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Star Pattern Identification Technique by Modified Grid Algorithm

A star pattern identification algorithm, called modified grid algorithm, for attitude determination of spacecraft is addressed. The proposed algorithm is closely connected to a general pattern recognition technique. Each star is characterized by a well-defined pattern that can be determined by the surrounding stars. The so-called grid algorithm is one of the star identification algorithms based upon the pattern recognition approach. The proposed algorithm, is motivated by the conventional grid algorithm. To enhance the performance of the conventional grid algorithm, a modified method using polar grid, virtual grid, and multi-references is proposed. Simulation study is conducted for the demonstration of the new algorithm. The proposed modified grid approach turns out to make the grid algorithm more robust and reliable.

I. INTRODUCTION

Various star identification algorithms have emerged for the past few decades [1–7]. One efficient star pattern identification technique, the grid-based algorithm, has also been introduced [8]. The grid algorithm is classified as a pattern recognition method. The algorithm is represented by a database in which each star is provided with a well-defined pattern formed by surrounding stars within the field of view (FOV) of star trackers. Measured star field by the star trackers is converted into a specified pattern by judicious methods. The pattern can be identified by finding the best matched set in the star pattern database. The grid algorithm has been generally known to be robust with respect to sensor noise [8]. It also relies on less computational resource compared with other algorithms due to its simple architecture.

A modified grid algorithm, in an effort to ensure more accurate and reliable identification performance, is investigated in this study. The principal idea of the new approach is to employ multi-reference stars with which specific patterns are identified. With

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noise existent in CCD (charge coupled device) image detector, a single reference star can be mis-identified with the generated grid database. However, the possibility of mis-identification can be reduced for final star identification by taking multi-reference stars as addressed in this study. Another useful approach to minimize the mis-identification is motivated by the virtual grid. The reference stars outside of the pattern radius have been eliminated in the original grid algorithm since they are located far from the selected reference star. This may also result in mis-identification for some cases due to the eliminated, but still useful reference stars. The reference stars ignored in the original algorithm are reused in this study by the virtually generated grids outside of the virtual CCD plane. The virtual grid covers the area beyond the original one defined by the pattern radius in the original algorithm.

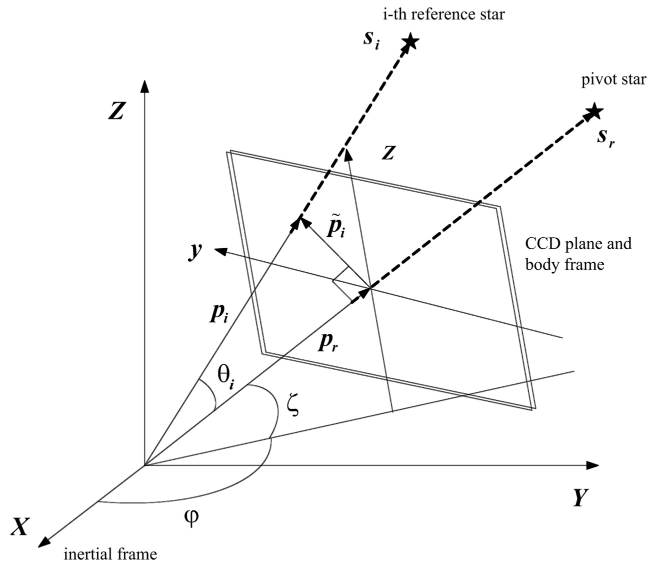

Fig. 1. Definition of inertial and CCD body frames.

II. GRID ALGORITHM

The grid algorithm can be classified as a pattern recognition approach for a star field detected in the CCD image plane of the star trackers. A set with stars in the specified FOV should be classified as a pattern. Each star in the set is called a reference star. The pattern is constructed by the following procedures [8]. First, a reference star selected in the set is called a pivot star. The pivot star is the star to be identified from the given database. Then, the surrounding sky is partitioned over the pattern radius (r_p) with the center located at the pivot star position. The pattern radius can be determined as a function of the FOV with a marginal value. Then, we translate the pivot star to the center of the FOV, so that the related reference stars are also translated in the same amount as the pivot star. One can select a closest reference star, alignment star, whose distance to the pivot star is marginally larger than the buffer radius (r_b). Next, we orient the alignment star to the reference frame so that the related reference stars are rotated at the same angle. Finally, a grid of size $g \times g$ in the pattern is constructed. If a grid cell contains a reference star, then we assign unity to the cell, otherwise zero in order to generate a standard format for the pattern. The grid cell bit pattern represents information of each star in the real sky.

