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Analysis of Star Catalog Model Based on The Nearest Star Composition and Brightest Star as Guide Star

A Ramadhana [1],* M A Saifudin [2], R E Poetro [1], and L Fathurrohim [1]

[1] Faculty of Mechanical and Aerospace Engineering, Bandung Institute of Technology, Indonesia.
[2] Satellite Technology Center, National Institute of Aeronautics and Space Indonesia (LAPAN).
* Correspondence: alif_ramadhana@students.itb.ac.id

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Star sensor is the most advanced attitude determining instrument for spacecraft with very high accuracy, and it is independent of other attitude sensors. However, the star sensor's accuracy and processing time depend on selecting the algorithm, which starts from detecting the star pattern until the matching process with the star catalog. The star catalog consists of the right ascension and declination of stars' position and magnitude for 250.000 stars which need a large memory size. Therefore, modifying a new star catalog consisting of guide stars' position, magnitude, and nearest star composition can reduce the required memory and processing time without losing accuracy. The nearest star catalog model in this paper used radial based feature where for each guide star candidate, the number of stars in each binary (bin) layer around the guide star will be calculated. This paper focuses on determining the best architecture for the nearest star catalog model, such as the number of bin layers and bin ranges, and the influence of star sensor field of view and guide star limitation with the model's accuracy. The proposed star catalog provides excellent performance in low-cost star sensors with a high and medium field of view.

Keywords: aerospace engineering, spacecraft, satellite, sensor, star sensor

1. Introduction

Attitude Determination is the part of ADCS (Attitude Determination Control System) subsystem on the spacecraft that has a function to determine the attitude of the spacecraft. There are several sensors for attitude determination such as star sensors, sun sensors, horizon sensors, magnetometer, GPS, and gyroscopes [1]. Star sensors is the most advanced attitude determining instrument with very high accuracy, and it is independent of other attitude sensors [2]. However, the star sensor's accuracy and processing time depend on selecting the algorithm, which starts from detecting the star pattern until the matching process with the star catalog. Basically, the working principle of the star sensors is by comparing the star data obtained from the star tracker with the star data from the star catalog. The star catalog generally uses Smithsonian Astrophysical Observatory (SAO) catalog that consists of the stars' inertial reference (right ascension and declination) and magnitude for 258,997 stars [3]. However, the basic SAO catalog still needs to be readjusted with the star pattern recognition algorithm that will be used. The amount of the data in the star catalog will affect the time of the star identification process and the accuracy of attitude determination. A large amount of catalog data will certainly provide better accuracy, but it will take longer processing time and required greater storage capacity. The Magnitude Filtering Method is the simplest method used to filter star catalog by its magnitude (star brightness level) [4]. Therefore, modifying a new star catalog consisting of stars' position, magnitude, and nearest star composition can reduce the required memory and processing time without losing accuracy. This approach was proposed by Silani and Lovera in 2006 with the Polestar Algorithm which uses the pattern of the nearest star from the guide star for each certain degree bin range and several bin layers [5]. There are so many variations of this nearest star catalog depending on its structure, such as bin range and number bin layers composition. This paper will focus on testing the model of the nearest star catalog to determine the best structure for the catalog.

2. Methodology

The methodology for testing the model of nearest star catalog is depicted in figure 1

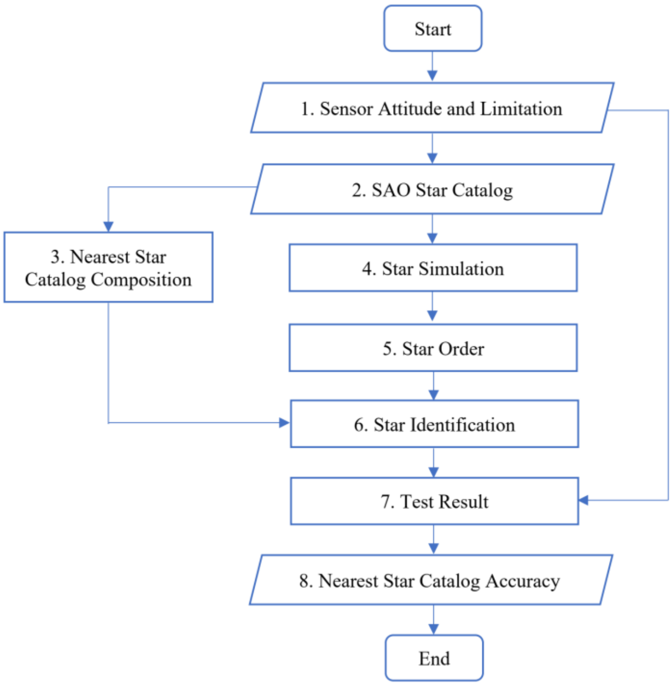

Figure 1. Flowchart of testing nearest star catalog model.

