# Labelling technique for the fast Star Identification

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Star sensor provides with the most accurate attitude determination method for the spacecraft. Its accuracy comes from the exact star positions on the image of sensor, and it is need to identify the stars exactly for the further determination process. Usually it is time consuming work with the limited computational power of star sensor, especially it takes much longer time when the star sensor is in the case of lost in space, which has no priori information of its attitude. Many star identification algorithms have been introduced to solve this identification issue aiming the fast identification speed. However, the faster identification algorithm is always required to satisfy the better performance of star sensor. At this study, a new star identification algorithm is proposed for the star sensor in the lost in space case. The algorithm is based on labelling technique that assign a label value for the each star combination. Using the label value, multiple stars are identified simultaneously without repeating the search work. This makes the efficient star identification with fast speed, and the fast speed supports high reliability of its identification result when the identification result can be confirmed with redundancy. Proposed algorithm is verified its performance with simulation under various conditions, and compared with other space proven algorithm.

**Key Words:** Star sensor, Star identification, Labelling, Fast search

**Nomenclature**

| | | |
|---|---|---|
| L | : | label |
| A | : | angle |
| Subscripts | | |
| 1 | : | initial |
| n | : | final |

## 1. Introduction

Star sensor is the most accurate sensor for the spacecraft attitude determination, and becoming essential device for many space missions. It estimates the attitude by comparing the star patterns of captured images by a camera with the reference data stored on the memory. A sequence of works is required in order to make comparable information from the captured image. The star positions on the image are extracted from the image at first, and their corresponding vector information is calculated with respect to the sensor frame. After that, a number of stars in the image should be identified as matched stars stored on the reference data. After the star identification, the attitude can be estimated using more than two matched star vectors between two different frames, the sensor frame and the inertia frame. Among those works, star identification is usually the most complicated and time-consuming work because it needs searching work to match the stars on the image to the stars on database.

Especially, star identification becomes more difficult work when it is on the case of lost in space, no priori information about the attitude of star sensor. For the lost in space case, many excellent algorithms have been introduced already. Those algorithms can be categorized by the characteristics, angle based algorithms, pattern based algorithms, and other experimental algorithms.6) However, all algorithms have same goal, extract some aspects from the sensor image, and find uniquely identified with the stored data on the memory of star sensor. Each algorithm has its own advantages. The angle based algorithm mainly uses the exact angular distances between stars. The representative one is the triangle algorithm among them. At the algorithm, the bright stars in the image are chosen to make a triangle. The three sides of the triangle and the brightness of each star are then compared with those in the database. The other algorithms have been also developed in this category and show the improved robustness and speed compared with the triangle algorithm. The pattern based algorithms use a strategy that locates the most similar image by comparing the entire image pattern with the patterns stored on the memory. The grid algorithm is one of the most famous algorithms in this category because of its intuitiveness and performance.5) Some algorithms use the idea of artificial intelligence such as neural network algorithms and genetic algorithms.7) And, a singular value decomposition method is also proposed for the work of star identification.

For the practical use, the two categories of the angle based algorithm and the pattern based algorithm are usually used on the orbit now. Each category has own relative advantages. Generally, angle based algorithms are faster when very accurate optic system is available. And the pattern based algorithms are more robust to individual star position errors because whole star pattern is used for the identification. However, angle based algorithms provide with more robustness to false stars because it uses only some of the stars in an image. The false stars on the image of star sensor include planet such as Neptune, debris on the orbit, or broken pixel on the image sensor. This false star is not just annoying one, but very critical problem for the star identification because false identification result is more dangerous than empty result. Pyramid algorithm is one of the most famous angle based star identification algorithm.4) It shows very quick identification work because of K-vector technique, and improved robustness to the false star is also guaranteed. Its improved robustness comes from multiple triangle comparison. As like the pyramid algorithm, the best way to avoid false star problem is to check multiple cases of star pattern as many as possible. However, this redundant comparison takes more time instead, and limited computation power should be considered. Actually, star identification is not the only work to do on the orbit for the star sensor. The credibility of result is important for an algorithm of star sensor, but the time consumption should be minimized at the same time.