After the pattern is constructed, we must determine which pattern in the database is closely matched to the actual pattern image in the CCD plane of the star trackers. The imaged pattern can also be developed in a standard format in the same way as the previous paragraph. If there are many shared or matched cells between patterns in the database, they can be candidate stars to be identified. When there exists only one candidate star, the candidate star can be treated as the matched star. If there are many candidate stars, the candidate star containing the maximum matching cells is assumed as the identified star.

A. Database Generation

At first, basic definition of coordinate systems and some useful notations are shown in Fig. 1. For instance, $\mathbf{s}$ denotes a unit star vector in the real sky with respect to the inertial frame. In addition, $\mathbf{s}_r$ is a pivot star vector and $\mathbf{p}$ is the star vector in the CCD image plane with respect to the body frame. And $\mathbf{p}_r$ is a pivot star vector with a length identical to the focal length (f). Let θ_i denote the angle between the pivot star and ith reference star. Then the length of $\mathbf{p}_i$ is determined by

$$\|\mathbf{p}_i\| = \frac{\|\mathbf{p}_r\|}{\cos\theta_i}. \qquad (1)$$

The x value of the imaged star vector is 0 with respect to the CCD body frame. Let φ denote the right ascension, and ζ the declination angles with respect to the inertial frame. $C_3(\varphi) \rightarrow C_2(-\zeta)$ Euler rotational sequences of the direction cosine matrix (C_I^B) of the CCD body frame with respect to the inertial frame are adopted. The set with a pivot star is limited by a threshold angle. Thus, the related reference stars in the set can simply be picked up by the inner product relationship

$$\theta_i = \cos^{-1}(\langle \mathbf{s}_i, \mathbf{s}_r \rangle) < \theta_t \qquad (2)$$

where θ_t is the threshold angle which is naturally determined by the FOV of the star trackers, and $\langle , \rangle$ represents the inner product. The star vector in the real sky can be transformed in terms of the direction cosine matrix as follows:

$$\mathbf{p}_i = \|\mathbf{p}_i\| C_I^B \mathbf{s}_i. \qquad (3)$$

TABLE I
Database Configuration

Star Index	Imaged Star Vector (**c**)
1	$c_{11}, c_{12}, c_{13}, \ldots, c_{1h_1}$
2	$c_{21}, c_{22}, c_{23}, \ldots, c_{2h_2}$
$\vdots$	$\vdots$
n	$c_{n1}, c_{n2}, c_{n3}, \ldots, c_{nh_n}$

By substituting (1) and (2) into (3), the star vector in the CCD plane is represented as

$$\mathbf{p}_i = \frac{f}{\langle \mathbf{s}_i, \mathbf{s}_r \rangle} C_I^B \mathbf{s}_i. \tag{4}$$

Equation (4) implies that ith star in the real sky with respect to the inertial frame is transformed into an imaged star vector in the CCD body frame.

The rotational procedure is applied to construct a standard format. An alignment vector, the closest reference star outside of the buffer radius, is selected. One can rotate the alignment vector, so that it can be aligned with y-axis in the CCD plane. All the neighboring stars in the set are also rotated at the same angular displacement. As a consequence, a well-defined pattern through the orientation process can be established. To quantitatively formulate the pattern with the cell indices, the CCD plane must be divided into grids. Finally, the database containing the imaged star vector ($\mathbf{c} \in R^h$) information for the conventional grid algorithm can be constructed (see Table I).

B. Pattern Generation from CCD Plane

From the CCD plane of the star tracker, an actual image of the star field can be obtained. The image pattern can be also converted into the standard format. It is necessary to relocate a selected pivot star at the center and neighboring stars are shifted. This task can be also easily done by sequential rotations. To reduce computational burden, it is assumed that the pivot star is close to the center. The process is constructed by Euler sequential rotation $C_3(\alpha) \rightarrow C_2(-\beta)$ with angles (α, β) between the x-axis vector of the body frame and the pivot vector.