First, given input for random sensor attitude at a celestial coordinate in the form of right ascension and declination also the sensor limitation in the form of camera's FOV size. Second, given input the data of SAO star catalog that has been filtered based on a certain magnitude. Third, the stars in the filtered SAO star catalog are then arranged in patterns of closest star number arrangement to become the model of the nearest star catalog. Fourth, the star pattern will be simulated based on the input that has been given. Fifth, for all stars inside the FOV that meets the structure limits (maximum size of bin range and bin layer number), the patterns of the closest star number arrangement will be arranged based on their magnitude. Sixth, the pattern of closest star arrangement for the brightest star in the star simulation results will be compared with the nearest star catalog model to identify the correct star and its attitude will be determined based on the nearest star catalog data. If the result does not match, the next brightest star will be chosen for the next matching process and so on. Seventh, the attitude determination result from star identification process will be compared with the input attitude to check the validity of the test results. Finally, for accuracy calculation, the guessed result of the star identification from star simulation is compared with the initial input in binary form (true or false). For example, when testing for one sample the identification result is wrong, the accuracy of the sample is 0%, then when testing for two samples all of the identification results are correct, the accuracy becomes 100%, and the graph accuracy will increase from 0% to 100% for 1 to 2 samples testing. The accuracy of the nearest star catalog model will be determined by using the convergence test for 1 up to 100 random samples.

As in figure 2, for arranging the model of the nearest star catalog, the arranging process starts by counting the number of stars around the guide in the closest degree bin range (first layer). Next, the number of stars in the next layer will be searched with the same bin range distance as the first layer bin distance. This continues until it reaches the outermost bin layer and the number of stars found in each layer will be arranged into a pattern of nearest stars. This process is carried out on each star so that a new catalog model is formed based on the pattern arrangement of the nearest star [6].

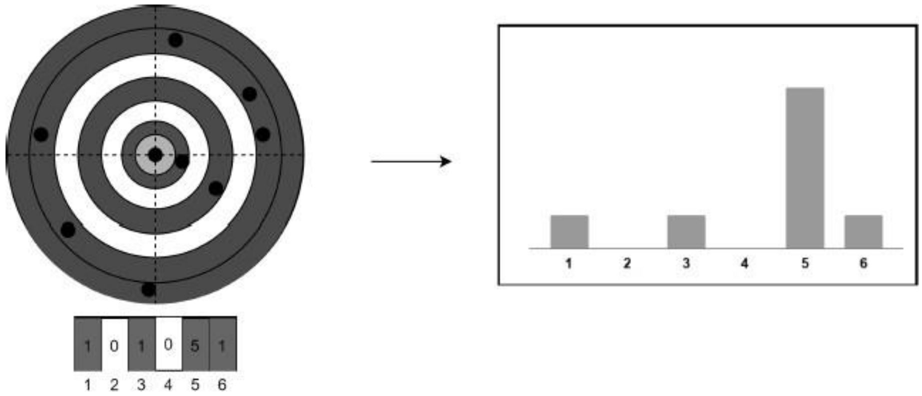

Figure 2. Example of extraction method for the nearest star catalog. Image is taken from [6]

2.1. Star sensor limitation

This paper will use the model from the star sensor camera of LAPAN-A3/LAPAN-IPB satellite with specifications as 1392 x 1040 pixel sensor size, 16 mm focal length, and $31^o \times 23^o$ FOV. LAPAN- A3/LAPAN-IPB is a satellite produced by LAPAN (National Institute of Aeronautics and Space) in Indonesia with missions of earth observation, ship monitoring, and earth magnetic field measurement [7].

