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A survey of algorithms for star identification with low-cost star trackers ☆

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ABSTRACT

This paper aims to present a set of lost-in-space star identification algorithms that works effectively for small satellites. Several algorithms are investigated for both phases of star identification: feature extraction and catalogue search. For feature extraction, it is shown that an algorithm using extended images with combined images works best, and for catalogue search, the Group Catalogue is shown to be most efficient. Therefore, this paper proposes an algorithm combining these three. Simulation results show the effectiveness of this algorithm for its robustness to various errors, and an application of this algorithm, ‘‘unequal'' star trackers, is introduced.

1. Introduction

As technologies have advanced, satellites have been able to execute various high-level missions. However, these satellites have concurrently grown so comprehensive and complex that efficiency has become a major problem in today's space exploration. High costs and long developmental periods are too steep for the riskiness of satellites, particularly their failure, which would lead to less access to space. One solution to these problems is the miniaturisation of satellites. Small satellites can be developed for a low cost in a short period of time and are expected to revitalise space exploration.

Recently, many universities and companies have begun to develop small satellites. One of them is Nano-JASMINE (Nano-Japan Astrometry Satellite Mission for Infrared Exploration) [1,2], an astrometry satellite developed by the University of Tokyo and NAOJ (National Astronomy Observatory of Japan) that is scheduled to be launched in 2011. I have been involved in this project for 2.5 years. Nano-JASMINE is the world's second astrometry satellite after HIPPARCOS [3]. Surprisingly, though HIPPARCOS and Nano-JASMINE can perform observations at a similar accuracy (3 mas (milli-arcsecond) at 7.5 magnitude stars), HIPPARCOS was 1000 kg while Nano-JASMINE is only 30 kg. With the combined data from Nano-JASMINE and HIPPARCOS, it is expected that we can update the accuracy of the Star Catalogue, which can be used for the navigation of future satellites.

Nano-JASMINE is a turning point for the industry of small satellites because it shows that even small satellites can complete a high-level mission similar to large satellites. This means that the conventional, high-level technologies developed for large satellites could also be applied to small satellites. One such technology, the star tracker, is the focus of this paper. For Nano-JASMINE to achieve the required attitude stability for its observations (740 mas/8.8 s), FOG (Fibre Optic Gyroscope) and star trackers are indispensable (the detailed attitude control system of Nano-JASMINE is shown in [2]). This paper investigates several algorithms and proposes a lost-in-space star identification software system that can be used for star trackers on small satellites and shows its effectiveness.

Star trackers on small satellites have several restrictions that those on large satellites do not have. Here,

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I focus on the satellites that are around 10–100 kg and were designed to cut the developmental costs. For these satellites, the FOV (field-of-view) of the star trackers should be small to maintain a high accuracy for attitude determinations because images from low-cost star trackers would have lower pixel fineness. Though Nano-JASMINE's star trackers have 1000×1000 pixels for an $8^\circ \times 8^\circ$ FOV, this paper assumes an even smaller FOV size, $4^\circ \times 4^\circ$ with 1000×1000 pixels.

Some of the technical language will be defined here. The body frame of the star trackers is defined as a local frame, in contrast to a global inertial frame. Star catalogues for star trackers are on the satellites, and are defined as on-board catalogues. This paper also assumes several types of errors for star tracker simulations. Image errors express errors in the determination of the centre of a star in the image. Uncalibrated misalignment errors indicate the star tracker alignment errors that cannot be cancelled beforehand. Gyro errors are the errors that occur from the results of the gyro sensors.

In this paper, the basic processes of star identification are introduced first. Then, the two phases of the star identification system, feature extraction and catalogue search, are investigated. Finally, this paper proposes a lost-in-space star identification system for small satellites and introduces one of its applications, "unequal" star trackers.

2. Star identification

A star tracker is one of the attitude sensors on satellites. Usually, it is used in a pair and estimates the attitude of the satellite using star images taken by it. Fig. 1 shows the basic flow of the star trackers' processing. The processing of the star trackers can be divided into three phases, feature extraction, catalogue search, and attitude estimation. The first two phases can be defined as the identification phase in a narrow sense, which this paper will discuss.

