MIND2} \quad (2)$$

$$\boldsymbol{\gamma} = \left| \frac{\boldsymbol{d_1}}{\boldsymbol{d'_1}} \right| \quad (3)$$

2.3 Problem

The TSM method calculates the coordinate of spacecraft according to the matched triangle and N or more number of craters around the triangle. However, it is generally difficult to estimate the N value. If N is set as a large value, the location is hard to be estimated because the large number of the matched craters are not guaranteed to be found. If N is set as small value, on the other hand, the wrong location may be estimated because the location is estimated with only small number of the matched craters.

3 Proposed Method

To tackle this problem, we propose two modifications: (1) Matching crater and triangle; (2) Multi-pairing method. In TSM system, the craters are judged as right craters or not by dot product and cross product calculation. The right craters are often judged as incorrect craters because of inappropriate threshold: slightly high dot or cross product. Matching crater and triangle contribute to judge craters adequately by redesigning threshold. Multi-pairing method help to detect the location with few craters. In TSM system, it is required that location is detected with few craters. For that reason, Multi-paring method is designed in order to improve success rate of detecting correct location. In Multi-paring method, TSM considers combinations of vectors consisting of crater and triangle center.

Concretely, the following approaches are employed in our pattern matching method: (i) to select the craters which seems to be correct, which satisfies the summation of the inner and cross products square 2 values; (ii) to determine that the matched triangles of the craters are correct when satisfying (a) the inner and cross products of all side vectors of the triangle, (b) the inner and cross products of the vectors between the gravity point of the triangle and the craters around the triangle and (c) the inner and cross products of vectors generated by the craters around the triangle.

We proposed and introduced two modifications into The Triangle Similarity Method: (1) Matching crater and triangle; (2) Multi-pairing method. In (1) Matching crater and triangle, we set the proper threshold to select the craters. This modification helps to increase the craters to be collated. In (2) Multi-pairing method, we use the vectors consisting of crater and triangle center.

3.1 Matching crater and triangle

The TSM method matches craters around the triangle with Eq. 1-3. However, Eq. 1 and 2 depends on the direction of displacement. For example, as shown in the Fig. 3, assuming triangle matched between crater database and camera shot image is correct and not deviated, crater around matched triangle in camera shot image matches toward that in crater database if that in camera shot image is within the yellow range. The yellow range is square having sides parallel to the long side ($|\overrightarrow{\boldsymbol{p_{hk}}}|$) of the triangle in crater database. For that reason, crater $\boldsymbol{i'}$ in camera shot image can be matched crater $\boldsymbol{i}$ in crater database, but crater $\boldsymbol{m'}$ in camera shot image cannot be matched that.

Due to this problem, we introduce Eq. 4 instead of Eq. 1 and 2. By using the Eq. 4, the shape of the range for matching craters around matched triangle becomes circular. In particular, as shown in the Figure, crater around matched triangle in camera shot image matches toward that in crater database if that in camera shot image is within the blue range. Eq. 4 can evaluate matching crater and triangle between crater database and camera shot image and increases the possibility of those.

$$\sqrt{\boldsymbol{I^2} + \boldsymbol{C^2}} \leq \boldsymbol{D} \quad (4)$$

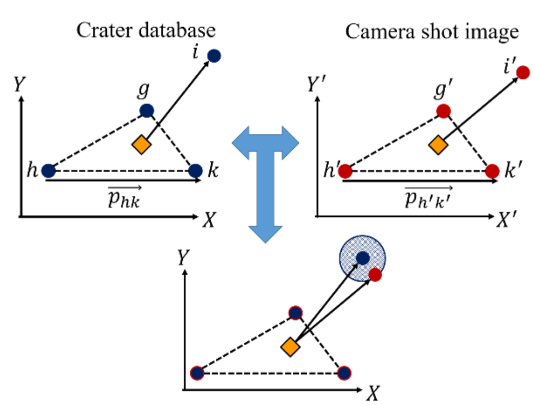

Figure 3: Matching triangle and around craters

3.2 Multi-pairing method

We propose Multi-Paring method in order to be able to match with few craters. The Multi-Pairing method evaluates

