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Research Article

A Star Pattern Recognition Algorithm Based on the Radial Companion-Circumferential Feature

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Attitude measurement is an important core technology of vehicle flight. It is of great significance to ensure the vehicle's accurate orbit entry and orbit change, high-performance flight, reliable ground communication, high-precision ground observation, and successful completion of various space missions. Star sensor is the core component to realize an autonomous attitude measurement of the vehicle. Autonomous star map recognition is a key technology in star sensor technology, and it is also the focus and difficulty of research. When the star sensor enters the initial attitude acquisition mode, according to the algorithm, the star sensor can quickly obtain the initial attitude and enter the normal working mode. This paper proposes a star pattern recognition algorithm based on the radial companion-circumferential feature with a noise compensation code to address the low recognition rate caused by position noise in the process of constructing star patterns in the traditional star pattern recognition algorithm based on the radial feature. In order to solve the problem of slow matching search speed, a maximum matching number algorithm has been innovatively adopted, which can improve the search efficiency in the process of star pattern recognition. Thus, the capacity of the star pattern recognition feature library is effectively reduced, and the stability and recognition rate of the improved star pattern recognition algorithm are further improved. The improved star pattern recognition algorithm first establishes radial and circumferential feature vectors based on the bit vector, then adds the noise compensation code according to the companion star position error, then modifies the radial and circumferential feature vectors, and finally calculates the minimum similarity difference between the feature vector of the star pattern observed by the star sensor and the feature vector of the navigation star in the feature library to obtain the unique star pattern recognition result. The identification star database adopts the maximum matching number algorithm, which can improve the search efficiency, reduce the amount of redundant matching, and shorten the matching time. The simulation results show that even in the presence of star position and magnitude noise, the improved star pattern recognition algorithm with radial companion-circumferential feature maintains a high recognition rate of more than 97 percent, demonstrating that the algorithm's robustness is superior to other algorithms. The revised method described in this work outperforms the classic triangle algorithm and the radial feature star pattern recognition algorithm without compensation code in terms of algorithm robustness, recognition success rate, and recognition time.

1. Introduction

Star sensor, which is currently the most precise space attitude measuring equipment, can perform tasks such as star pattern acquisition, centroid extraction, star pattern identification, and attitude determination. It is crucial in aeronautical and navigational technology to use astronomical starlight. [1]. Automatic star pattern recognition is a key technology in star sensor technology, as shown in Annex 1. At present, star pattern recognition algorithms proposed for star sensors mainly include the triangle angular distance matching algorithm, the main star recognition method [2, 3], the probability statistics method [4], the polygon angular distance matching algorithm [5], and the grid algorithm [6, 7]. Among them, the triangle algorithm is good, and the main star recognition method is the most widely used [8, 9]. Although the triangle algorithm is simple to implement, due to the drawbacks of a large amount of star point angular distance calculation and many times of angular distance redundant matching, many scholars have proposed two main directions for improvement, such as improving the recognition success rate and reducing the recognition time to meet real-time performance. The improved methods include various improved triangle algorithms [10, 11], quadrilateral algorithms [12], grid algorithms [13], KMP algorithms [14], connected clustering star recognition algorithms, and character matching based algorithms [15]. In order to reduce the matching times, star library search algorithms such as the K vector method [16] and the P vector method have been proposed, which can improve the search efficiency of the triangle algorithm [17]. The literature [18] saves the star diagonal distance and tolerance set of triangles by constructing a two-dimensional linked list array, which avoids the repeated calculation and search process of star diagonal distance by building a hash table, changing the matching mode of star diagonal distance, reducing the number of star diagonal distance matching, and greatly reducing the time complexity of triangular star pattern recognition. Reference [19] proposed a star pattern recognition algorithm based on the star triangle. The corresponding pattern vector is constructed according to the star triangle, arranged in ascending order according to the circumference of the triangle, and the auxiliary index vector is constructed to improve the search efficiency. Literature [20] proposed an all-sky autonomous, fast triangle recognition algorithm independent of magnitude information. By constructing the maximum internal angle of the triangle and its two sides as matching feature triangles, an all-sky navigation feature library is established. The hash function is constructed according to the maximum internal angle value of the generated feature library and is stored in blocks.