In the feature extraction phase, the feature, or the star data, is extracted from the image for star identification. In the catalogue search phase, the star data in the images are matched to those in the star catalogue. Based upon these identified stars, the estimated attitude is calculated.

3. Feature extraction

In the phase of feature extraction, the most important problem is what information in the images should be extracted. Several algorithms have been proposed for this phase.

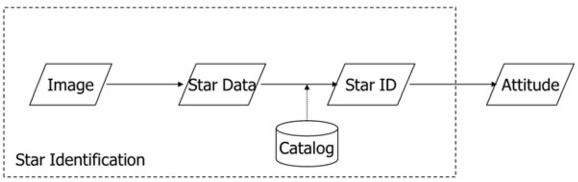

Fig. 1. Basic flow of the star trackers' processing. The square indicates the processes involved in star identification.

3.1. Pattern matching

One of the proposed algorithms is "pattern matching", as shown in [4]. This technique involves assigning a pattern for each star in the catalogue according to the location of other stars in a grid superimposed over the FOV, as shown in Fig. 2. The following steps are necessary to perform this technique:

1) Select one star and find its closest neighbouring star.
2) Rotate the captured image so that the selected star is at the centre of the FOV and its neighbouring star is on the x-axis.
3) Create a bit vector for every square in the grid. If the star in the captured image is in a square, the vector of that square will be 1, and if not, it will be 0.
4) Identify the star pattern of the image using the star catalogue (Catalogue search).

In this algorithm, the feature used for star identifications would be the star patterns. This type of feature extraction has several advantages. This algorithm is robust against positioning errors; if the grid size was far larger than the expected positioning errors, the errors would not seriously affect the result.

Also, this algorithm is robust against the false stars. The inexpensive star trackers for small satellites may have many image errors that can be mistakenly perceived to be stars. The algorithm for "pattern marching" uses the entire pattern for identification, and therefore, a few image errors would not be a large problem.

However, this algorithm also has a major disadvantage in that it is only effective when a large number of stars, at least six, are captured. This disadvantage makes this algorithm ineffective for small-FOV star trackers, such as those on the small satellites, because they can only capture a few stars. For example, in the case of a $4^\circ \times 4^\circ$ FOV and a Maximum Visible Magnitude of 6.0 (discussed later), more than 70% of the images capture only two stars or less, which is far

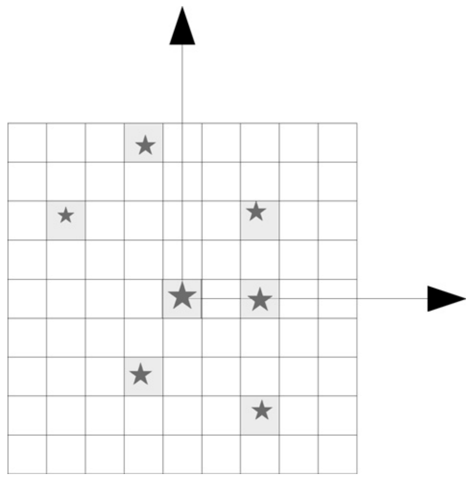

Fig. 2. Concept of pattern matching. Though this algorithm has an advantage in its robustness, it requires a large number of stars to perform the star identification.

smaller than the required six stars for pattern matching. Therefore, pattern matching is not appropriate for star trackers on small satellites.

3.2. Angular separation

For star trackers that cannot capture a large number of stars, which is true for those on the small satellites discussed here, "angular separation" would be the best algorithm. In this method, pairs of stars are made in the image, as shown in Fig. 3, and the angular separation of the pairs and their brightness are used for star identification. This condition can be expressed as the following,

$$\left| d(s_k^b, s_e^b) - d(s_m^i, s_n^i) \right| < \mu_1 \tag{1}$$

where s_k^b are the coordinates of kth star on the body frame, s_m^i are those of mth star on the inertial frame, $d(s_k^b, s_e^b)$ is the angular separation of s_k^b and s_e^b, and μ_1 is the permissible errors.

