A SPEARMAN CORRELATION BASED STAR PATTERN RECOGNITION

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ABSTRACT

High accuracy is required for determining the orientation of a satellite in space. Amongst the existing sensors, a star tracker provides a very high accuracy of attitude determination. When no prior attitude is available, it operates in the "Lost-In-Space (LIS)" mode. Star pattern recognition is the most crucial part of a star tracker in the LIS mode. In this paper, a novel star pattern recognition approach is proposed, which constructs a signal from the features extracted in the star image and utilizes spearman correlation for identifying the correct stars. The proposed technique achieves a high identification accuracy of 99.67%. The results from the simulations show that this technique is also highly recognition reliable to the cases of missing stars, deviation in star positions, magnitude uncertainty, and false stars compared to the existing star identification algorithms.

Index Terms— star pattern recognition, lost-in-space mode, spearman correlation, star sensor

1. INTRODUCTION

An accurate and reliable attitude determination system is one of the most important requirements for satellite missions. Sun sensor, magnetometer, and gyroscope are some of the commonly used sensors for attitude determination [1]. Star trackers (aka star sensors) have become very popular in the last two decades because they provide very accurate orientation information in terms of arc seconds [2], [3].

A star tracker basically consists of an image sensor for capturing the image of the stars within a particular field of view (FOV) and an on-board stored star pattern database (SPD), which is prepared offline. When no prior attitude is available, it operates in the "Lost-In-Space (LIS)" mode and the objective is to identify the stars in the captured image by comparing the features extracted from the image with those stored in the SPD. This process of star pattern recognition is the most important part of the star tracker in the LIS mode.

In the past few decades, achieving a reliable star identification has evolved into a challenging problem. Many star pattern recognition techniques have been proposed in order to solve this problem over the past two decades [4]–[17]. Basically, star pattern recognition techniques adopt two different approaches: geometric approach and pattern based approach. The former approach utilizes various features such as the angular distances, radial distances, and the area formed by the star clusters (three or four stars) for recognition. Liebe [4], Pyramid [5], and planar triangle [6] are one of the earliest methods which suggested this approach. Recently, techniques such as geometric voting [7] and a probabilistic approach [8] were proposed which considered all the stars that lie within the FOV of the reference star for identification.

The pattern based approach was first proposed by the grid algorithm [9]. In this type of approach, a well-defined pattern code is formed by utilizing the position of all the neighbouring stars within the FOV, which is then used for recognition purposes. Many star recognition algorithms have been developed based on this approach [10]-[13]. The technique in [12] proposed to construct the pattern code from translation and rotation invariance of the *k*-nearest neighbouring stars. An improvement of the grid algorithm was also suggested in [13].

Although the existing star pattern recognition techniques provide a high identification accuracy in an ideal case, they fail drastically when the captured images are swayed and biased from the on-board SPD. These biased images result because of the magnitude uncertainty of the image sensor in space, deviation in star positions, and false stars present in the image captured. In this paper, we propose a novel star recognition approach, which constructs a discrete signal from the features extracted in the star image and utilizes spearman correlation for identifying the correct stars in the image. The proposed approach is specifically developed to achieve a high robustness and recognition reliability in the cases when existing star pattern recognition techniques fail.

The rest of the paper is organized as follows. Section 2 describes the feature extraction, construction of the discrete signal, and preparation of the SPD for the proposed technique. Section 3 explains the spearman correlation based star pattern recognition technique. In this section, we also describe the reasons as for why spearman correlation is selected for comparison and the experimental reason behind the number of samples selected for the construction of the discrete signal. In Section 4, we simulate the star images and test the performance of the proposed technique along with the state-of-the-art star pattern recognition techniques. Finally, the contribution of the paper is concluded in Section 5.