This paper improves the radial feature of the star map, constructs the feature vector based on the radial companion feature in the form of the bit vector, and adds the angular distance information between companion stars and the compensation information of position noise to the feature vector, so as to effectively reduce the impact of position noise, magnitude noise, and interfering stars on the construction of the star pattern and reduce recognition failures due to star pattern construction errors. In this paper, an improved radial companion-circumferential feature star pattern recognition model based on the compensation code is constructed. The maximum matching number algorithm can split and create the navigation star database in a reasonable manner, substantially reducing the database's size and improving the search efficiency without compromising the recognition rate. At the same time, compared with the traditional triangle algorithm and the radial characteristic star pattern recognition algorithm without the compensation code, the recognition success rate of the improved method is higher than that of the traditional radial characteristic star pattern recognition algorithm and the traditional triangle algorithm under the same conditions of star position noise and magnitude (brightness) noise, which can effectively reduce the data capacity of the navigation star database and shorten the star pattern recognition time.

2. Construction of the Star Pattern Recognition Model under Different Feature Modes

2.1. Star Pattern Recognition of Traditional Radial Features. The radial feature star pattern recognition algorithm refers to a star pattern recognition algorithm that classifies other stars (called companion stars) in a certain neighbourhood of the observation star (or navigation star) according to their radial distance from the observation star as the feature pattern of the observation star [21].

The radial feature composition method is as follows: take the observation star S as the center, make a circular neighbourhood with R_r as the radius, and divide the neighbourhood of S into Nmax rings along the radial direction. Nmax is the effective digits of the radial feature vector. The radial feature diagram is shown in Figure 1.

$$N_{\max} = \frac{R_r}{e}. \tag{1}$$

The angular distance between S and A is marked as V_{sa}, the angular distance information is discretized, and its discrete value is marked as V_{sa}^*; then,

$$v_{sa}^* = \frac{v_{sa}}{e} + 1. \tag{2}$$

According to the dispersion value of the angular distance information, the position $[V_{sa}]$ in the radial feature vector of the observed star can be determined to be 1 from (3). For example, if the star's angular distance dispersion value to SA is 27.25, then point 27 in the observed star's radial feature vector will be 1. Figure 2 shows a schematic representation of the radial feature pattern's creation.

$$V_{sa} = \text{ floor } \left(v_{sa}^*\right). \tag{3}$$

The angular distance between companion stars A and B may be calculated using the same method and the spatial distribution relationship between companion stars in the vicinity of observation stars, and its discrete value V_{sa}^* is as follows:

$$v_{sa}^* = \frac{v_{sa}}{2e} + 1. \tag{4}$$

Then, the bit (set to 1) in the eigenvector of the observation star companion star can be determined according to formula (3). According to Figure 3, the maximum angular distance between companion stars is 2rR, and the divisor in formula (4) is set to 2e to ensure that the number of bits of radial eigenvector of the observation star and the companion star eigenvector is the same. The construction method of the observation star companion feature vector is shown in Figure 3.

2.2. Triangular Star Pattern Identification. A common isomorphic star map recognition algorithm of a subgraph is the triangular star pattern identification technique. It has the advantage of high reliability and is still widely used in engineering practice [22].

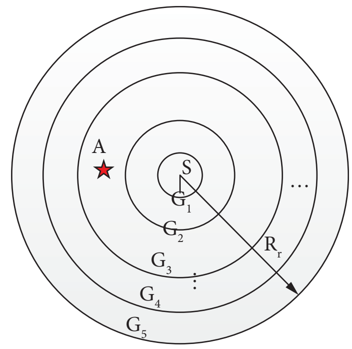

Figure 1: Schematic diagram of the radial feature.