There are two types of sequences of angular separation. The first one chooses a star as a reference and identifies the angular separation between that star and others. The flow of this method would be as follows:

1) Select β brightest stars in the captured image.
2) Calculate the angular separations between the brightest star and the other stars.
3) Identify the angular separations using the star catalogue (Catalogue search).

The second one identifies the angular separations between the several brightest stars. The flow of this method would be as follows:

1) Select β brightest stars in the captured image.
2) Calculate the angular separations between every pair.
3) Identify the angular separations using the star catalogue (Catalogue search).

In this algorithm, the feature used for the star identification would be the angular separations. The magnitudes of the stars can also be identified in the same way as the angular separations, and they are often used with the angular separations when the positioning errors are large.

Without any errors, the stars can be identified and the attitude can be determined with only one star pair ($\beta=2$), or two stars. But in fact, the information from two stars is not enough for star identification due to large image errors, which are defined as the errors in the determination of the centre of a star in the image. Therefore, this paper chose to calculate the star identification only when at least three stars are captured in the image.

The star identification starts from a pair consisting of the two brightest stars, whose centres of gravity are easiest to define. Even when three stars are used, if there is ambiguity in the star identification, the remaining stars are used, from the brightest to the dimmest, until the identification succeeds. However, the time for identification increases with an increasing number of stars, which decreases the efficiency of the algorithm. Therefore, this paper chose the maximum number of stars to be used for identification, and if the stars still cannot be identified, then the identification is defined as unsuccessful.

3.3. Angular separation—using tracking

If the image errors are small, the method in the previous section can produce good results for lost-in-space star identifications. However, when the image errors are large, that method would require another technique to handle the "Ambiguity" cases, in which there are still multiple candidates for identification after all the captured stars have been used.

The tracking technique is effective in such cases. By tracking, one can keep the candidates for the stars captured during the previous time steps and use them to perform the star identification in the current time step. The concept of the tracking technique is shown in Fig. 4. The flow of tracking would be as follows:

1) When the star identification finishes at time step t, record the final candidates of all the stars in that image.
2) For all stars recorded in step 1, calculate the changes in positions using the data from the gyro sensors, estimate their positions at time step $t+1$, and record them.
3) When the star tracker captures an image at time step $t+1$, match the stars in the image with the recorded stars and identify the stars by a decreasing order of brightness. If that identification fails, the identification ends in failure.

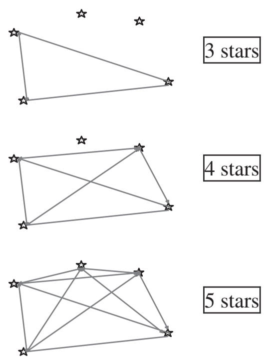

Fig. 3. Concept of the star identification using angular separations. This algorithm works well for star trackers with a small FOV.

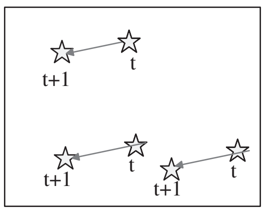

Fig. 4. Concept of the tracking technique. This technique is effective when the image errors are large.

The feature extracted from the image in this technique is also the angular separations, but in addition, this algorithm uses the image of the previous time step. This can improve star identification in those cases where the image errors are very large.

3.4. Angular separation—using extended images

Ideally, it is possible to identify the stars and determine the attitude with only the identification algorithms in the previous sections. In actuality, however, there are many cases in which a sufficient number of stars for identification, at least three stars, cannot be captured in the small satellites' star trackers due to their small FOVs ($3^\circ \times 3^\circ$–$6^\circ \times 6^\circ$). One solution to this problem is to extend the captured image, as shown in [5], which is expected to help improve the low success ratio of star identifications.