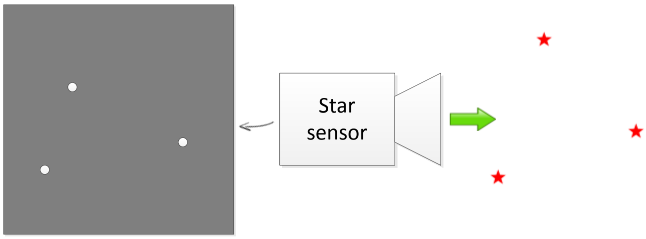


Fig. 1. Star sensor and image of stars

Fig. 2. Example of the real stars image from star sensor

In this study, a new star identification algorithm is proposed for the fast star identification. The proposed algorithm is based on labelling technique to identify multiple stars simultaneously without searching process. Labelling technique uses a label value defined for a group of stars, and the label values are stored on the memory of star sensor as sorted database. The label value is calculated from the image of star sensor using its ratios between angular distances, not angular distance itself. Because multiple stars are represented by a label value, finding same label value on the database identifies multiple stars at the same time. Also, this quick identification speed is key factor for the improved robustness because it makes possible redundant comparisons within limited time. And, the label value of ratio gives robustness against environmental changes of star sensor. Also, this labelling technique does not use the brightness information of stars for the identification work. It is very tempting to use star brightness for the quick identification speed. However, its value is not fixed one on the both side of image sensor and stored database. Variable stars are the good examples, and the other stars are also difficult to define accurate instrumental magnitude. Excluding the star brightness provides with the robustness about that, and it is very convenient at the night sky view test on the ground.

## 2. Labelling

The labelling technique proposed at this document is based on uniqueness of the label value for a group of stars. At first, a group of stars are selected in the image, and the distances between each star are calculated. When s number of stars is selected, C(s, 2) distance combinations are appeared for the group. The distance combinations represent the unique characteristics of the group of stars. And the distances are not used directly for the calculation of label value. The ratios are calculated using the longest distance, and it provides with more robustness against the environmental tolerance on the orbit, such as focal length changes. When the group uses the more number of stars, the label value has the stronger uniqueness. However, limitation of computing resources should be considered for the practical use in the star sensor. Three stars start to show unique label values with three distances when star sensor uses enough precision for its measurements, but it is very risky to depend on the precise measurements. Actually, there are many tolerances on the measurements of star position on the image. Four stars have six distances, and usually enough uniqueness is guaranteed as already suggested at the pyramid algorithm. Even five or six stars will give the stronger unique label values, it would be good choice when the star sensor has enough computing resources.

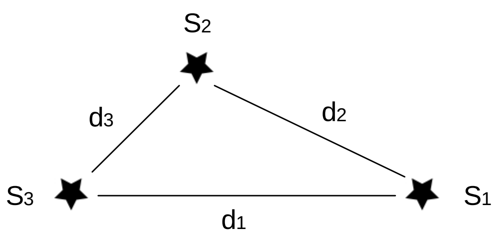


Fig. 3. Three stars and its distances on the image

### 3.1. Sub-label

For the label, sub-labels are should be calculated first. Sub-label is a ratio value between the each distance and the longest distance in the combination. Sub-label is calculated between the value of 0 and 1 as like equation (1) when number of stars is *s*.

$$l_{1i} = \frac{d_i}{d_1} \quad (1)$$

$$i = 2..n$$

$$n = C(s,2) - 1$$

$$s : The\ number\ of\ stars$$

$$d_1 : The\ longest\ distance\ in\ the\ combination$$

### 3.2. Label

These sub-labels are combined to make a label value to characterize the group with one value. When sub-labels are combined, it is important each sub-labels should not be mingled each other to preserve its characteristics. Because of that, each sub-label is rounded to the nearest integer after multiplied by some common decimal number to make short integer number. And, a label is calculated by the summation of these sub-labels on the different digit order.

$$L_{1i} = [\alpha l_{1i}],\ \alpha = 10^r \quad (2)$$

$$L = \sum_{i=2}^{n} \alpha^{n-i} L_{1i} \quad (3)$$

Proper multiplication number and the order of each sub-label should be selected carefully. It depends on the resource of star sensor such as the accuracy of optical system, available memory, and computational power. And, this label value does not need to have precise value as like sub-label. Because when a label is calculated with the measured star position, its value has tolerance because of many reasons. Actually, several groups of stars have the same label value calculated from different sub-labels using some tolerance.

