A NOVEL STAR PATTERN RECOGNITION ALGORITHM FOR STAR SENSOR

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Abstract:

Triangle algorithm is used widely in the field of star pattern recognition, but it also has disadvantage that recognition reliability decreases seriously in areas where there are many stars existing small angular separation. The character match algorithm can solve this problem and it has small size of guide star database, but it can not recognize a star image with displacement caused by camera movement and rotation. To overcome this disadvantage, an effective star pattern recognition algorithm is proposed in this paper. This algorithm divided the entire celestial sphere into a lot of square areas based on some bright stars during constructing guide star database, and then it used sub-areas selected from these square areas for star pattern recognition according to characteristic of star image sensed by star sensor. The simulation results show that the algorithm in this paper not only inherits advantages of character match algorithm, but also has strong robustness against star image displacement.

Keywords:

Star sensor; Star pattern recognition; Character match

1. Introduction

A reliable attitude determination system is critical to the success of a space mission, and a spacecraft that does not know its orientation in space is unable to perform flight task. At present, star sensors have been widely used for attitude determination in both orbiting and interplanetary spacecraft thanks to its high measuring accuracy, not accumulating the attitude error, and quick recovery from fault. The most important stage of the attitude determination process using a star sensor is the star pattern recognition process, and the recognition reliability and recognition time are the most important criteria to assess an algorithm of star pattern recognition [1, 2].

In the field of star pattern recognition, there are many algorithms: the polygon angular match algorithm [3, 4], the triangle algorithm [5, 6], the improved triangle algorithm [7] and the pole star pattern recognition algorithm [8]. These algorithms have been developed widely, but they all have the disadvantage that recognition reliability decreases seriously in areas, where there are many stars existing small angular separation.

In allusion to this disadvantage of these algorithms, a star pattern recognition method of star sensor with KMP (Knuth-Morris-Pratt) algorithm is presented in [9]. The star pattern recognition is considered as a bit stream mode match. First, the entire celestial sphere is divided into a lot of un-overlapped square areas, and for each area, every bit 1 refers to a guide star while every bit 0 not, then a guide star database is constructed with this 0-1 methods. Subsequently, the data in a star image are also processed with this 0-1 methods, i.e. every bit 1 refers to an observed star while every bit 0 not. At last, star pattern recognition is implemented by KMP algorithm. This algorithm avoids decreasing recognition reliability in areas, where there are many stars existing small angular separation. But the size of the guide star database is very large.

In order to compress the size of the guide star database in [9], an improvement of star pattern recognition method with KMP algorithm is presented in [10]. First the image in each square area is filtered using wavelet transform, and its low frequency part is adopted, then the guide star database can be constructed using 0-1 methods [9]. The size of guide star database and the recognition time with this algorithm are approximately a quarter of those with the algorithm in [9]. But most of data in the guide star database are useless for star pattern recognition.

A storing guide star database method for star pattern recognition using character match is proposed in [11] to eliminate the useless data in the guide star database in [9, 10]. In each un-overlapped square area of guide star database in [10], the bit stream data are processed as follows: an integer and an extra 0 are combined to represent the number of successive original bit 0s, and 11 represents an original bit 1, these resulting bit data are stored in corresponding region of guide star database. The resulting bit data in all square areas of the entire celestial sphere are stored orderly as the guide star database. The size of guide star database is reduced greatly with the algorithm.

2. Principle of constructing guide star database

Although the algorithm proposed in [11] reduces the size of guide star database greatly, it divides the entire celestial sphere into a lot of un-overlapped square areas in the process of constructing guide star database. This method of constructing guide star database is also applied in [9, 10]. In practice, however, it is very difficult to make a star image sampled by star sensors overlap one square area in guide star database completely due to camera movement and rotation shown in Figure.1. If a star image cannot overlap any one square area in guide star database completely, the star image cannot be recognized using these algorithms in [9-11]. In order to overcome the disadvantage of these algorithms, a novel method of constructing guide star database is proposed in this paper, in which a lot of bright stars are first selected as main guide stars from the entire celestial sphere, and then the entire celestial sphere is divided into a lot of square areas whose centers are main guide stars, finally the guide star database is constructed using the method in [11] for star pattern recognition.