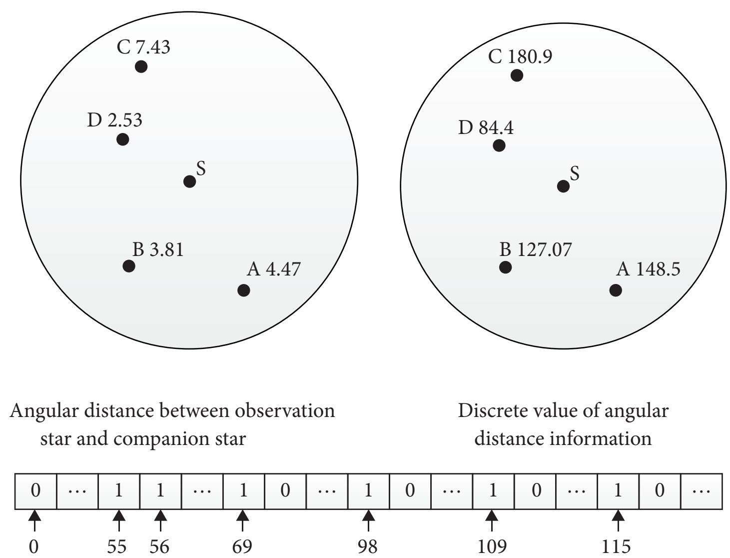

Figure 2: Construction diagram of the radial feature mode.

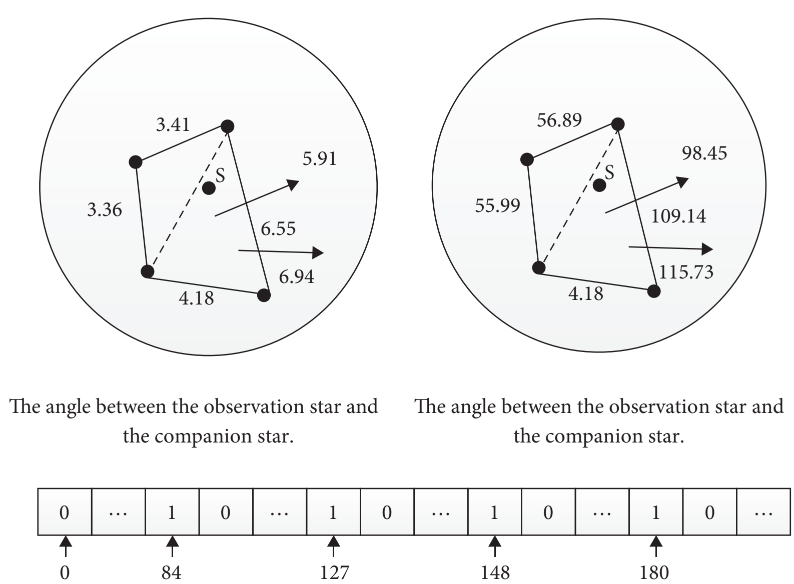

Figure 3: Construction method of the companion star eigenvector of the observation star.

The implementation process of the triangular star pattern recognition algorithm is to select three noncollinear stars from the real-time star pattern of the star sensor to form a star triangle to be recognized. By comparing with the star triangles in the navigation star catalog, the star pattern recognition is completed under the matching constraints.

However, in the process of triangular star map recognition, star points need to be traversed, where there is redundant matching and false matching, and the recognition efficiency is low [23, 24].

2.3. Construction of the Radial Companion Circumferential Feature Mode Based on the Compensation Code. Firstly, the observation star circumferential feature mode is established. The construction of the observation star circumferential feature mode is shown in Figure 4, and the construction method is as follows:

(i) As shown in the figure, take S as the main star to determine the circumferential mode of radius R_c (this paper takes T_1, T_2, and T_3 as companion stars for example);

(ii) Taking the main star S as the center, calculate the included angles $\angle T_1ST_2$, $\angle T_2ST_3$, and $\angle T_3ST_1$ between companion stars, respectively;

(iii) Taking the side with the minimum companion angle (the ST_1) as the starting edge, the circular neighbourhood is divided in the circumferential direction, and the circumference is equally divided into 8 quadrants;

(iv) According to the distribution of companion stars in each quadrant, an 8 bit vector V is formed in a counterclockwise direction. As shown in the figure, $V = [11001000]$, the circumferential distribution feature of S is the vector V.