### 3.3. Data structure on the memory

The calculated labels are stored on the memory of star sensor as database. The progress of electronics is dramatic even now, and the memory capacity of on board computer is getting bigger, but still has restriction compare to ground system. It is need to make a rule to minimize the usage of memory. One label has data as like below on the memory.

$$\text{Label}, ID_1 .. ID_s \quad (4)$$

IDs of stars should be kept its sequence by a determined rule. In the case of ID, its attached distances are used for the purpose. Each star has distances with other stars in the group, the summation value of the angular distances is used to sort the IDs, and IDs are stored in descending order of the summation value. Any unique identification number can be used for the ID of star. In this study, star ID for the database is used for the purpose. In the case of figure 3, the number of star *s* is 3, the IDs are arranged as like below.

$$ID_1 = ID(S_1)\ has\ d_1 + d_2 \quad (5)$$

$$ID_2 = ID(S_2)\ has\ d_1 + d_3$$

$$ID_3 = ID(S_3)\ has\ d_2 + d_3$$

$$ID_1, ID_2, ID_3\ when\ d_1 + d_2 > d_1 + d_3 > d_2 + d_3$$

Calculated label values are sorted with descending order to minimize searching work. Usually, the database of label values shows a curve as like Figure 4.

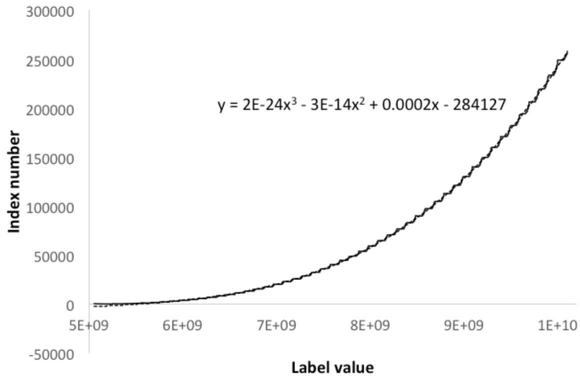


Fig. 4. Index number by the label value on database, and its trend line

In the typical sorted label values graph, there are many ways to accelerate the speed of finding a specific label. In this study, polynomial trend line equation of dot line is used for the work. When a calculated label value is needs to be matched with the label value of database, near index is calculated by the trend line equation.

## 4. On Board Database Generation

There are several open star catalogs to make a database of reference. For our database, Hipparcos star catalog constitute the base set of group of stars. Several preprocesses are required to make suitable database from the catalog. At first, it is need to remove too dark stars of bigger visual magnitude than the sensitivity of the considered star sensor. When the star sensor takes the image of stars, too close stars is appeared as one star because of the optical limitation. The stars with close distance are needs to be merged as one star in database.
After the preprocessing, required number of stars in the field of view are selected from the catalog. The selection number is depends on the available computing resources of star sensor. In this study eight stars in FOV are selected to make database. Generally, brighter stars of low visual magnitude are selected because it is easier to be detected on the image. After selection, its combinations of distances are calculated, and the each sub-labels and the label are also calculated from the distances. After that, the label value and IDs are stored on the database.

When database is generated for the all combinations in the field of view, boresight of star sensor moves to 1.0deg, and repeat the database generation again to scan all area of celestial sphere. Finally, database is sorted by label value in ascending order, and stored it on the memory keeping the sequence of IDs. In this study, eight stars are selected to make combinations of four stars which is used for the group of stars. The darkest stars for the database has visual magnitude of 5.2, the field of view is 24degree. It makes 258,474 combinations for the whole area of celestial sphere. Each combination has label value of 8bytes, four IDs of 8bytes. As the result, the each combination needs 16bytes, and 4.1Megabytes of memory capacity is required to store the database. Also this Labelling technique needs star catalogue data for the final confirmation of the minimum angle error. In this study 2055 stars are used with the size of 53Kilobytes memory.