The concept of identification algorithms using extended images is shown in Fig. 5. With the angular velocities, the image can be extended similar to the tracking technique mentioned above. The procedure of this algorithm at time step $t+1$ is as follows:

1) When the star identification finishes at time step t, record the final candidates of all the stars in that image.
2) For all stars recorded in step 1, calculate the changes in positions using the data from the gyro sensors, estimate their positions at time step $t+1$, and record them. If the stars are not in the actual image at time step t or $t+1$, deduce the extended image, as in Fig. 5, and also perform this procedure on these stars.
3) When the star tracker captures an image at time step $t+1$, compare that image with the recorded stars in the actual image and identify the stars in decreasing order of brightness. If that identification does not succeed, proceed to step 4.
4) Identify the stars recorded in the extended image in step 2. If that identification fails, the identification ends in failure.

The feature extracted from the image in this technique is also the angular separations, and this method also uses previous data. Notably, this method uses stars that are outside of the image. This algorithm works well in the cases where the FOV is too small to capture at least three stars in the actual image that are necessary to make the identification successful.

However, this algorithm has one defect. When the gyro sensors have large errors, which often happens in low-cost satellites, the position estimation at time step t will be inaccurate, which deteriorates the performance of this algorithm. This effect will be simulated later.

3.5. Angular separation—using combined images

Another technique that was developed for the small FOV star trackers on small satellites is combining the images from two or more star trackers. To succeed in identification, the algorithm in Section 3.2 requires at least three stars to be captured for each star tracker. Of course, it is possible to determine the attitude with the conventional one star tracker identification algorithm even if only one star tracker captures at least three stars, but it is impossible for that algorithm to determine the attitude if neither star tracker captures at least three stars, which happens often if the FOV size is limited.

To solve this problem, an algorithm can be used, as is shown in Fig. 6 and [6,7]. In this algorithm, the stars captured by two pictures are combined and identified together. The procedure is as follows:

1) Identify the stars in the image from the main star tracker in decreasing order of brightness, similar to the solid line in Fig. 6. If that identification does not succeed, then go to step 2.
2) Identify the stars in the image from the other star tracker in decreasing order of brightness, similar to the dashed lines in Fig. 6. If that identification fails, the identification ends in failure.

Note that the angular separations within the image of the main star tracker should be identified before those across the images. This is because the former is free from the effects of misalignment errors between two star

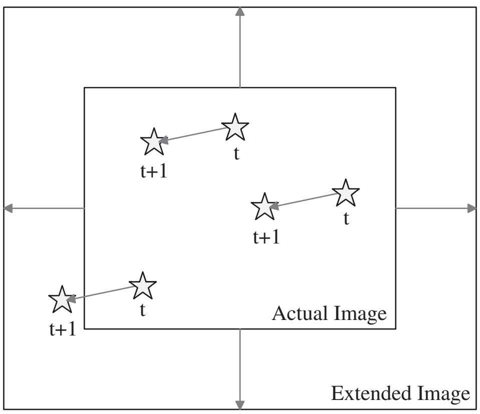

Fig. 5. Concept of the technique using extended images. This technique is effective when the FOVs are small but ineffective when the gyro errors are large.

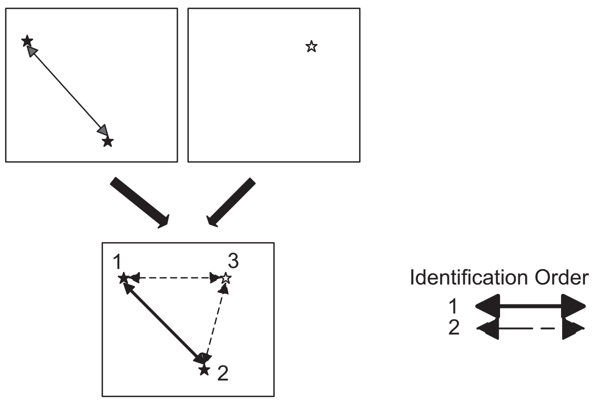

Fig. 6. Concept of the technique using combined images. This technique is effective when the FOVs are small but ineffective when misalignment errors are large.