III. MODIFIED METHODS

In this section, we introduce a useful strategy to enhance the conventional grid algorithm. The principal idea is to use a polar coordinate grid as shown in Fig. 2. The polar cell which occupies more marginal space in the angular direction than the radial direction is designed for reducing the position error due to the rotations. One can conceive various methods to make the grid index sequence for the polar coordinate

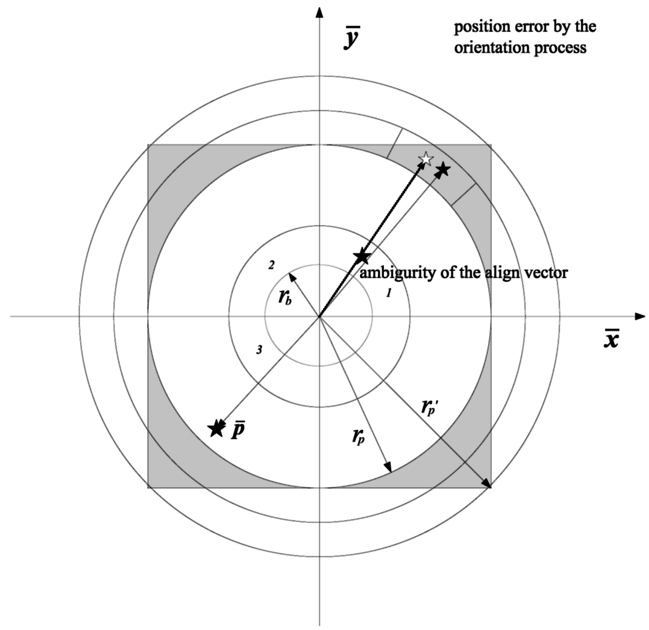

Fig. 2. Grid pattern in polar coordinate.

system. By employing a normalized radius, the length difference between the outer and inner neighboring circles is set to 2π. The polar grid is divided into g_λ cells in radians. To make the size of each cell evenly distributed, the nondimensionalized radius (integer) up to g_r is used. Then, the grid index of ith reference star about kth star in the star catalog can be defined as

$$c_{ki}(\bar{r}_i, \lambda_i) = \text{int}\left[\frac{g_\lambda \bar{r}_i(\bar{r}_i + 1)}{2} + 1\right] + \text{int}\left[\frac{\lambda_i}{2\pi}(g_\lambda + 1)\right] \tag{5}$$

where int is the integer value of the bracket and the nondimensionalized radius is expressed as

$$\bar{r}_i = \text{int}\left(\frac{r_i}{r_p'} g_r\right). \tag{6}$$

Consequently, the ith reference star position is denoted as $\bar{\mathbf{p}}_i = (\bar{r}_i, \lambda_i)$.

The standard format of the conventional grid is primarily determined by the given CCD image plane area. The pattern radius is equivalent to half the CCD plane width. When the pivot star is relocated at the center of the CCD plane, the reference stars outside of the pattern radius cannot be expressed properly. Namely, even if a reference star located outside of the buffer radius is crucial in identifying the pattern, it should be eliminated due to the limited buffer radius. Such area is displayed in Fig. 2 in gray color. To accommodate the reference stars outside of the pattern radius, the pattern radius should be larger than half the CCD plane width.

We propose the virtual grid that can be generated virtually outside of the CCD plane. The virtual grid is also displayed outside of the CCD plane in Fig. 2.

In order to take advantages of the virtual grid, the database is regenerated by replacing the pattern radius. In this process, extra reference stars can be added in the database. Obviously, the database size tends to be larger than the case with a smaller pattern radius.