This huge database size is one major disadvantage of Labelling technique. Figure 5 shows how much size of memory is required for the each identification algorithm, Pyramid and Labelling. Under the same condition, Pyramid algorithm needs just 0.2Mbytes.

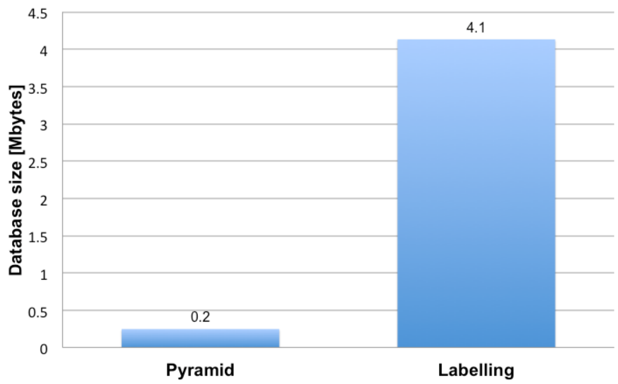


Fig. 5. Database size between Pyramid and Labelling

## 5. Identification with Labels

The labelling technique is to start with a label value of the group of stars. It is important to use a suitable identification flow to search subsequent label on the database because the searching work determine not just the speed of identification, but the robustness also. The right choice of the candidate of the same label shows minimum angle error between the measured angle values and the angle values on the database. Before all the detail of the proposed labelling algorithm, it is need to summarize the major logical steps in Figure 6, and subsequently, we go into detail of the minimum angle error.

Before the identification work, it is assumed that the database of reference is on the memory, the position of stars on the image is also already acquired by the centroiding work. Then now, it is time to identify the measured stars with the stars of database. First, several bright stars are chosen, and calculate the label value. Second, using the polynomial trend line equation, the nearest index is calculated. Third, it is need to find candidates of the same label on the database, and usually same label value is appeared on the database within several search steps from the nearest index. It is easy to expect only one unique data has same label value, but practically many candidates have same label value. Because the label value is not a value of high precision to absorb the tolerance of star position, multiple candidates are appeared with the same label value. And, even in the case of unique candidate of the same label value, it is need to be checked for the angle error with measured star positions. Final step is to find the candidate of the minimum angle error between the measured stars and the data of database.

The angular distances between measured stars are naturally calculated by the unit vector of each star after centroiding work. And the angular distances between stars on the candidate can be calculated with the IDs and the star catalogue on the memory.