Based on the radial companion feature pattern [25], the circumferential feature pattern is introduced. Although it can well describe the finer feature distribution relationship of star points, position noise is still easy to interfere with this feature. In this paper, a position noise compensation code is added to the radial companion-circumferential feature mode to compensate for the companion drift caused by position noise. As can be seen from Figure 5, the discrete value of the angular distance between observation star S and companion star A is at the boundary of ring 76 and ring 77. In order to compensate for the adverse effect of position noise on identification, it can be assumed that companion star A is in ring 76 and ring 77 at the same time. In order to control the number of compensation codes added, a threshold can be set, that is, $\delta_L = 0.3$, $\delta_H = 0.7$. Only if the decimal of the angular distance dispersion of S and A is less than σ_L or greater than σ_H, add a compensation code (set it to "1") in bit $[v_{sa}] - 1$ orbit $[v_{sa}] + 1$ of the eigenvector.

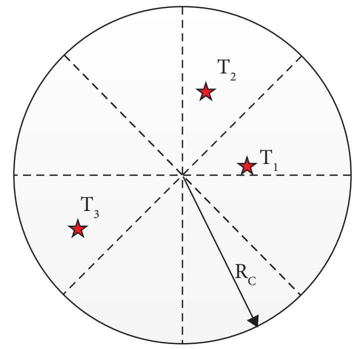

Figure 4: Construction diagram of the observation star circumferential pattern mode.

3. Improved Star Pattern Recognition of Radial Companion-Circumferential Features

3.1. Establishment of Feature Database. There are two elements in a navigation database: a navigation star catalog and a navigation star feature database. A navigation star catalog is a simple star catalog created by choosing navigation stars from the basic star catalog that fall within a specific brightness range and combining their position (right ascension and right latitude) and brightness information. In addition to the navigation star catalog, the feature extraction technique requires the creation of a navigation star feature database. The following features are part of the experimental feature library

(i) Annex 2 provides a simple catalog. The table is a 4908 ∗ 4 matrix, with the first column containing the star number, followed by numbers 1 through 4908; the second column containing the star's right ascension data; the third column containing the star's declination data (unit of right ascension and declination data: angle); and the fourth column containing the star's magnitude data. Smaller storage and faster matching speeds can be obtained by simplifying the star list while retaining the same recognition rate. Table 1 shows the precise simplification findings;

(ii) In Annex 3, Axx to Hxx represent the star point numbers in the star map in turn. The data is a ∗ 3 matrix that stores the picture coordinate system location information for the N star image points. The first column is the star image point number; the second column is the image coordinate system's x-axis coordinate of the star image point centroid center; and the third column is the image coordinate system's y-axis coordinate of the star image point centroid center. The field of view of the star sensor is 20 ∗ 20, and the number of pixels is 1024 ∗ 1024.

The technique is based on a comparison of the star map and the vector characteristics of the stars in the library with the highest number of matches. The eigenvalues of the actual

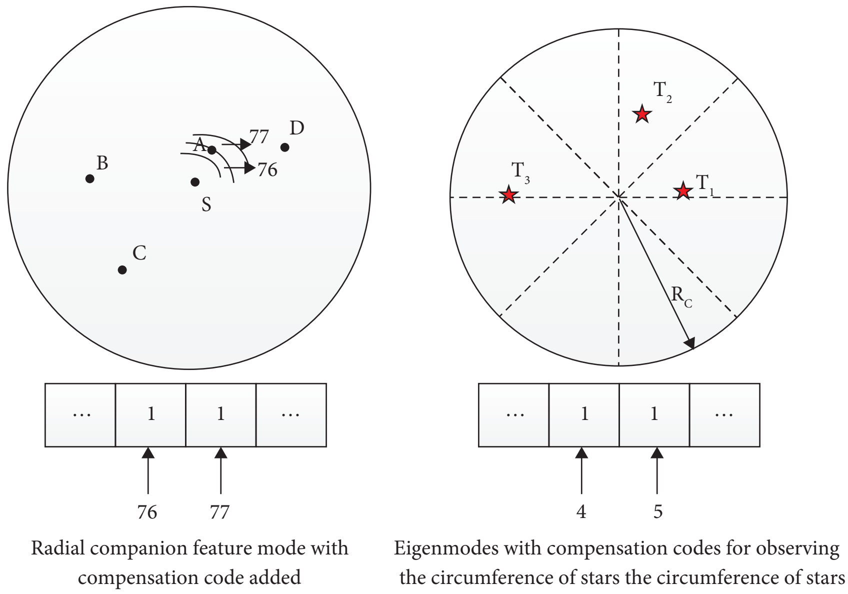

Figure 5: Radial circumferential companion feature mode with compensation code added.