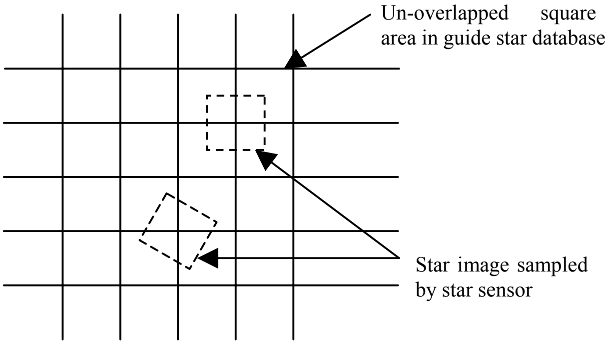

Figure 1. Star image displacement due to camera movement and rotation

3. Constructing guide star database procedure

According to the principle of constructing guide star database, the steps for constructing guide star database in this paper are listed below.

1) Every other a certain step of right ascension θ_{ra} and a certain step of declination θ_{de} in the entire celestial sphere, we select a star as a main guide star, which is the brightest star within an area, so a lot of main guide stars are obtained from the entire celestial sphere. Then we select a lot of second brightest stars as subaltern guide stars, which are the closest to corresponding main guide stars.

2) We use each main guide star as center to divide the entire celestial sphere into a lot of square areas, each of which is greater than that covered by a single FOV (field of view), and to make one side of every square area parallel line from each main guide star to each subaltern guide star. Each pair of main guide star and subaltern guide star is included in each square area.

3) We use each main guide star as center to rotate each square area in order that one side of each square area is horizontal, i.e. the line from each main guide star to each subaltern guide star is horizontal.

4) In each square area of the entire celestial sphere, original bit stream data are achieved using the 0-1 methods [9]. In order to reduce the size of guide star database, the method in [11] is adopted that an integer and an extra 0 are combined to represent the number of successive original bit 0s, and 11 represents an original bit 1, these resulting bit data are stored in corresponding region of guide star database. The procedure repeats until the resulting bit data in all square areas of the entire celestial sphere are stored orderly, and then the final guide star database is achieved.

4. Star pattern recognition procedure

The steps for star pattern recognition in this paper are listed below.

1) We select a main observed star from center area of a star image, which is the brightest star within this center area. Then we select a subaltern observed star, which is a second brightest star within this center area and close to the main observed star.

2) A rectangle sub-area of maximum size is selected from the star image to make its one side parallel line from the main observed star to the subaltern observed star, and to make the sub-area include the main observed star and subaltern observed star in star image.

3) The main observed star is used as center to rotate the rectangle sub-area in star image in order that one side of the rectangle sub-area is horizontal, i.e. line from the main observed star to the subaltern observed star is horizontal shown in Figure.2.

4) All data in the rectangle sub-area of star image are processed using the 0-1 methods [9]: every bit 1 refers to an observed star while every bit 0 not to achieve a 0-1 matrix, and then all elements in the 0-1 matrix are rearranged from left to right and from up to down to achieve 1-dimension bit stream data. The number of 1s in the 1-dimension bit stream, which is the number of observed stars in the sub-area, is calculated. These values are then calculated with Eq.1a and Eq.1b.

$$n_{start} = n - \varepsilon \tag{1a}$$

$$n_{end} = n + \varepsilon \tag{1b}$$

where n is the number of 1s in the 1-dimension bit stream and ε is number error of observed stars in advance.