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2. FEATURE EXTRACTION AND STAR PATTERN DATABASE CONSTRUCTION

2.1. Feature extraction

As the captured image might be translated and rotated in contrast to SPD, the features extracted must be translation and rotation invariant. The proposed technique uses– euclidean distances from the center star and the relative angle that the consecutive neighbouring stars make with the center star as the two features, which are shown in Fig. 1. We use the star catalogue SAO J2000 [18] and every star id which has a relative magnitude M_v less than 6.0 is considered for forming the SPD for the proposed star pattern recognition technique. Each star id is considered at the center of the FOV and all the neighbouring stars which lie in the FOV of the center star are considered for extracting the above-mentioned two features. Both the features are calculated by (1) and (2) respectively.

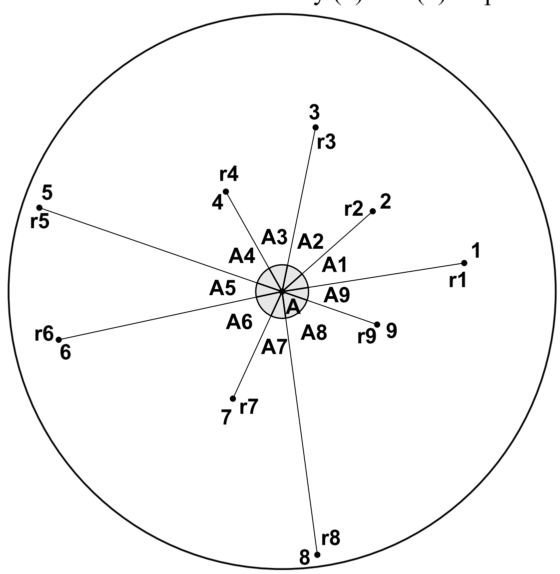

Fig. 1. Feature extraction for the proposed technique.

$$r_n = \sqrt[2]{(x_n - x_c)^2 + (y_n - y_c)^2} \tag{1}$$

$$A_n = \tan^{-1}\frac{(y_n - y_c)}{(x_n - x_c)} \tag{2}$$

where x_n and y_n are the pixel co-ordinates of the star in the image, and x_c and y_c are the co-ordinates of the center star A.

2.2. Signal construction

As explained in Fig. 1, there are two features extracted – relative angles and euclidean distances. We propose that the relative angles extracted can be visualized as time domain and the corresponding radial distances can be visualized as the amplitude of the signal. For example, in Fig. 1, we have nine stars surrounding the reference star A. Thus, there are nine radial distances and relative angles, namely – {r1, A1, r2, A2…r9, A9}. Every radial distance rn corresponds to its relative angle An (i.e. r1 corresponds to A1 … r9 corresponds to A9). The maximum relative angle between two neighbouring stars in the image can be 180^0 or π radians. Thus, we construct a discrete signal (in Fig. 2) which depicts the star pattern of the reference star A (in Fig. 1). As shown in Fig. 2, the signal has relative angles in an increasing order of their value on the x-axis (visualized as time domain) and their corresponding radial distance value (visualized as amplitude). This constructed signal (solid line – SPD) is now utilized for SPD preparation as explained later in this section.

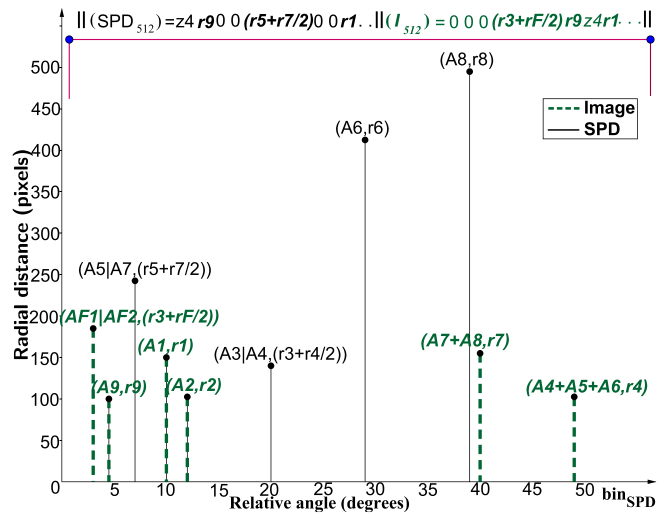

Fig. 2. Signal and SPD construction for the proposed technique along with signal comparison with that of the captured image.