Table 1: Simplified Tycho_ 2-star catalog.

Simplified catalog			
Asterisk	Right ascension	Declination	Magnitude (ordered star)
No. 1	α_1	δ_1	...
...	...	...	...
No. M	α_M	δ_M	...

must be present in the library, and the number of matches for the eigenvalues of known stars in the navigation library (as shown in Figure 6) is much greater than the number of matches for the eigenvalues of false stars, so the maximum number of matches identification method is used.

Using this method, a navigation star feature database characterized by angular distance is constructed. Compared with the traditional database construction method, this method eliminates a large number of redundant eigenvalues and greatly reduces the storage space.

3.2. Improved Star Pattern Recognition Algorithm of Radial Companion- Circumferential Feature. When the improved matching group star map recognition model encounters the error problem caused by position noise, the star map recognition efficiency is low, the matching speed is slow, and there will be a certain misjudgment rate. To solve this problem, a radial companion-circumferential feature star pattern recognition model with a compensation code is constructed. The feature vector of the navigation star is represented by the model in the form of a bit vector. The radial feature of the observation star, the circumferential feature of the observation star, and the position feature of the companion star of the observation star make up the feature vector.

The radial companion feature is used to complete the initial matching and narrow the search range in the process of radial companion annular star map recognition based on compensation code, and then the observation star is

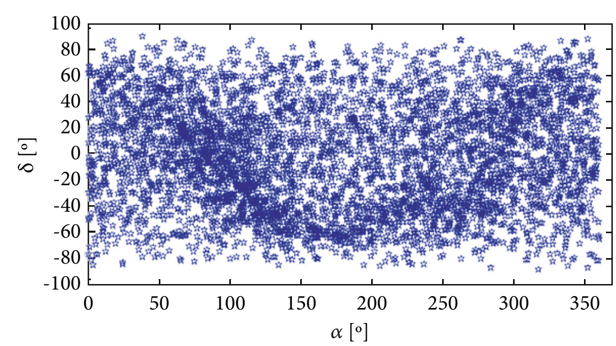

Figure 6: Star point distribution of all navigation stars.

uniquely identified by screening according to the correlation of the position information of each star point in the field of view. T_f is defined as the minimum similarity difference between the navigation star feature vector and the observation star feature vector in the feature library. The observation star whose minimum similarity difference is not greater than the threshold F is selected as the candidate star.

$$f_T = \left[T_s - \sum_{i=1}^{N_{\max}} S'(i)\right]^2 + \left[T_a - \sum_{j=1}^{N_{\max}} C'(j)\right]^2 + \left[T_v - \sum_{k=1}^{8} V'k\right]^2,$$

$$\begin{cases} T_s = \sum_{i=1}^{N_{\max}} S(i) \& S'(i), \\ T_a = \sum_{j=1}^{N_{\max}} C(j) \& C'(j), \\ T_v = \sum_{j=1}^{8} V(k) \& V'(k), \end{cases} \tag{5}$$