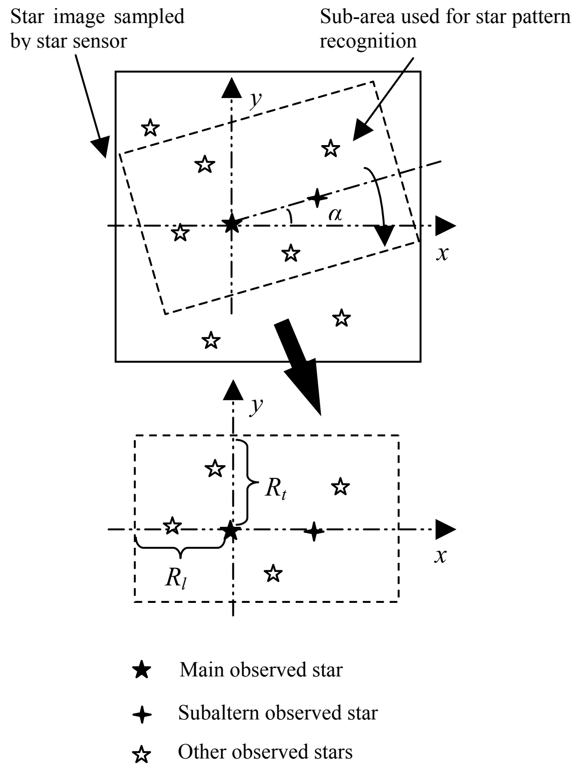

Figure 2. Procedures of selecting sub-area from star image

5) A rectangle sub-area including main guide star and subaltern guide star is selected from each square area in guide star database for star pattern recognition. The size of each sub-area is equal to that of the sub-area in step 2), and the distance (R'_l in Figure.3) between the main guide star and left side of the rectangle sub-area is equal to the distance (R_l in Figure.2) between the main observed star and left side of the rectangle sub-area in step 2), meanwhile, the distance (R'_t in Figure.3) between the main guide star and upside of the rectangle sub-area is equal to the distance (R_t in Figure.2) between the main observed star and upside of the rectangle sub-area in step 2).

6) If the number of guide stars in this rectangle sub-area is between n_{start} and n_{end}, then the sub-area is reserved as candidate sub-area, and the star pattern recognition procedure goes to step 7), otherwise, discards this sub-area and searches next square area in guide star database.

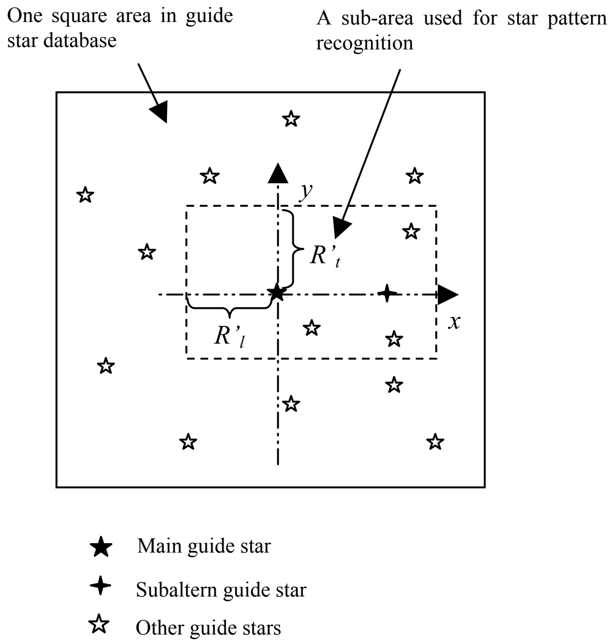

Figure 3. Selecting a sub-area from a square area of guide star database for star pattern recognition

7) In each candidate sub-area of guide star database, the bit stream data are rearranged from left to right and from up to down to achieve 1-dimension bit stream data. By using these 1-dimension bit stream data and those 1-dimension bit stream data obtained from star image in step 4), star pattern recognition is implemented by the algorithm, which is discussed in detail in [11].

8) For all the candidate sub-areas, the number (k_i, i=1,2…m) of 1s, which results from logical AND operation in algorithm [11], is calculated. The successful candidate sub-area is

$$k_{\max} = \max(k_1, k_2, \cdots k_m) \tag{2}$$

where m is the number of candidate sub-areas in guide star database.

In practice, positional noise of observed star in star image always exits due to the hardware of star sensor and the algorithm extracting image plane coordinates of observed star. In order to avoid spurious recognition caused by it, we use image plane coordinates of each observed star as center to construct some circular areas in the star image. The radius of every circular area is R, and only one observed star is included in every circular area. All the bit data are assumed bit 1 in every circular area. In the process of star pattern recognition, if only one bit is recognized successfully in every circular area, then we believe the observed star included in the circular area is recognized successfully.

5. Results and discussion

To compare the simulation results between the algorithm in this paper and the algorithm in [11], we extract 5062 stars brighter than magnitude 6.0 as guide stars from SKY2000 Guide Star Catalog. The CCD pixel is 512×512, and the FOV size is $10^o \times 10^o$. Each square area in guide star database is 1.5 times that covered by a single FOV. The positional noise of imaged stars is set at 0.5 pixels (standard deviation). Some other experiment parameters are: θ_{ra} =5°, θ_{de} =5°, ε =2, R = 2 pixels.

Subsequently, we produce 800 star images with simulated sensor from the entire celestial sphere, and classify these star images into four groups. Group 1 has 200 star images, each of which overlaps one square area in guide star database in [11]. Group 2 has 200 star images, each of which does not overlap any one square area in guide star database in [11]. Group 3 has 200 star images, in each of which main observed star and subaltern observed star overlap main guide star and subaltern guide star in one square area of guide star database in this paper respectively. Group 4 has 200 star images, in each of which main observed star and subaltern observed star do not overlap main guide star and subaltern guide star in any one square area of guide star database in this paper.