Pattern 1 and 2 of multi-pairing method show Fig. 4. Pattern 1 is calculation of absolute difference of dot product between the camera shot image and crater database and that of cross product between those using the vector of triangle short side (black line, $\overrightarrow{p_{kg}}$) and the vector of the centroid of the matched triangle to crater around that (red line). While, pattern 2 uses the vector of triangle middle side (black line, $\overrightarrow{p_{gh}}$) instead of the vector of triangle short side (black line, $\overrightarrow{p_{kg}}$). Pairing method robust to crater of matched triangle deviation because of using centroid coordinates of matched triangle. In particular, crater not used in the paring method (crater g) may deviate greatly. Thus, by multi-pairing of pattern 1 and 2, craters not used in the paring method (crater h, k or g) are checked.

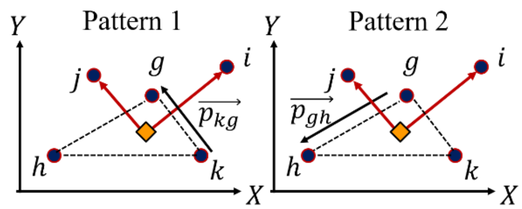

Figure 4: *Matching pattern based triangle*

Pattern 3 and 4 of multi-pairing method show Fig. 5. In pairing method and multi-pairing of pattern 1 and 2 matches craters around matched triangle based that, while pattern 3 and 4 matches craters based mated craters around matched triangle. Fig. 3 shows craters matched by pairing method. Crater h, k and g are craters formed matched triangle and crater i and j are craters matched its around matched triangle. Pattern 3 calculates pairing method using vector formed craters around matched triangle (black line, $\overrightarrow{p_{ij}}$) and vector formed crater i and craters constituting the triangle.

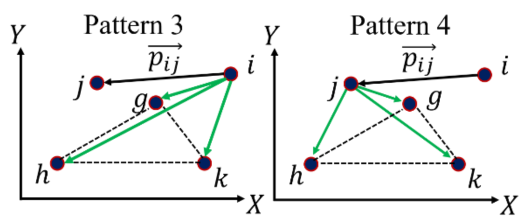

Figure 5: *Matching pattern based around craters*

4 Experiment

4.1 Environments

To evaluate an effectiveness of the proposed method in the environments that simulate the actual problem environment, the proposed method, the old TSM method, and the senbun matching method that is proposed by Kariya [3] are applied to the problems that are added various noise to the camera shot images of the simulation. There are 10 environments as shown in Tab. 1. Environment 400 is not added the camera shot image noise and the other 9 environments are added the photographical noises. But all environments have deviation of detection position of the crater and craters with only one of the camera shot image and database. Each environment has 1000 camera shot images. The photographed places of the 1000 camera shot images are different. But even if the environment is different, the photographed places are not changed (changing only the type of the added noise).

Table 1: *Environments*

Environment	Kind of noise
400	No noise
403	Brightness noise
404	Contrast noise
405	Bokeh
406	Luminance noise
407	Radiation noise
409	Distortion
411	Shake noise
412	Visnetting
430	Sun altitude noise

4.2 Evaluation criteria

There are various restrictions on SLIM mission setting by JAXA. A case where the difference between the estimated coordinate and the answer coordinate is within 3 pixels is defined as successful. A case where the difference is more than 3 pixels is defined as unsuccessful (mismatching). The system must estimate the coordinate within 3 seconds after photographing the camera shot image with the field-programmable gate array (FPGA) in small unmanned spacecraft.

In this paper, the following evaluation criteria were designed considering the above restrictions.

1. Estimation accuracy

   TSM method estimated the current spacecraft location, “ok” is expressed that the difference (Δ) between the estimated coordinate and the answer coordinate is 3 pixels or less, and “mismatch (mm)” is expressed the difference is more than 3 pixels. “not found (nf)” is expressed that the TSM method cannot estimate the current spacecraft location. The more the number of the “ok” case, the better the accuracy of the method is.

Since the “mm” has an adverse effect on the spacecraft control, the “nf” case is preferable to the “mm” case.