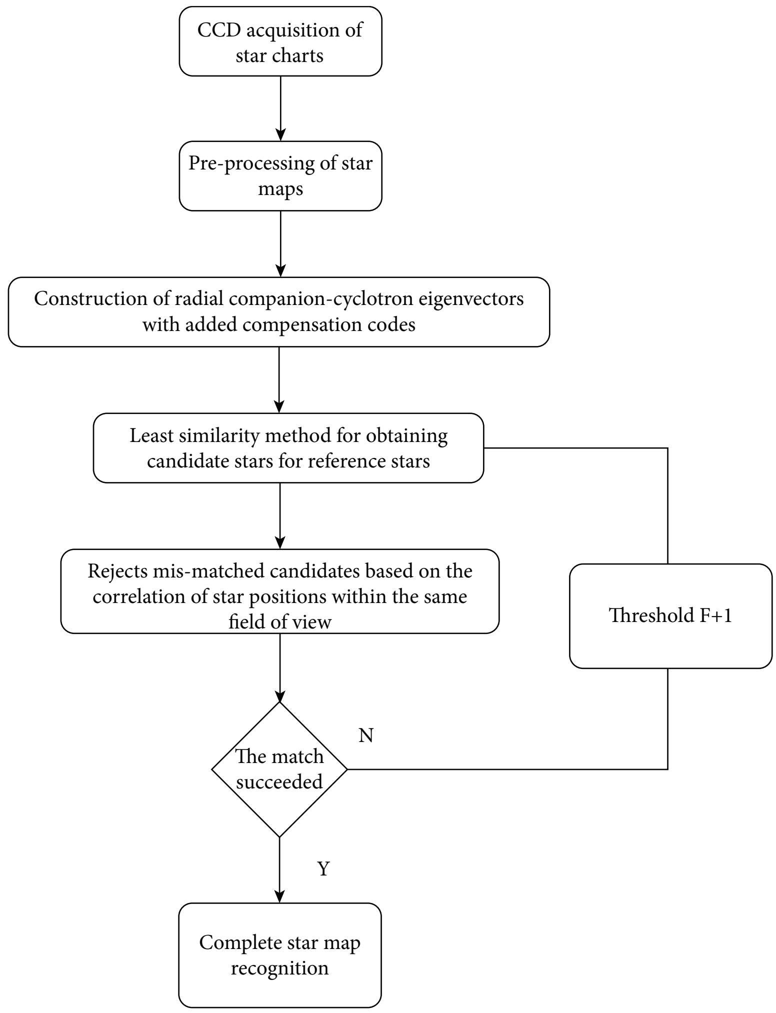

Figure 7: The star pattern recognition process of radial companion-circumferential feature based on the compensation code.

where $S(i)$ is the i th bit of the observation star's radial feature vector and $S(i)$ is the i th bit of the navigation star library's radial feature vector. $C(j)$ is the j-th bit of the observation star's companion star feature vector, and $C(j)$ is the j-th bit of the navigation star library's companion star feature vector. The k-th bit of the annular feature vector of the observation star is represented by $V(k)$, and the k-th bit of the annular feature vector in the navigation star library is represented by $V(k)$. Equation (6) determines the candidate stars.

$$f_T \leq F. \quad (6)$$

The candidate stars are obtained by the minimum similarity difference method, and other constraints should be considered, such as the star's angular distance being less than the field angle. The specific methods are as follows in Figure 7 below: screen the preprocessed star map and adjust the threshold F; if the selected candidate stars are unique, the candidate stars are uniquely matched to complete the star pattern identification; if the candidate stars obtained by screening are not unique, it is necessary to reduce the value of F for screening; if no candidate star can be obtained through screening, increase the value of F and repeat the above process to match the candidate star uniquely.

4. The Experimental Results and Analysis

The experimental data are shown in the supplementary material files (available here), which come from the national postgraduate mathematical modeling competition of China. The performance of the improved star pattern recognition algorithm based on radial companion-circumferential feature is evaluated in order to verify the effectiveness, timeliness, robustness, and storage space requirements of the improved star pattern recognition algorithm based on radial companion-circumferential feature. In the known star pattern, the experiment should match the star number corresponding to each star picture point. The point spread function approach of Gaussian surface fitting is used for star image processing, while the neighborhood means of the filtering method are used for picture denoising. To extract the recorded star coordinate data, the star pattern is first filtered, and three-star pattern recognition algorithms are then run in conjunction with the navigation star data in the field of view.

Table 2: Identification results.

Number of star image points in the star pattern	Star number	Number of star image points in the star pattern	Star number
G01	1525	G22	1603
G02	1572	G23	1415
G03	1443	G24	1692
G04	1748	G25	1453
G05	1780	G26	1432
G06	1675	G27	1492
G07	1720	G28	1488
G08	1503	G29	1648
G09	1634	G30	1646
G10	1577	G31	1566
G11	1757	G32	1688
G12	1586	G33	1655
G13	1536	G34	1505
G14	1610	G35	1373
G15	1681	G36	1576
G16	1606	G37	1545
G17	1670	G38	1424
G18	1477	G39	1375
G19	1790	G40	1825
G20	1502	G41	1401
G21	1631	G22	1603

4.1. The Results of Simulation Star Pattern Experiment. Process any star map, extract the star point coordinate data, and identify the star pattern in combination with the navigation star data in the field of view. Features are used for the initial identification of star points. Table 2 shows the results of the initial identification (due to space constraints, only some initial identification results are given here).

