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A Novel Algorithm Reducing All-sky Star Pattern Recognition's Delay Time

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Abstract: A novel algorithm reducing all-sky star pattern recognition's delay time is proposed. Because of shortages of the all-sky star pattern recognition such as too much delay time and low precision of measured attitude , the novel algorithm can calculate the position of boresight axis' projection of star sensor when all-sky star pattern recognition is completed and starts a localized star pattern recognition in the area centred at the boresight axis' projection to improve time delay and precision of attitude. Simulation results show that the novel algorithm has less delay time and more precision of attitude than the traditional all-sky star pattern recognition.

Key Words: Star Pattern Recognition, Reduce Delay Time, Star Sensor, Precision Of Attitude

1 INTRODUCTION

In all navigation methods, celestial navigation[1] is one of the most important navigation methods. The celestial navigation can provide the most accurate attitude of the space vehicle thanks to the improvement obtained by the star light defocusing technique which increases the precision of the starlight direction identified by statistical approaches. In the celestial navigation, star pattern recognition is one of the important parts of the celestial navigation. The all-sky star pattern recognition algorithm[2,3] plays an important role in the star pattern recognition. The key important parts of the all-sky star pattern recognition algorithm are the star pattern recognition ratio and star pattern recognition time delay.

In the all-sky star pattern recognition algorithms, all-sky angel-distance recognition algorithm and all-sky triangle recognition algorithm are two popular methods. In all-sky angel-distance recognition algorithm[4], two navigation stars can be captured through charge coupled device (CCD)'s field[5] of view(FOV) and from the two navigation stars we can obtain three navigation factors: two navigation stars' visual magnitudes and their angel-distance. The two navigation stars can match with the stars of candidate star database. The all-sky angel-distance recognition algorithm has the fault of low star match ratio. In order to increase the star recognition ratio, an all-sky triangle recognition algorithm is proposed. In the all-sky triangle recognition algorithm, CCD can capture three stars from the sky and from the three navigation stars we can obtain six navigation factors: three navigation stars' visual magnitudes and their angel distances. The all-sky triangle recognition algorithm has higher recognition ratio than the angel-distance recognition algorithm. But the all-sky triangle recognition algorithm needs long computing time, so the measured attitude is a time-delay attitude which is not accurate.

In this paper, a novel algorithm is proposed to reduce all-sky star pattern recognition's delay time. This algorithm can increase the star pattern recognition rate through reducing the area of star pattern recognition. This algorithm can not only obtain high all-sky star recognition ratio, but also improve all-sky star recognition's time delay.

2 THE ALGORITHM REDUCING STAR PATTERN RECOGNITION'S DELAY TIME

2.1 Start all-sky star pattern recognition

In this step, three navigation stars are captured through star sensor and all-sky star pattern recognition starts in all celestial sphere area. In the course of all-sky star pattern recognition, the following steps 2.2~2.6 are used.

2.2 Determine the moving direction of the star sensor's boresight axis

In the space vehicle rotational phase, star sensor captures the image of star field that is similar to the one represented in Fig. 1. It corresponds to a shutter time[6] of 0.25s and the angular velocity vector, almost orthogonal to the boresight axis and directed toward the lower left corner of the field of view(FOV). The stars appear in this picture as elongated stripes rather than circular spots because their images have had a displacement of several pixels during the image capturing. So the moving direction of the boresight axis can be determined by the direction of the elongated stripe. In the course of star pattern recognition, the starting point of the elongated stripe is extracted from the image as the star's position.

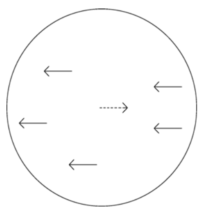

Fig.1 The elongated stripes captured during star sensor rotation phases (The real line denotes the moving direction of the stars. The broken line denotes the moving direction of the boresight axis)

2.3 Determine the positions of stars in the overlapping area in the two star images

Firstly, two star images are captured by star sensor in time t_0 and t_1. And the boresight axis' moving direction line L_{t_0}F is extended to intersect with the first star image's FOV circle at the point F. In the first star image FOV circle, two stars g_4, g_5 nearest to point of intersection F are selected.

Secondly, the two selected stars g_4,g_5 are matched with the stars in the second star image circle using angle-distance match algorithm. If the match is successful, the two selected stars can be determined in the overlapped area of the two star images' FOV circles. The positions of the stars g_1, g_2, g_3, g_4, g_5 are presented in Fig.2, where L_{t_i} is the projection of boresight axis on celestial sphere at time t_i, i=0,1,2, ···.