2. Error distance

“ave_d” means the average value of the difference between the estimated coordinates and the answer coordinates in the system estimated case (without the “nf” cases). “max_d” means the maximal difference between the estimated coordinates and the answer coordinates in the system estimated case.

3. Calculation time

“max_time” means the maximum estimated time in the “ok” and “mm” cases, and “worst_time” means the maximum time in all cases (within the “nf” cases). These two criteria are not the time of executing the method on the FPGA but the time executed by a general computer (Intel Core i7-4790 @3.60 GHz CPU and 16.0 GB RAM). In order to satisfy the restriction time in the FPGA, the execution time on the computer needs to be less than 30 msec.

These evaluation criteria are summarized in Tab. 2.

Table 2: *Evaluation criteria*

Criteria type	name	mean
Estimation accuracy [times]	ok	$\mathbf{\Delta \leq 3\ pixels}$
	mismatching (mm)	$\mathbf{\Delta > 3pixels}$
	not found (nf)	No estimation
Error distance [pixel]	ave_d	Average value of the error
	max_d	Maximum value of the error
Calculation time [ms]	max_time	Maximum time without the not found case
	worst_time	Maximum time within the not found case

4.3 Experimental results

The experimental result of the proposed TSM method is shown in Tab. 3, the result of the old TSM method is shown in Tab. 4, and the result of the senbun matching method is shown in Tab. 5. Comparing Tab. 3 and 4, we can see the effect of the mechanism added this proposed TSM method. The important features are: (i) significant reduction of the “mm” case with a small decreasing the “ok” case; (ii) significant reduction of the “max_d” and “avr_d” (in the “mm” case); and (iii) There were no big change in calculation time (the “max_time” and “wrst_time”).

The average value of the number of the “mm” case decreased from 2.7 to 2. In environment 430, the number of the “ok” case decreased by 15. Although the correctly estimating accuracy (the number of the “ok” case) of the proposed TSM method is lower than that of the old TSM method, it can be said that the proposed TSM method is more practical because there are fewer the “mm” cases.

In the “mm” case that estimated coordinate 3 pixels or more away from the answer coordinate, the maximum value of the distance from the answer coordinate was less than 7 pixels in each environment. Even in environments where the number of the “mm” case was not decreased (environment 407 and 430), the maximum value of the distance was decreased. From these results, it can be seen that there is no the “mm” case where the proposed TSM method estimated the different point far away from the answer coordinate.

Despite the introduction of Multi-Paring method, the proposed TSM method did not show a large increase in the maximum value (“max_time”) and the worst value (“mrst_time”) of the calculation time. The maximum value of these values is less than constraint time (30msec).

From the viewpoint of the accuracy (the estimation accuracy and the error distance) and the calculation time, the proposed TSM method is more practical than the old TSM method.

The “ave_d” of the proposed TSM method is smaller than the “ave_d” of the senbun matching method in all cases. The average of the “max_time” and the “worst_time” of the proposed TSM method are smaller than the those of the senbun matching method. The proposed TSM method is more practical than the old TSM method and the senbun matching method.

5 Discussion

5.1 Increasing the number of the matching

Matching triangle and craters method of the proposed TSM method increase the opportunity the matching the triangle and the craters. Fig. 6 shows the matching tolerance of the old TSM method and it of the proposed TSM method. The left side of the figure is the matching tolerance of the old TSM method. The right side of the figure is the matching tolerance of the proposed TSM method. The ranges

Table 3: Result of the proposed TSM method

env	400	403	404	405	406	407	409	411	412	430
ok	1000	984	669	592	998	973	999	999	999	776
mm	0	0	3	0	2	8	1	1	1	4
nf	0	16	328	408	0	19	0	0	0	220
avr_d	0.908	0.912	0.967	0.909	0.907	1.004	0.823	0.905	0.897	0.969
max_d	3.32	3.359	6.761	3.024	4.614	5.147	3.029	3.677	3.817	4.34
max_time	17	17	20	13	10	24	13	14	18	17
wrst_time	17	17	33	13	10	24	13	14	18	21