Finally, the so-called multi-pivot selection strategy is proposed to identify captured stars under system noise. The position error problem of the alignment vector can be resolved, to a certain extent, by employing the polar coordinate grid discussed in the previous section even if the position error of the pivot vector is unavoidable. However, when a spurious star is treated as a pivot star or alignment vector, the grid algorithm may fail in identification. In this case, one can select another reference star as the pivot star and alignment vector irrespective of the stars already selected. The new selected stars must be located as far as possible so that the pre-selected stars can be excluded from the selection process as the alignment vector. If the position difference between the first and second pivot stars is allowable, one can assure that the best matching star is an identified star. If it is not allowable, it is assured that the star identification algorithm fails.

IV. SIMULATION STUDY

Numerical simulations are conducted to test the proposed algorithm. The new algorithm is compared with the original grid algorithm under the same condition. The Bright Star Catalog (BSC) consisting of 9,110 stars is used in this paper. The star tracker configuration for the simulation is assumed to be 8×8 deg FOV with an image plane consisting of 512×512 pixels. The sensitivity (or threshold) of the star tracker is assumed about 8.0 units apparent stellar magnitude. It is also assumed that every star in the catalog can be detected by the star tracker. To create a reasonable simulation environment, Gaussian noise with standard deviation of 0.4 unit apparent stellar magnitude is added so that some stars may not be detected in the CCD image plane. The pattern radius is selected as 4 deg half the FOV, and the buffer radius is selected as 10 pixels. The conventional grid algorithm makes use of 20×20 grids for pattern generation. For the polar coordinate grid approach, the pattern radius is also designed as 4 deg and $g_\lambda = 4$, $g_r = 20$, respectively.

The probability of star identifications is displayed in Fig. 3. The result is generated with 1,000 randomly selected bore sights of the star tracker at each position error. The probability of the proposed polar grid algorithm is somewhat better than the conventional grid method. However, for navigation purposes, the probability of star identifications shown in Fig. 3 may not be satisfactory. To improve the efficacy of the algorithm, the proposed method is applied to the

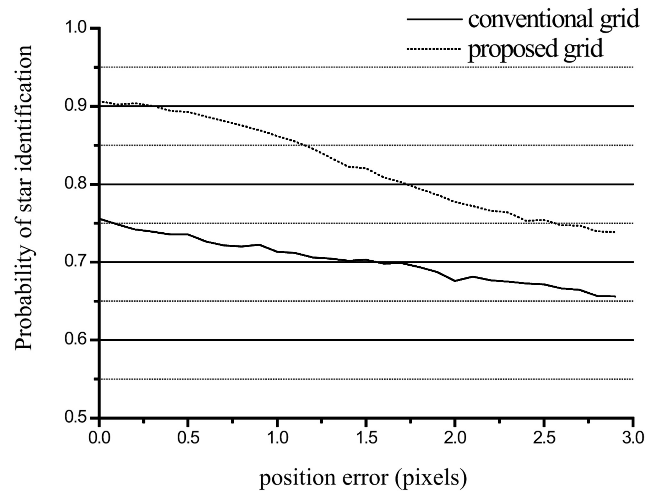

Fig. 3. Probability of star identification by different grid types.

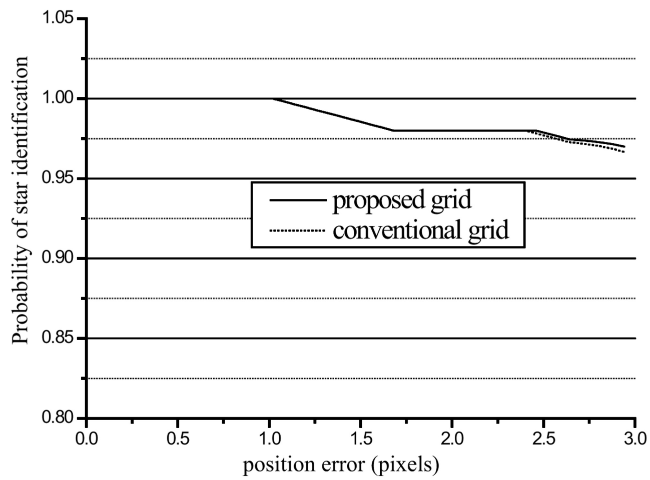

Fig. 4. Probability of star identification using virtual grid.

previous simulation results. A simulation result by the virtual grid algorithm is presented in Fig. 4. As it can be shown, the virtual grid technique enhances the grid algorithm performance significantly in the presence of position error. Not only the polar, but also the conventional grid algorithms improve star identification probability when they are implemented with the virtual grid.