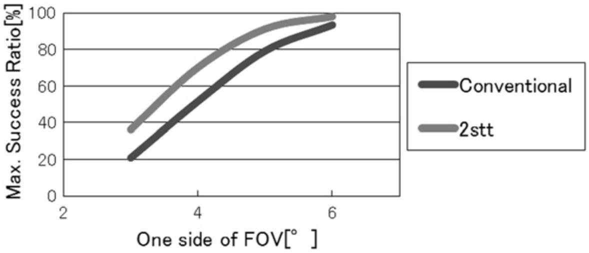

Fig. 7. Maximum success ratio (5000 cases) of the conventional algorithm (Conventional) and the algorithm combining two star trackers (2stt.).

trackers. If this algorithm is used, it only needs a total of three stars to be captured by the two star trackers, which increases the success ratio remarkably. (Though the angle between the star trackers and even the number of the star trackers can vary, this paper assumes two star trackers that are 90° apart from each other for simplification.)

The features extracted from the image in this technique include not only the angular separations in the image, but also those across the images. Similar to using the extended images, this algorithm is also expected to work well in the cases where the FOV is too small to capture at least three stars in the image to make the identification successful.

Fig. 7 shows the maximum success ratio for identification, or the success ratio without noise, of the conventional algorithm in Section 3.2 and this algorithm using combined images.

This figure shows that the algorithm using combined images is far better than the conventional one. For example, in the case of a $4^\circ \times 4^\circ$ FOV, the maximum success ratio of this algorithm is about 2.5 times that of using only one star tracker. This demonstrates the powerful ability of this algorithm.

Note that this is not the actual success ratio because there are noise and alignment errors in real situations. The performance with noise will be investigated later.

However, as with the algorithm in the previous section, this algorithm using combined images also has a defect. When uncalibrated misalignment errors, or the variant part of the misalignment errors, between the star trackers are large, which is true in many low-cost satellites, the identification between the star pairs across the image will not work well.

4. Catalogue search

After the phase of feature extraction, the star tracker would search the catalogue to match the stars in the captured image to those in the catalogue. This chapter explains the methods used for catalogue search and determines, which one works well for small satellites.

4.1. HIPPARCOS/TYCHO star catalogue

HIPPARCOS, the only astrometry satellite so far, was launched by the ESA in 1989 [3]. During its four-year operation, it had executed the accurate measurement of the positions, brightness, parallaxes, and proper motions of the stars. With these collected data, the HIPPARCOS Catalogue, which included more than 100,000 stars, and the TYCHO Catalogue, which included more than 1,000,000 stars, were published in 1997. These were followed in 2000 by the TYCHO-2 Catalogue that included more than 2,500,000 stars, which is 99% of the stars down to magnitude 11. These catalogues are used for various engineering and scientific purposes, including for star trackers (Both TYCHO and TYCHO-2 are mentioned in [3]).

For star identification by star trackers, the position of the stars and sometimes the brightness are necessary. These data should be included in a catalogue on the satellite, called the on-board catalogue. Also, faint stars that are not usually visible need not be included in the on-board catalogue. Therefore, the catalogue, similar to what is shown in Table 1, can be extracted from the HIPPARCOS/TYCHO Star Catalogue for star identification, which includes only the stars brighter than a certain Maximum Visible Magnitude that is set as 6.0 here.

Though this catalogue is simple to understand and small in size, it is not sufficient for "efficient" star identification. There have been many algorithms and additional catalogues proposed to make star identification efficient, which are mentioned in the following sections.

4.2. Star neighbourhood approach

An interesting approach to the star catalogue is the Star Neighbourhood Approach [8]. In this approach, an additional catalogue, as is shown in Table 2, is created according to the angular separations between the stars.

In this catalogue, every star has several nearby stars recorded, all of which should be within [$0^\circ \pm$ the diagonal size of FOV] from that star. When a star is in the image,

Table 1
Necessary information for star identification from the HIPPARCOS/TYCHO Star Catalogue (Maximum Visible Magnitude = 6.0).

Star no.	Right ascension	Declination	Magnitude
88	00:02:04.60	−48:48:35.5	5.71
107	00:01:20.11	−50:20:14.6	5.53
122	00:01:35.85	−77:03:55.1	4.78
124	00:01:37:02	+61:13:22.1	5.58
145	00:01:49.44	−03: −1:38.9	5.13
…	…	…	…

Table 2
An example of the Star Neighbourhood Approach's additional catalogue. Every star has its several nearest stars listed, and only these stars have to be searched for in the catalogue like Table 1.