2.3. Star Pattern Database construction

The SPD is constructed as an N sample signal for every star id. The pattern is broken into N samples (bins) and the amplitude is the radial distance of the data point. For a particular bin, if there is no data point, it is assigned a value of zero; if there is more than one data point, it is assigned a value equal to the average of the data points (e.g. (r5 and r7); (r3 and r4) in Fig. 2); if there is a single data point, it is assigned the value of the radial distance of that data point. The bin number for a particular data point is given by (3).

$$bin_{SPD} = round\left(\frac{Angle^0}{(180^0/N)}\right) \tag{3}$$

where N is the number of samples (bins).

Depending upon the value of N, there can be many bins which will have zero value in between two data points. So, if there are more than three zeroes between two data points, they are represented by *z_number_of_zeroes*. For the example in Fig. 2 and also for constructing the SPD, we have selected N as 512 and thus, there will be many zeros for a 512 sample signal. Hence, the 512 sample signal for the pattern of reference star A (in Fig. 1) is prepared as SPD_{512} (in Fig. 2)– {z4, r9, 0, 0, (r5+r7/2), 0, 0, r1, …}. Similarly, the 512 sample signal is constructed for every star id and the SPD is prepared offline and stored. The reasoning behind selecting N as 512 is explained later in part 3.2 of Section 3 of this paper.

3. PROPOSED STAR PATTERN RECOGNITION

For the purpose of explaining the process of star pattern recognition using spearman correlation, we will be using the example shown in Fig. 3. The image captured is represented by the dotted circle, with I_c being the center of the image. Let us say that star A is the closest to I_c and thus, it will be selected as a reference star to be identified. The SPD of star A (Fig. 1) is represented by the solid circle in Fig. 3. It should be noted from Fig. 3, that the captured image does not contain the stars 5, 6, and 8 which are a part of the SPD of star A. Also, the image contains a false star F which is not a part of the SPD of star A. Stars 5, 6 and 8 are missed due to patch mismatch or magnitude uncertainty. Thus, the example shown in Fig. 3 has all the problems which a star pattern recognition technique will face (described in Section 1 of this paper). Hence, the aim of the proposed technique is to identify the stars in the image correctly despite these problems.

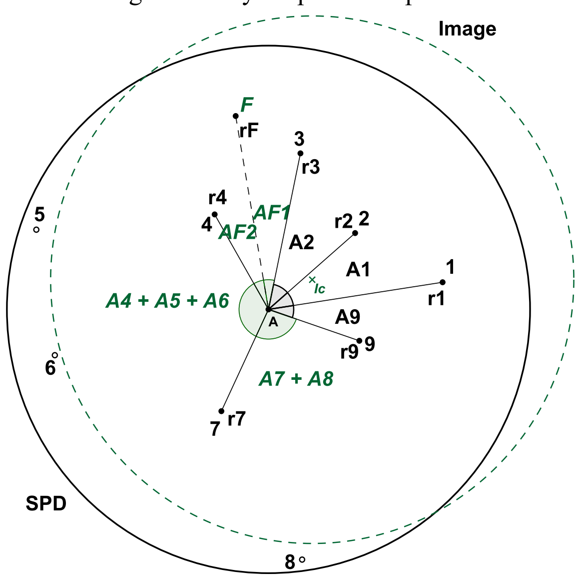

Fig. 3. An example of image captured for explaining the proposed star pattern recognition technique.

3.1. Pattern recognition using spearman correlation

The 512 sample signal is constructed by the same process as was used for preparing the SPD (section 2 of this paper). For the image acquired in Fig. 3, the construction of 512 sample signal is shown in Fig. 2 and it is labeled as I_{512} (dotted line - Image). It is important to note that because of the problems faced by the star tracker, there can be many missing data points in the signal constructed from the image acquired when compared to the signal of the reference star stored in the SPD (which is also evident in Fig. 2). Thus, there is no definite relationship between the data points of the image acquired and those of the SPD of the reference star. Due to this, the best way to measure the match of the image with the SPD is by calculating the *spearman correlation co-efficient* (instead of the *pearson co-efficient*) between the signal constructed from the image acquired and the signals stored in the SPD. The data variables must have a constant variance and exhibit a linear relationship for the *pearson co-efficient* [19]. On the other hand, *spearman correlation* is a non-parametric measure of correlation and is appropriate for ordinal scale signals [20]. It does not assume a normal distribution of data or any definite relationship between the data points. Hence, *spearman correlation* will be an appropriate measure for the match between the image and the SPD. The spearman correlation coefficient (rs) is calculated by (4) and (5).