Table 4: Result of the old TSM method

env	400	403	404	405	406	407	409	411	412	430
ok	1000	985	670	595	997	977	1000	998	998	781
mm	0	0	8	0	3	8	0	2	2	3
nf	0	15	322	405	0	15	0	0	0	216
avr_d	0.843	0.862	1.751	0.877	0.861	1.192	0.782	0.843	0.852	0.996
max_d	3.245	3.284	272.272	3.122	5.023	219.136	2.811	3.326	6.18	61.945
max_time	17	16	26	10	14	19	28	12	20	16
wrst_time	17	16	26	10	14	19	28	12	20	18

Table 5: Result of the senbun matching method

env	400	403	404	405	406	407	409	411	412	430
ok	998	981	703	606	998	981	999	999	999	794
mm	2	2	2	1	2	5	1	1	1	7
nf	0	17	295	393	0	14	0	0	0	199
avr_d	1.11	1.115	1.13	1.123	1.119	1.112	1.097	1.113	1.071	1.401
max_d	3.517	3.643	5.427	3.385	3.668	3.893	3.246	3.531	3.385	94.461
max_time	28	25	20	19	26	21	24	24	27	23
wrst_time	28	25	20	19	26	21	24	24	27	23

that satisfies Eq. 1 and 2 are the square area in the left of the figure. The range that satisfies Eq. 4 is the sector area in the right of the figure. The sector area encompasses the square area. Matching triangle and craters method of the proposed TSM method increase the opportunity the matching the triangle and the craters. The introduced method contributes to reduction of the calculation time and the number of the "nf" case.

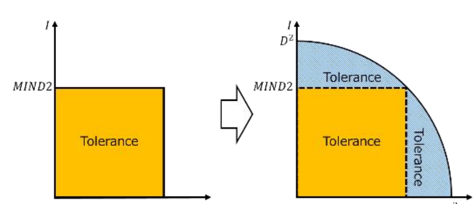

Figure 6: Matching tolerance

5.2 Improving the matching accuracy

Just introducing the matching triangle and craters method may increase the number of the "mm" case.

In order to increase the number of the “ok” case, it is necessary to add constraints to find the correct the triangle and the craters combination. The cause of the “mm” case in the old TSM method is the deviation of the craters making up the triangle. Since the pairing method (Fig. 2) uses the positional relationship (inner and a cross products) between the centroid of the triangle and the craters that do not form the triangle, the deviation of the craters making up the triangle has only one-third effect. With the pattern 3 and 4 the pairing method (Fig. 3) based on craters that do not form the triangle, the proposed TSM method can correctly grasp the deviation of the craters making up the triangle. The proposed method was able to suppress the number of the “mm” case.

6 Conclusion

For the pinpoint landing on the moon by small unmanned spacecraft (SLIM mission), it is indispensable to estimate the position of highly accurate probes. This paper focused on minimizing estimation errors. In the actual mission, it is important that there is no false estimation case (the “mm” case) or even if there are some false estimation case, the error is small. The old TSM method has a problem that estimating the coordinate of a location which is significantly different from the answer coordinate when there are few points to be matched with the database and the camera shot image.

To overcome this problem, this paper proposed the revised TSM method that is introduced matching triangle and craters method and multi-pairing method for practical application of the TSM method. The matching triangle and craters method increases the number of craters to match the database and the camera shot image. The multi-pairing method selects the craters that can be used for highly accurate the location estimation.

In order to verify the performance of the proposed TSM method, we simulated one crater database and 10 different environments (each environment have 1000 camera shot images). This method greatly reduced the number of misjudgment case (the “mm” case) and the error distance when the “mm” case without significantly reducing the number of correct cases (the “ok” case). From the viewpoint of the accuracy (the estimation accuracy and the error distance) and the calculation time, the proposed TSM method is more practical than the old TSM method and the senbun matching method.

We apply the proposed method into the 10000 test cases. The results show that the proposed method can improve success rate of correct location. Surprisingly, the proposed method decreases not only “Not found” case and also “Miss detection” case.

Such important directions must be pursued in the near future in addition to the following future research: (1) adaptation to the environment with complex noise added; (2) adaptation to the environment where the pose of the small unmanned spacecraft is abnormal; and (3) adaptation to the other environments where the small unmanned spacecraft is landing.

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