2.2. Star catalog

This paper will use the SAO star catalog that consists of 258,997 stars with its ID number, inertial reference position (right ascension and declination), and magnitude. The stars catalog data will be filtered with a maximum 6 Mv magnitude that consists of 5,102 stars data and then sorted from the lowest magnitude (brightest star). Guide star will be chosen from the stars that have maximum of 4 Mv magnitude, then the patterns of the closest star number arrangement will be arranged based on predefined bin range and bin layers number. Table 1 is the example of the nearest star catalog model with a 7 bin layer and 0.5-degree bin range. Based on table 1, the number of star data will be decreased to 480 stars.

Table 1. Nearest star catalog data for 5 bin layer and 0.5-degree bin range.

	Star ID	RA	DE	Magnitude	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
0	151880	100.736	-16.646	-1.6	0	0	1	3	2
1	234479	95.710	-52.667	-0.9	0	1	0	0	1
…	…	…	…	…	…	…	…	…	…
478	138720	-175.663	-0.389	4.0	1	0	0	0	0
479	128512	-0.815	6.587	4.0	0	0	0	1	0

2.3. Star Simulation

Input data from sensor limitation, sensor attitude, and star catalog will be simulated into star composition at certain attitude for certain FOV. Table 2 is the example of star composition at 0^o right ascension and 0^o declination for $31^o \times 23^o$ FOV.

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Table 2. Star data at 0° right ascension and 0° declination.

	Star ID	RA	DE	Magnitude
0	147419	10.270	-18.261	2.2
1	108377	-14.433	14.936	2.6
…	…	…	…	…
125	109191	5.709	1.663	6.0
126	165932	-2.517	-14.529	6.0

2.4. Testing and determining the accuracy of the nearest star catalog model

The star data from star simulation that meets FOV and structural (bin range and bin layer) constraints will be generated into nearest star composition data and the structure (bin range and bin layer) must be the same as the structure of the nearest star catalog model. The brightest star in the nearest star composition data from the simulation will become the guide star candidate and will be matched with the nearest star catalog data. This matching process starts sequentially starting from the brightest star in the nearest star catalog and will stop when it finds the same star pattern arrangement composition with the guide star candidate from the simulation. The result of sensor attitude will be compared with the input of sensor attitude to verify the attitude result. Convergence test is used starting from 1 until 100 random samples of sensor attitude to determine the trend of catalog model accuracy. This process will be repeated on other nearest star catalog models with variations of 3, 4, 5, 6, and 7 bin layers numbers for variations of 0.5, 1, 1.5, 2, and 2.5 degrees bin range. In addition, the test is also carried out for different camera FOV and guide star magnitude limits. The accuracy of the nearest star catalog model is considered good and accepted if the accuracy value converges above 90%.

2.5. Programming

All programs that are used in this test are written in Python 3.6 and run with Google Colab.

3. Results and Analysis

In this section, all of the nearest star catalog models will be tested, including the variations of 3, 4, 5, 6, and 7 bin layers number; variations of 0.5, 1, 1.5, 2, and 2.5 degrees bin range; variations of camera FOV; also variations of guide star magnitude limits.

3.1. Comparison of convergence test result for each degree bin range and bin layer number

This section is the comparison of convergence results for each degree bin range starting from 0.5, 1, 1.5, 2, until 2.5 and for each bin layer number starting from 3, 4, 5, 6, until 7 layers.

Table 3. Comparison of the percentage accuracy of the convergence test result for each bin range and bin layer number.

	0.5 Degree	1 Degree	1.5 Degree	2 Degree	2.5 Degree
3 Layer	15	45	65	85	90 [a, b]
4 Layer	30	65	95 [b]	95 [a]	90
5 Layer	40	95 [a, b]	95	90	-
6 Layer	55	95	100 [a, b]	-	-
7 Layer	70 [a]	90	95 [b]	-	-

[a] The optimum accuracy for each degree bin range.

[b] The optimum accuracy for each bin layer.