The simulation is carried out with the four groups of star images mentioned above. All of the work is completed in a VC++6.0 environment, using a PC with an Intel Pentium 800MHz processor under Windows 2000 and the simulation results are shown in Table 1.

Table 1. Simulation results between algorithm in this paper and algorithm in [11]

Algorithm	Star image	Recognition reliability (%)	The number of areas for star pattern recognition
Algorithm in [11]	Images in group 1	100	The entire celestial sphere
	Images in group 2	0	
Algorithm in this paper	Images in group 3	100	54
	Images in group 4	98.82	34

From Table 1, we can see that recognition reliability is 100% with the algorithm in [11] and the algorithm in this paper when star images in group 1 and group 3 are selected for star pattern recognition. This demonstrates that all the two algorithms have fine performance in recognizing star images without displacement. But in the case of using star images in group 2 and group 4 for star pattern recognition, recognition reliability is 0% with the algorithm in [11], while recognition reliability achieves 98.82% with the algorithm in this paper. The reason is that the algorithm proposed in [11] divides the entire celestial sphere into a lot of un-overlapped square areas in the process of constructing guide star database. When a star image does not overlap any one of square areas in guide star database completely due to camera movement and rotation, the star image cannot be recognized at all. But the algorithm in this paper has considered these factors in the process of constructing guide star database, so the algorithm in this paper is not sensitive to star image displacement, and still has fine performance in recognizing the star images with displacement.

During star pattern recognition, the algorithm in [11] needs to recognize all square areas in the guide star database, while the algorithm in this paper only recognizes the sub-areas of square areas in guide star database where the number of guide stars is between n_{start} and n_{end}. There are at most 54 square areas used for recognition in guide star database shown in Table 1.

In order to assess the performance of the algorithm in this paper further, we also compared it with typical triangle algorithm. At first, we produced stochastic field of view $10^o \times 10^o$ with simulated sensor to obtain 500 star images by using Monte Carlo method. Then these star images were classified into two categories: the first one is normal star image; the second one is star image with small angular separation. Other experiment conditions are the same as those in Table 1, and the simulation results are shown in Table 2.

Triangle algorithm employs angular separation for star pattern recognition, while small angular separation maybe result in spurious recognition, so triangle algorithm maybe decrease recognition reliability in areas, where there are many stars existing small angular separation. Table 2 shows that recognition reliability drops from 98.86% to 95.82% when star images with small angular separation are used for star pattern recognition. But in the process of star pattern recognition using the algorithm in this paper, every bit 1 refers to a star while every bit 0 not in the sub-area of star image. Therefore, in the areas, where there are many stars existing small angular separation, only a number of successive bit 1s are increased, and the same number of bit 0s are decreased, but the total number of bit remains the same. Accordingly, the results of star pattern recognition are not affected, which is shown in Table 2 that recognition reliability is still 98.93% with the algorithm in this paper when star images exist small angular separation. This demonstrates that the algorithm in this paper has strong robustness against small angular separation in star image.

Table 2. Simulation results between algorithm in this paper and triangle algorithm

Algorithm	Star image	Recognition reliability (%)	Recognition time (ms)
Triangle algorithm	Normal star image	98.86	66.39
	Star image with small angular separation	95.82	66.18
Algorithm in this paper	Normal star image	98.93	8.49
	Star image with small angular separation	98.93	8.49

During the star pattern recognition, most operations are logical AND operations and only a few addition, subtraction, multiplication, and division operations are used with the algorithm in this paper, while all the operations are addition, subtraction, multiplication, and division operations with triangle algorithm. Accordingly, recognition time of the algorithm in this paper is much less than that of triangle algorithm. Table 2 shows that the maximum recognition time of triangle algorithm is 66.39 ms, while recognition time of the algorithm in this paper is only 8.49 ms.

6. Conclusions

In this paper, a novel autonomous star pattern recognition algorithm is proposed. On one hand, this algorithm inherits advantages of character match algorithm: the algorithm has strong robustness against small angular separation in star image, small size of guide star database, little recognition time, and high recognition reliability. On the other hand, it overcomes the disadvantage of character match algorithm: a star image cannot be recognized in the case of the star image has relative displacement to the every sub-area in guide star database. The algorithm in this paper has considered the problem of star image displacement in the process of constructing guide star database, so it has strong robustness against the star image displacement. Moreover, this algorithm only employs a part of square areas in guide star database for star pattern recognition, which avoids lost-in-space.

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