$$e = \sum_{i=1}^{n} \left| A_{i,measured} - A_{i,database} \right| \quad (6)$$

$$n = C(s,2) - 1$$

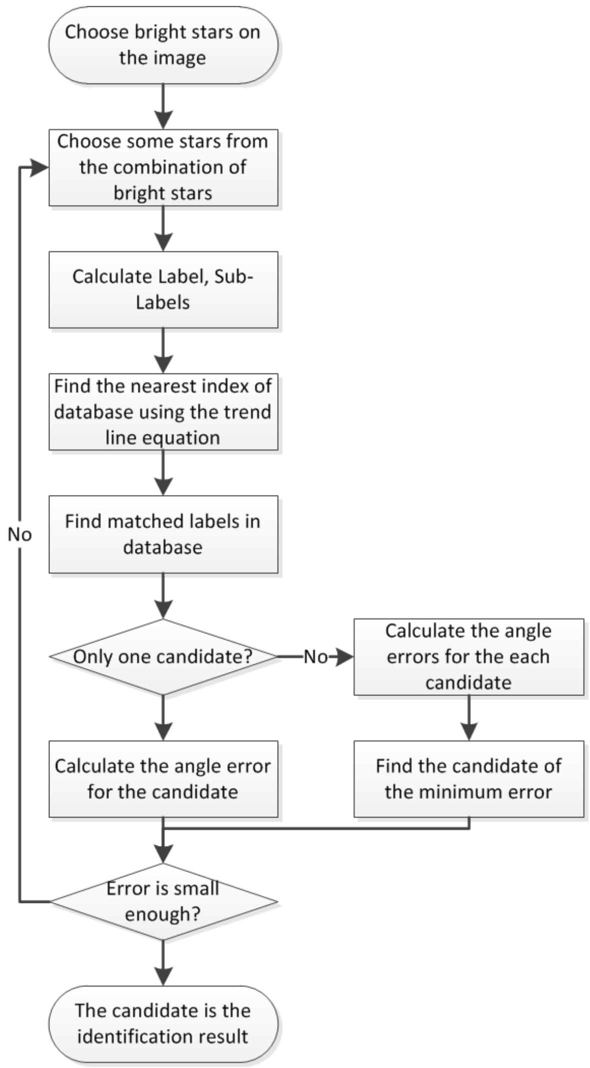


Fig. 6. Flow chart of the star identification of Labelling technique

The labelling technique contains several important new features. The first is to identify multiple stars with one label value, instead of repeating search work to find suitable star pairs. The database of label is built a priori for some given working magnitude threshold and the field of view of the star sensor. Essentially, the database is a structural of all cataloged group of stars that could possibly fit in the camera field of view over the whole sky. The group of stars is ordered with ascending order of label values. Actually, it is the key factor of the fast search work. And the polynomial equation of trend line gives the nearest index value, it makes minimal set of label values to find the target label value. Sometimes, the label value represents several groups of stars, not an unique group. It is possible to make the label values to have unique relationship with only a group of stars with high precision. However, it should be considered the tolerance of measured distances on the image of star sensor. When the label has the candidates has same label value, the angle error is used to select the candidate of the minimum error. The second new feature is to use the ratio of distances, not to use distances itself. The distance measurement has some error in practical star sensor because of optical error and environmental change. It provides with improved robustness against it, especially for the change of focal length. Also, this labelling technique uses only angular distances for the identification work, and does not use the brightness information of stars. Even it makes some more complexity for the searching work or data structure, but it gives advantages of robustness avoiding brightness variance, and convenience of night sky view test.

## 6. Simulation Result

Several simulations are repeated to confirm the performance of the proposed labelling technique under a variety of different conditions. The configuration of star sensor for the simulation is based on the actual star sensor under development. The configuration used for the simulations has 24 x 24 degree field of view with an image sensor of 1200 x 1200 pixels. The minimum sensitivity of the sensor was set to the apparent stellar magnitude of 5.2. The dimmer stars which have bigger apparent magnitude were not appeared on the image of simulation. The image of simulation has intentional star position error with one sigma value of 38 arcsec with assumption of half pixel size random error.

This study choose pyramid algorithm to compare the results because pyramid algorithm is one of the most successful star identification algorithm. It has efficiency, robustness, and first of all it showed excellent practical performance on the orbit already. Actually, it is not easy to compare the identification performance accurately between different algorithms. Even the same hardware is used for the both algorithms, they have their own characteristics and their parameters should be optimized for the best performance. For the proper comparison, the parameters are optimized with caution for the both algorithms, and over ten thousand simulated images were applied with randomly chosen boresight directions.

### 6.1. Identification speed

First, the mean values of the identification speeds are compared for the each algorithm. Table 1 shows its result, and Figure 7 shows its result with % values. On the simulation, Labelling technique needs just 25% of time for the identification. Because of its huge database size, it is very natural that Labelling technique shows much faster speed on the simulation. This identification speed is very important in many ways. The faster identification speed make it possible to output the attitude information more frequently, and the accuracy of attitude control can be improved. Also, many people want to use star sensor as rate gyroscope if the star sensor provides with fast output rate.