$$r_s = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \tag{4}$$

$$d_i = rg(X_i) - rg(Y_i) \tag{5}$$

where $rg(X_i)$ and $rg(Y_i)$ are the ranks of each observation in the samples X and Y, and n is the number of samples. The maximum correlation co-efficient calculated between the 512 sample signals of star ids in the SPD and the I_{512} is regarded as the correct match for the reference star in the image. Once the star id which gives the maximum correlation co-efficient is identified as the reference star, all the neighbouring stars to the reference star in the image can be recognized from the sequence of the SPD of the identified reference star id.

3.2. Why 512 sample discrete signal?

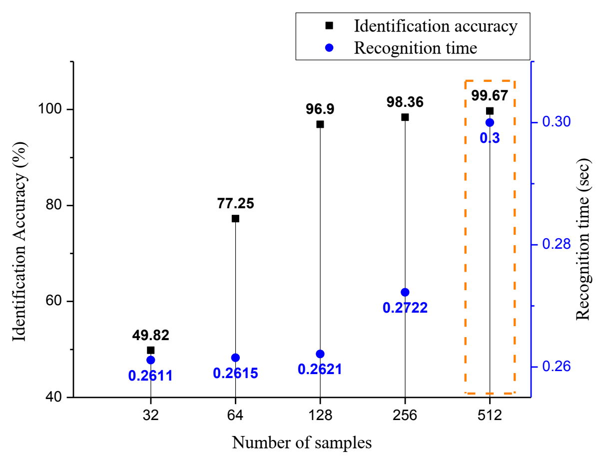

Fig. 4. Comparison of performance of the proposed star pattern recognition technique for different number of samples.

The justification for selecting N as 512 is shown in Fig. 4. This selection is based on the test results of the performance of the proposed technique for different sample sizes (N). The performance is measured in terms of identification accuracy and recognition time required for different sample sizes. As can be seen from Fig. 4, 32-sample signal gives a very low identification accuracy and the identification accuracy increases with the number of samples. The recognition time also increases with the number of samples, however, the increase in the recognition time is not drastic. We choose 512 sample size because the identification accuracy is very high and the recognition time is also reasonable.

4. SIMULATIONS AND EXPERIMENTAL RESULTS

The performance of the star pattern recognition techniques was tested on 16200 simulated images (full sky scan) generated by the MATLAB software. Resolution of the simulated image being 1024 x 1024 and pixel size equal to 13 µm, the FOV being 15^0 full cone. The stars having a magnitude threshold M_v less than 6 from the star catalogue SAO J2000 were considered. The platform PC specifications were - Intel core i7, 3.4 GHz processor and 8GB RAM. The proposed technique is compared with state-of-the-art star pattern recognition techniques, namely a high identification accuracy Pyramid algorithm [5], a fast search tree optimized database (STOD) algorithm [16], and a highly robust geometric voting technique [7]. The results are shown below.

4.1. Ideal case

In an ideal case, there is no noise, magnitude uncertainty, or positional deviation. The performance of the star pattern recognition techniques for ideal case is shown in Table I.

Table I

Benchmarking of star pattern recognition techniques – Ideal case.