To demonstrate the virtual grid with respect to the spurious stars in the CCD plane, a Monte-Carlo simulation has been performed. Fig. 5 shows the resultant star identification probability versus number of spurious stars. The multi-pivot selection method is activated only when there are less matched reference stars than the threshold value of minimum reference stars. We assume the following scenario for simulation study. A spacecraft with a built-in star tracker is orbiting in the form of sinusoidal motion as in Fig. 6. To simulate the noisy environment, 1.5 pixels of position error in random Gaussian noise and 0.4 units apparent stellar magnitude random Gaussian noise are arbitrarily introduced. The overall identification rate

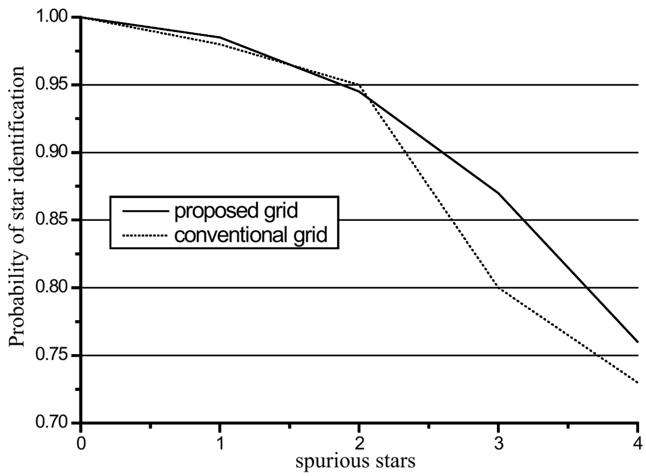

Fig. 5. Probability of star identification according to spurious stars.

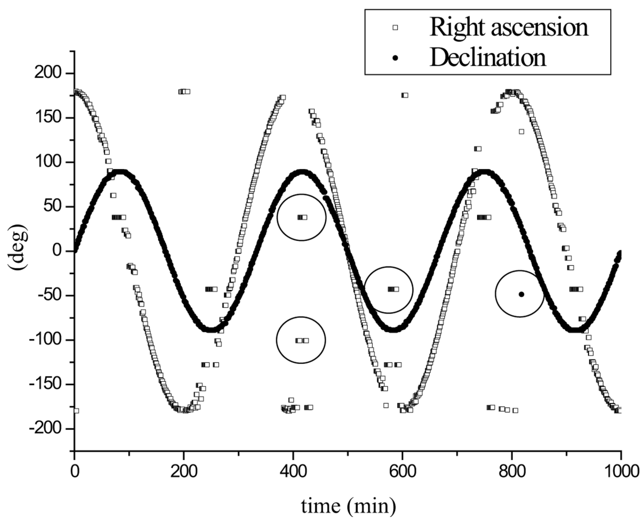

Fig. 6. Scenario result by proposed star identification.

TABLE II
Average Computational Time

Field of View (°)	Running Time (ms)
6	19.1
8	51.1
10	105.4
12	142.9

for this scenario turns out to be over about 98.5% in the case of lost-in-space. The stars inside the circles of Fig. 6 represent images impossible to identify by the multi-pivot selection algorithm.

To evaluate the computational burden of the algorithm, a personal computer of INTEL Pentium 4 CPU 3.06 GHz, 512 RAM has been used. The computational time of the proposed algorithm with respect to the conventional approach tends to increase in proportion to the virtual grid area, because the increment of the virtual grid means the increment of the FOV (see Table II).

V. CONCLUSION

A modified grid algorithm has been proposed with successful simulation demonstration. The proposed algorithm is an enhanced version of the existing grid algorithm. It turns out to provide robust star identification performance in the presence of star location errors. The polar grid algorithm produced improved identification results. The virtual grid showed that it plays a crucial role by increasing star identification rate. Both the polar and conventional grid algorithms produced enhanced star identification probability when combined with the virtual grid logic. The multi-pivot selection strategy is also a promising idea to prevent possibility of mis-identification.

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