The star pattern in Figure 8 is recognized in the experiment, and the matching numbers of star image points and stars are listed in Table 2. All-stars in the field of view of star pattern 1 are indicated by " $*$," and stars in the field of vision of star pattern 1 are highlighted with red boxes.

Figure 8 shows that three stars are not visible in the area of vision. These three stars are at the edge of the field of vision, as seen in the diagram. They do not appear in the field of vision because the spacecraft's attitude moves around the optical axis of the star sensor, preventing stars that should appear at the edge of the field of view from entering it. The three models can successfully perform the recognition task in the experiment. In the problem of the broad field of view multistar image point matching, it was discovered that the star pattern recognition model of radial companion-circumferential pattern with the compensating code has greater calculation efficiency when compared to the computation speed.

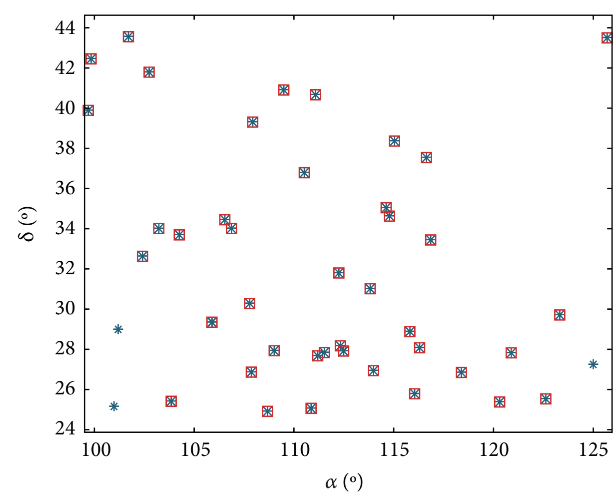

Figure 8: Stars in the field of view.

4.2. Comparison and Analysis of Simulation Results. First, add the noise to the star pattern created by the simulation at the start point position, with a mean value of 0 and a standard deviation of 3 pixels, and follow the Gaussian distribution (0.015 mm is 1 pixel long). Observe the star pattern recognition results of the three recognition algorithms and count the recognition rate. Figure 9 shows the comparison of the results.

Then, to the star pattern created by the simulation on the magnitude, add noise with a mean of 0 and a standard deviation ranging from 0 to 1 Mv, and follow the Gaussian distribution. Observe the recognition results of the star pattern by the three recognition algorithms and count the recognition rate. Figure 10 shows the comparison of the results.

Finally, the recognition time is counted. Under the same conditions, the three algorithms match and recognize 900 simulated star patterns without noise, calculate the average time of each algorithm, and count the average matching time rounded up every 100, as shown in Table 3.

It can be concluded from Table 3 that compared with the triangle algorithm, the improved recognition algorithm proposed in this paper improves the recognition time by 640 ms, is better than the matching group algorithm, and

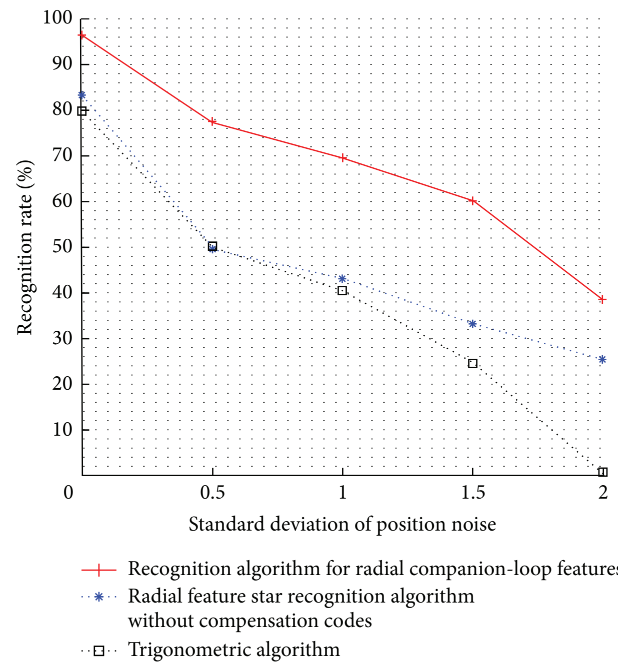

Figure 9: Effect of position noise on the recognition rate.