Star no.	Neighbour stars			
…	…	…	…	…
3341	4132	4579	4580	4131
3342	4161	3707	1555	902
3343	267	553	95	988
3344	208	237	410	1003
3345	4634	4140	4141	4590
…	…	…	…	…

every other star in that image is a ''neighbour'' of that star. Therefore, with this additional catalogue, it is not necessary to search the whole catalogue in Table 1 but rather only the nearest stars from that catalogue to perform the identification.

This method can greatly decrease the searching time and is very efficient. However, it can still be improved because it requires numerous calculations to search all the possible star pairs that are near each other.

4.3. Group catalogue

As mentioned in the previous section, it requires many calculations to search all the possible star pairs that are near each other. The improved catalogue of the Star Neighbourhood Approach is a Group Catalogue, as shown in [9].

In this method, a Group Catalogue like Table 1, in which the star pairs within [$0^\circ \pm$ the diagonal size of FOV] in angular separation are made beforehand and are divided into a number of groups by their angular separations or the cosines of them.

The Group Catalogue is searched as follows:

First, the following inequality must be true,

$$|x-y| < \mu \tag{2}$$

where x is a cosine of the angular separation of the star pair to be identified on the body frame, y is a cosine of that on the inertial frame, or the catalogue, and μ is the permissible error. This permissible error can be derived from μ_1 in Eq. (1), but is not identical to μ_1.

Then, the catalogue search can be defined as a search of y that meets the condition of Eq. (2) using x derived from the image.

Next, find n and m that meet the following equations.

$$n = INT\left(\frac{1-x-\mu}{\Delta h}\right)+1 \tag{3}$$

$$m = INT\left(\frac{1-x+\mu}{\Delta h}\right)+1 \tag{4}$$

$INT(z)$ means the largest integer that is not larger than z.

The n and m represent both ends of the group that meets the condition in Eq. (2). This means that any star pairs that are not included in the nth, $n+1$th… mth group do not meet the above condition, and that any star pairs that are included in the $n+1$th, $n+2$th… $m-1$th group do meet the above condition. In conclusion, only the star pairs included in the nth and mth groups should be evaluated using Eq. (2).

A similar catalogue can also be created for the star pairs across the images (Table 4), which are necessary for star identification in the algorithm using combined images in Section 3.5. If the two star trackers are separated 90°, this catalogue includes star pairs within [$90^\circ \pm$ the diagonal size of FOV $+\alpha$] of angular separation divided into a number of groups, where α is the maximum possible misalignment error. With this catalogue, the star identification across the images can also be completed with the same efficiency as those in the same image.

Similar to the method using combined images in Section 3.5, the catalogue of Table 4 can also be utilised in cases with more than two star trackers as long as they are all separated from one another by a certain angle, which is assumed to be 90° in this paper but can vary.

This Group Catalogue can decrease the searching time from that necessary for searching all pairs to that necessary for searching only the pairs contained by two groups. According to Nakasuka [9], in an example image with an $8^\circ \times 8^\circ$ FOV and a magnitude limit of 6.0 and a catalogue with 800 groups, on average only 80 rounds of calculation are needed for searching one star pair with the Group Catalogue while it needs 2,995,128 rounds without it. This is a remarkable improvement in the catalogue search.

Furthermore, another advantage of a Group Catalogue is its scalability. Even if the size of the FOV increases, the searching time is still the same because only two groups are searched.

Though the performance of a Group Catalogue is very good, the size is a serious problem. The total size of each catalogue necessary for each FOV size is shown in Fig. 8. However, this paper assumes that there is enough memory size for the catalogue and does not investigate this problem further.

5. Star identification for small satellites

Using the above algorithms for feature extraction and catalogue search, this chapter will investigate which algorithm is good for small satellites' star trackers.

As mentioned above, small satellites often have small FOV star trackers on it due to the low cost of the image sensors. From this point of view, the algorithm using extended images (including the tracking technique) and the one using combined images seem to work well as feature extraction algorithms.