From table 3, the best structure for the 0.5 degree bin range is enough at 7 layers, for the 1 degree bin range is enough at 5 layers, for the 1.5 degree bin range is enough at 6 bin layers, for the 2 degree bin range is enough at 4 layers, and for 2.5 degree bin range is enough at 3 layers. In the other side, the best structure for 3 layers bin is enough at 2.5 degree bin range, for 4 layers bin is enough at 1.5 degree, for 5 layers bin is enough at 1 degree bin range, for 6 layers is enough at 1.5 degree, and for 7 layers is enough at 1.5 degree. Before reaching the optimum value, the increasing of bin range or bin layer number will increase the number of stars used for star pattern composition so the data will be more specific and accurate. However, after reaching a certain point, the increases of bin range or bin layer number will not increase the accuracy of the star identification, because the number of guide star candidates in the star image that will be used for star identification will be decrease so the accuracy will less accurate. The value of degree bin range and bin layer number in this condition is the optimum structure for the nearest star catalog model.

3.2. Comparison of convergence test result for FOV variation

This section is the comparison of convergence results for the same degree bin range and bin layer number but with the different FOV starts from original FOV, FOV with an additional 25%, and FOV with an additional 50%.

Table 4. Comparison of the percentage accuracy of the convergence test result for FOV variation.

	0.5 Degree Bin Range and 3 Layers Bin	0.5 Degree Bin Range and 7 Layers Bin	2.5 Degree Bin Range and 3 Layers Bin
Original FOV	20	75	90
FOV with extra 25%	20	75	95
FOV with extra 50%	20	90	100

From table 4, for 0.5 degree bin range and 3 layers bin, the increasing size of FOV will not improve the accuracy of the nearest star catalog model. However, for other models, the increase of FOV value will increase the accuracy of the nearest star catalog model because the increase of FOV size will increase the number of guide star candidates, so the probability of selecting a unique star is increased. From table 4, although the FOV size affects the accuracy of the nearest star catalog model, the accuracy of the nearest star catalog model is highly dependent on the structural quality of the nearest star catalog model. The better model structure accuracy, the greater accuracy increases were given, and vice versa. However, the increase of FOV size also has several drawbacks such as the increased risk of the star sensor being disturbed by sunlight and providing more star data.

3.3. Comparison of convergence test result for guide star magnitude constraint variation

This section is the comparison of convergence results for the same degree bin range and bin layer number but with the different guide star magnitude, starting from 4, 4.25, and 4.5 Mv guide star magnitude.

Table 5. Comparison of the percentage accuracy of the convergence test result for guide star magnitude constraint variation.

	0.5 Degree Bin Range and 3 Layers Bin	0.5 Degree Bin Range and 7 Layers Bin	2.5 Degree Bin Range and 3 Layers Bin
4 Mv Guide Star Limit	20	90	75
4.25 Mv Guide Star Limit	20	90	75
4.5 Guide Star Limit	20	90	75

From table 5, the increasing of guide star magnitude constraint does not significantly affect the accuracy of the nearest star catalog model. This phenomenon occurs because the matching process uses the brightest star so it is not affected by the guide star magnitude constraint. However, the increasing of guide star constraint will also increase the size of star data, so this is not necessary.

3.4. Comparison of star catalog data size

This section is the comparative analysis of star catalog data size. Based on table 6, filtering the star catalog by magnitude is reduces the data size significantly. In addition, the selection of the nearest star catalog can also reduce the size of the catalog data. The increasing guide star constraint, as well as the selection of the star catalog structure, also affect the size of the given data. With the proper bin layer structure, the size of star catalog data can be drastically reduced without compromising accuracy.

Table 6. Comparison of star catalog data size.

Catalog Description	Data Size
SAO star catalog	10,280 kB
Filtered star catalog with magnitude bellow 6 Mv	205 kB
Nearest star catalog for guide star magnitude below 4 Mv and 6 bin layer	38 kB
Nearest star catalog for guide star magnitude below 4.5 Mv and 6 bin layer	65 kB

4. Conclusions

From the results and analysis above, the accuracy of the nearest star catalog model is largely determined by its structure in the form of the degree bin range and bin layer number. Increasing the FOV size can also improve the accuracy of the star catalog model, but it has several drawbacks such as the increased risk of the star sensor being disturbed by sunlight and providing more star data. Changing the guide star magnitude constraint does not significantly affect the accuracy of the star catalog, however, it increases the star data size. Generally, the data size of the nearest star catalog model is smaller than the ordinary star catalog. With the proper bin layer structure, the size of star catalog data can be drastically reduced without compromising accuracy. This work does not include disturbance due to noise. In future work, this nearest star catalog model will be implemented in star pattern matching process using the deep learning method.

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