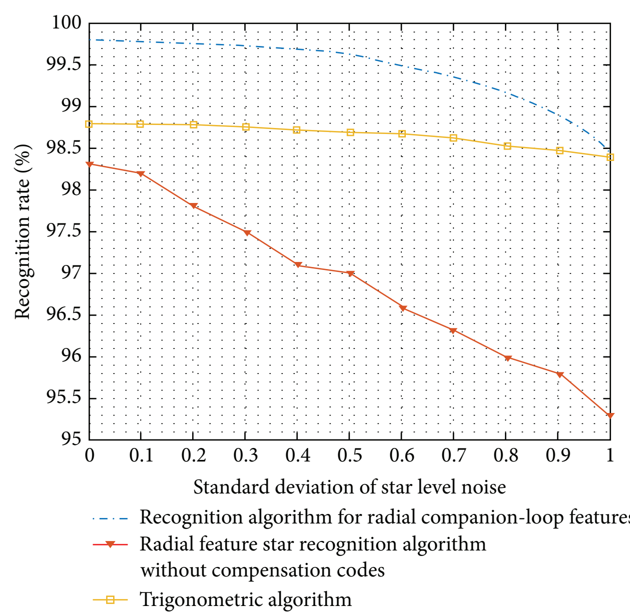

Figure 10: Effect of magnitude noise on the recognition rate.

Table 3: Comparison of recognition time of three recognition algorithms.

Algorithm	The traditional triangle algorithm	The radial feature star pattern recognition algorithm without the compensation code	The star pattern recognition algorithm based on the radial companion- circumferential feature
Identification time(ms)	800	700	160

maintains a fast recognition speed. It shows that the improved maximum matching number algorithm can reduce the matching redundancy and recognition time. In addition, the algorithm can reduce the storage space of the star database and improve the rate of recognition success.

5. Conclusion

A star pattern identification method with a radial companion ring feature and a compensation code is proposed in this work. The algorithm adds the compensation information for position noise on the basis of star radial feature, reduces the influence of position noise, and stores the feature vector based on radial companion feature in the form of a bit vector, which greatly reduces the memory requirement of the algorithm.

In terms of matching, this method uses a recognition algorithm based on the maximum matching number, which improves search efficiency significantly. In order to reduce the matching rate due to the influence of interference stars and the nonuniqueness of matching star pairs, this method adopts logic and operations, which greatly reduces the recognition time of the algorithm.

The suggested approach is more resilient to position and magnitude noise than the other two traditional algorithms, and the average recognition time is also improved to some extent, according to the experimental findings of simulated star patterns. The recognition success rate of this method may reach more than 97 percent in simulation.

Data Availability

The data come from the national postgraduate mathematical modeling competition in China. The data used to support the findings of this study are included within the supplementary information files.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Supplementary Materials

Annex 1 is the relevant background of this project. Annex 2 provides a simple catalog. The table is a matrix in which the first column is the number of stars, numbered from 1 to 4908; the second column is the right ascension data of stars; the third column is the right ascension data of stars (right ascension and right ascension data unit: angle); and the fourth column is the magnitude information of stars. Annex 3 contains 8-star map data. For the sake of distinction, the numbers are represented by axx~hxx in turn. Taking C as an example, the data is a matrix, which records the position information of 7-star image points in the image coordinate system. The first column is the star image point number (numbers are c01~c07 in turn), the second column is the x-axis coordinate of the star image point centroid center in the image coordinate system, and the third column is the y-axis coordinate of the star image point centroid center in the image coordinate system. The field of view of the star sensor recorded in A~ F files is $12^o \times 12^o$, and the number of pixels is 512×512. The field of view of the star sensor recorded in G and H files is $20^o \times 20^o$, and the number of pixels is 1024×1024. . (*Supplementary Materials*)

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