However, both of them also have their defects. The former algorithm does not work well when the gyro errors are large, and the latter one does not work well when the uncalibrated misalignment errors are large. Therefore, this paper proposes the use of an algorithm that combines them both for small satellites. By doing this, the performance is expected to be robust for both the gyro and uncalibrated misalignment errors.

Additionally, the algorithm proposed here also works well when the two star trackers used for identification have different qualities in their errors. This feature of the

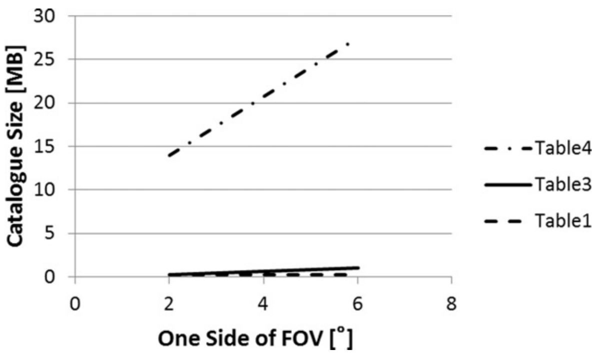

Fig. 8. Size of each catalogue. Table 4's catalogue is far larger than the other two.

algorithm would make a good application for it possible, which will be introduced in Section 5.2.

For catalogue search, the Group Catalogues seem to work well. Though the catalogue size is a problem, it is still efficient because the time required for the searching process can be decreased. Therefore, this paper proposes the use of a Group Catalogue. Both Group Catalogues in Tables 3 and 4 are used for the star identification within the same image and across the images, respectively.

5.1. Simulation for small FOV star trackers

To test the performance of the algorithm proposed above, a simulation is done here. One good indicator of that performance is the lost-in-space star identification, which is how many time steps, or how many seconds, is needed until the star identification succeeds, when starting from a random attitude. This indicator is defined as "time to relock". A shorter time indicates a better lost-in-space performance.

Table 5 shows the settings for the simulation, and the results are shown in Fig. 9. In Fig. 9, the horizontal axis show the star tracker misalignment and gyro errors, which are the weak points in the algorithms using either extended images or combined images from two star trackers, respectively, and the vertical axis is the "time to relock".

Several features can be considered and confirmed in Fig. 9.

When both the gyro and misalignment errors are small, this algorithm gives a very good performance. This is because there are no errors that prevent the use of extended images and combined images.

When both the gyro and uncalibrated misalignment errors are large, this algorithm still shows a better performance than the conventional algorithm in Section 3.2. Importantly, this new algorithm performs better, including a robust response to errors, than the conventional one. Therefore, the algorithm proposed here is shown to be very effective in small FOV star trackers.

Table 3
A Group Catalogue, where k=cos(the diagonal size of FOV). With this catalogue, efficient star identification would be possible.

Group no.	Cos(angular separation)	Star pairs		
1	$1\sim 1-\Delta h$	0083–0082,	0189–0188,	…
2	$1-\Delta h\sim 1-2\Delta h$	0088–0082,	0088–0083,	…
…	…	…	…	…
m	$1-(m-1)\Delta h\sim 1-m\Delta h$	0034–0012,	0377–0319,	…
…	…	…	…	…
$(1-k)/h$	$k-\Delta h\sim k$	0476–0386,	0640–0497,	…

5.2. Simulation for unequal quality star trackers

As mentioned above, one application of this new algorithm is a case that uses two unequal star trackers. Intentionally using one fine star tracker with a coarse one is cheaper than using two fine ones but performs better than using two coarse ones. This idea of efficient design can be used for small satellites' star trackers when decreases in costs are needed without affecting performance seriously.

For such cases, the algorithm using both combined images and extended images, including Group Catalogues, works quite well. If one of them has a larger image error than the other, the conventional algorithm in Section 3.2 would execute the identification independently. However,

Table 5
Settings of the simulation.