Table 1. Execution time for the identification.

| Identification algorithm | Execution time [sec] |
|---|---|
| Pyramid | 0.003 |
| Labelling | 0.00076 |

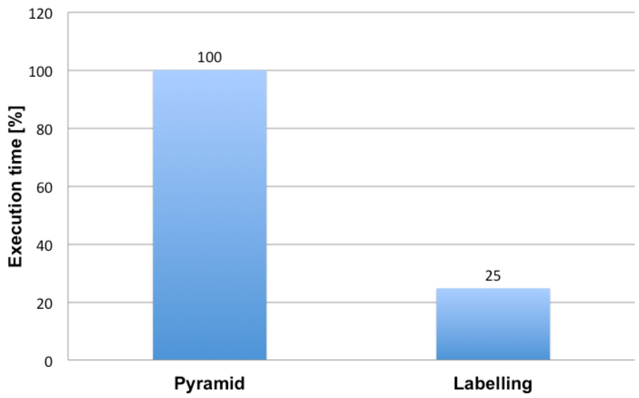


Fig. 7. Execution time between Pyramid and Labelling

### 6.2. Success rate with the focal length error

The advantages of Labelling technique is the robustness against the focal length change. Actually, focal length is very critical parameter in star sensor, it determine the angular distances. Usually, the optical system of star sensor is designed for the small tolerance of focal length, but still has some risk of error such as temperature changes. Labelling technique uses the ratio values between angular distances, and it shows really strong robustness when its focal length has error. On the Figure 8. Labelling technique shows no failure rate until 1% error of focal length, and no identification time changes. The focal length error is enough for the serious problem on pyramid algorithm which uses the angular distances itself. Pyramid algorithm shows worse than 40[%] success rate, and its identification time is rapidly increasing.

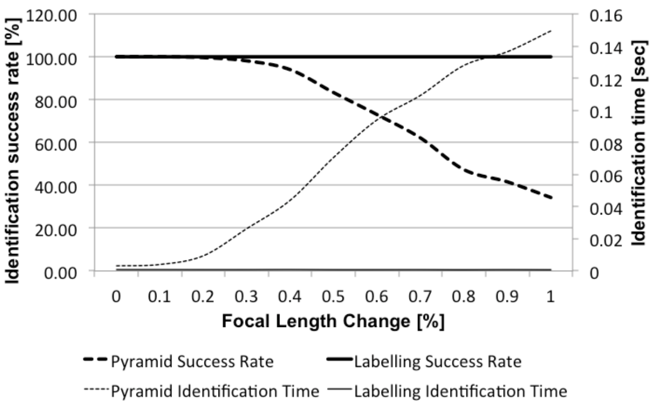


Fig. 8. Success rate with focal length error

### 6.3. Identification time with false stars

False stars consumes identification time, and sometimes the long identification time can not be supported by the limited computational power of star sensor. Figure 9 shows the identification speed with the number of false stars. Each algorithms needs much identification time as the number of false stars are increasing. However, the identification time of Labelling algorithm shows shorter time consumption, and it is possible to deal with more false stars within same identification time compare to the Pyramid algorithm.

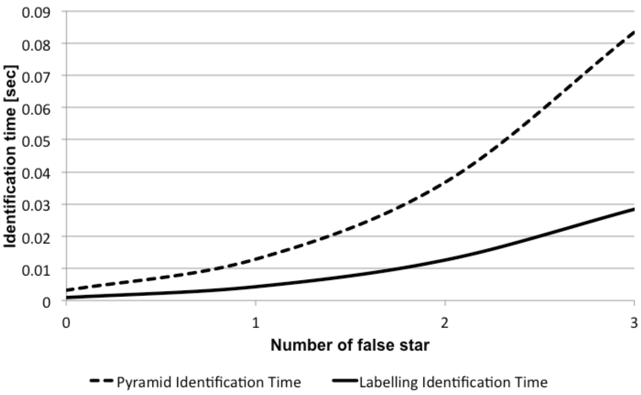


Fig. 9. Identification time with false stars

## 7. Conclusion

In this study, a new star identification algorithm is proposed using the Labelling technique, multiple stars are identified by a label value and its IDs simultaneously. This makes fast identification speed without time consuming searching work. Simulation results confirm its fast identification speed, and its robustness is also confirmed for the focal length change. The speed of labelling technique increases the chance of versatile function, robustness against the false stars is one of them.

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