Technique	***Identification accuracy (%)***	***Run-time (sec)***	***SPD size (MB)***
GMV [7]	94.3	0.567	1.31
STOD [16]	90.3	0.21	1.4
Pyramid [5]	95.78	0.319	0.78
Proposed technique	**99.67**	**0.3**	**1.21**

4.2. Positional deviation of stars

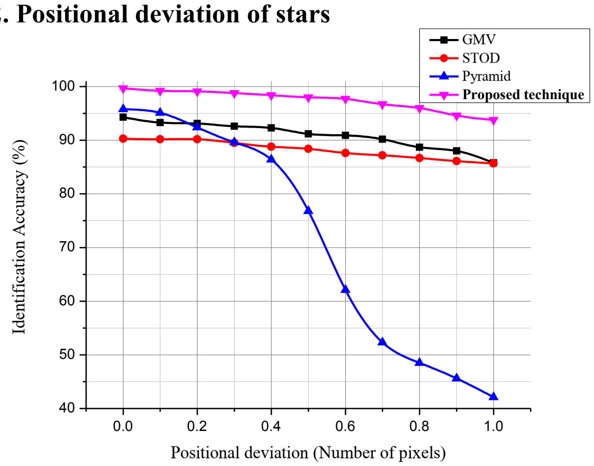

Fig. 5. Performance of star pattern recognition techniques with positional deviation.

Due to the vibrations and disturbances experienced by the satellite throughout the period in its orbit, the image captured by the star tracker is distorted. To simulate this scenario, the deviation in pixel position of the stars was introduced from 0.0 to 1.0 pixels and the identification accuracy of the star pattern recognition techniques was tested, as shown in Fig. 5.

4.3. Magnitude uncertainty and false stars

Some low brightness stars might get missed to be captured in the image because of the magnitude uncertainty of the image sensor in space. At the same, there might be false stars present in the image. To simulate both the scenarios, we have given a relative magnitude uncertainty in the image from 0.0 to 0.4 and added up to 5 false stars (random position and brightness) to the image. The recognition reliability of the star pattern recognition techniques for both the above-mentioned cases is shown in Fig. 6 and Fig. 7 respectively.

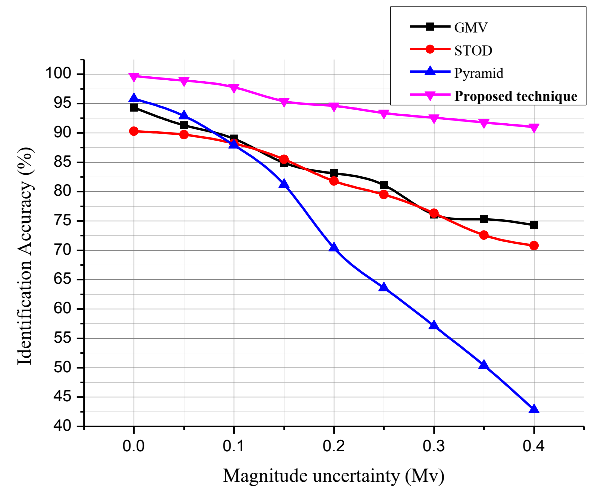

Fig. 6. Performance of star pattern recognition techniques in the case of magnitude uncertainty.

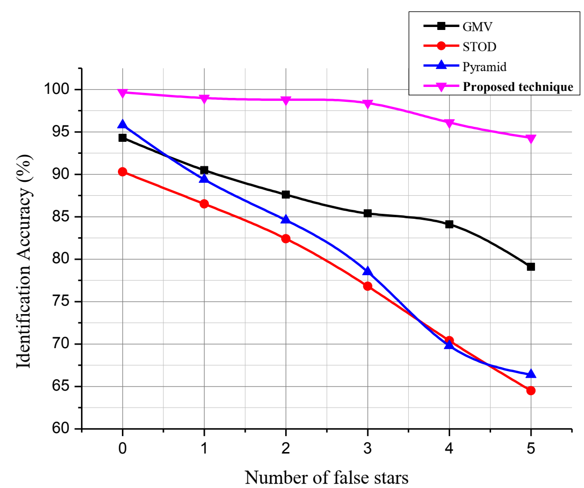

Fig. 7. Performance of star pattern recognition techniques in the case of false stars in the image.

5. CONCLUSION

A novel star pattern recognition technique using spearman correlation is proposed in this paper. The proposed approach attains a high identification accuracy of 99.67%. The high recognition reliability achieved by the proposed technique also suggests that it is suitable for actual space missions.

6. REFERENCES

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