Number of cases	1000
FOV size	$4^\circ\times 4^\circ$
Extended FOV size	$8^\circ\times 8^\circ$
Pixel number	1000×1000
Number of groups for catalogues	60,000
Catalogue stars	5037
Positioning errors (1 sigma)	1 pixel
Magnitude errors (1 sigma)	0.1
Visible Magnitude Limit	6.0
Maximum number of stars for identification	4
Angular velocity	0.01 rad/s

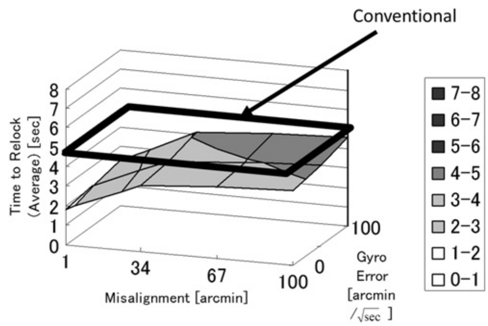

Fig. 9. Results for small satellites. The conventional data are from the algorithm in Section 3.2. It can be seen that the results of the proposed algorithm perform robustly for both the misalignment and gyro errors.

Table 4
A Group Catalogue, where k=cos(90° ± the diagonal size of FOV $+\alpha$). With this catalogue, efficient star identification across the images would also be possible.

Group no.	Cos(angular separation)	Star pairs		
1	$-k\sim -k+\Delta h$	0105–0000,	0418–0190,	…
2	$-k+\Delta h\sim -k+2\Delta h$	0911–0116,	0945–0174,	…
…	…	…	…	…
m	$-k+(m-1)\Delta h\sim -k+(m+1)\Delta h$	0293–0049,	0593–0254,	…
…	…	…	…	…
$2k/\Delta h$	$k-\Delta h\sim k$	0386–0042	0438–0082	…

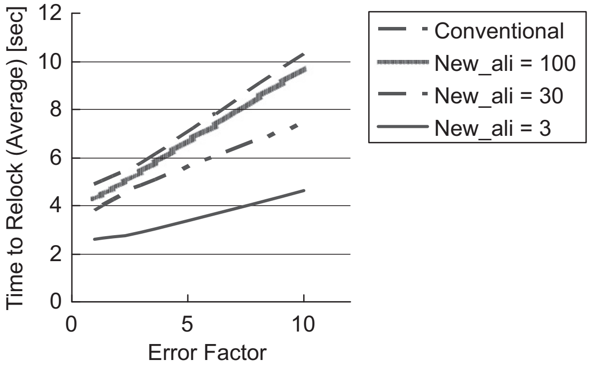

Fig. 10. Results for unequal star trackers for the conventional algorithm (Conventional) and the new algorithm with a misalignment error=3, 30, 100 arcmin (New_ali=3, 30, 100). The Error Factor is the ratio of the positioning errors from the larger one to the smaller one.

this new algorithm can make the better star tracker compensate for the worse one.

The results of the cases for unequal quality star trackers are also simulated and the performance can be seen in Fig. 10. The Error Factor is the ratio of the positioning errors of the stars in one star tracker to those in the other. This figure shows that the slope of the curve is smaller when the new algorithm is used. This indicates that in the new algorithm, when the error factor increases, the degradation of performance would not be as great as with the conventional algorithm.

6. Conclusion

In this paper, several algorithms are listed for both phases of star identification, feature extraction and catalogue search, and a lost-in-space star identification system for small satellites is proposed.

For feature extraction, an algorithm using both extended images and combined images was shown to be the best algorithm for small satellites. For catalogue search, the Group Catalogue was shown to be the most efficient for small satellites.

Simulations showed that the algorithm proposed in this paper has robustness for both gyro errors and misalignment errors. Also, this algorithm was shown to perform well when one of the two star trackers is inferior to the other. This feature enables a good application of this algorithm, "unequal" star trackers, in which one fine star tracker and one coarse one are used intentionally for efficiency.

In conclusion, this new algorithm is shown to work well for small satellites. This would improve the success ratio of star identification for small FOV star trackers and make it realistic to use star trackers on small satellites. This research would enable small satellites to perform many high-level missions that require accurate attitude control and determinations, like astrometry missions, and we expect it can improve the future of low-cost space exploration.

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