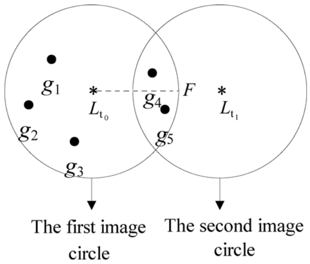

Fig.2 Two stars are selected in the overlapped area of the two star image's FOV circle

2.4 Build star g_1–g_2 coordinate system and star g_4–g_5 coordinate system

The vector of star g_1 is (0, 0, 1) and the vector of star g_2 is (0, $\sin\theta_{12}$, $\cos\theta_{12}$). Let g_i be the star i, i=1,2,···, i is a positive integer. θ_{ij} is the angle between vector $\overrightarrow{og_i}$ and vector $\overrightarrow{og_j}$. So, the star g_1–g_2 coordinate system is established. Celestial sphere is assumed as a unit sphere and all stars in the sky locate at the unit sphere curve. In the same way, the star g_4–g_5 coordinate system can also be established. The vector of star g_4 is (0, 0, 1) and the vector of star g_5 is (0, $\sin\theta_{45}$, $\cos\theta_{45}$). Thus, the vectors of L_{t_0} in the star g_1–g_2 coordinate system and Lt_1 in the star g_4–g_5 coordinate system can be determined. The star g_1–g_2 coordinate system and star g_4–g_5 coordinate system are presented in Fig. 3,4, where O and O' are the positions of space vehicle in the star g_1–g_2 and star g_4–g_5 coordinate system.

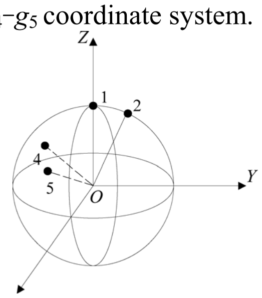

Fig.3 The star g_1-g_2 coordinate system

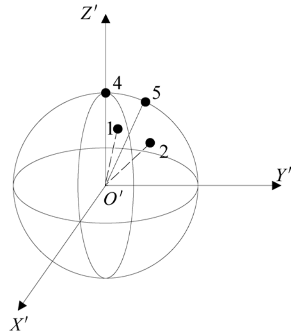

Fig.4 The star g_4–g_5 coordinate system

2.5 Determine the vector $S_{L_{t_0}}^{1-2}$ of L_{t_0} in the star g_1–g_2 coordinate system

Firstly, denote the vector of L_{t_0} in the star g_1–g_2 coordinate system is $S_{L_{t_0}}^{1-2}$=(x_{t_0} , y_{t_0} , z_{t_0}) and the vector of L_{t_1} in the star g_4–g_5 coordinate system is $S_{L_{t_1}}^{4-5}$, where $S_{L_{t_k}}^{i-j}$ presents the vector of the borelight axis' projection L_{t_k} in the g_i–g_j coordinate system, i,j,k=1,2, 3,···. Lt_0 can be presented in Fig.5.

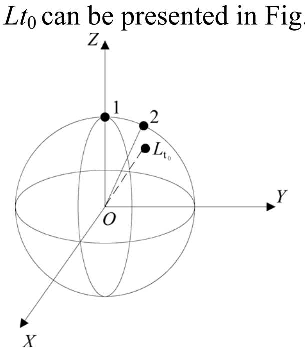

Fig.5 The vector of L_{t_0} in the g_1–g_2 coordinate system

In order to determine the vector $S_{L_{t_0}}^{1-2}$, denote S_1^{1-2}=(x_1, y_1, z_1), S_2^{1-2}=(x_2, y_2, z_2) as the direction cosine vectors of star g_1, g_2 in the g_1–g_2 coordinate system, where S_k^{i-j} presents the vector of the star g_k in the g_i–g_j coordinate system, i,j,k=1,2,3,···. The equations decribing S_1^{1-2}, S_2^{1-2}, $S_{L_{t_0}}^{1-2}$ can be written as:

$$
\begin{aligned}
&S_1^{1-2} = (0,\ 0,\ 1)\\
&S_2^{1-2} = (0,\ \sin\theta_{12}\ ,\ \cos\theta_{12}\ )\\
&S_{L_{t_0}}^{1-2} = (\ x_{t_0}\ ,\ y_{t_0}\ ,\ z_{t_0}\ )\\
&\sqrt{(x_{t_0}^2 + y_{t_0}^2 + z_{t_0}^2)} = 1\\
&S_1^{1-2}\cdot S_{L_{t_0}}^{1-2} = \left|S_1^{1-2}\right|\left|S_{L_{t_0}}^{1-2}\right|\cos\theta_{1L_{t_0}}\\
&S_2^{1-2}\cdot S_{L_{t_0}}^{1-2} = \left|S_2^{1-2}\right|\left|S_{L_{t_0}}^{1-2}\right|\cos\theta_{2L_{t_0}}
\end{aligned}
\tag{1}
$$

The angel $\theta_{12},\theta_{1L_{t_0}},\theta_{2L_{t_0}}$ can be measured by star sensor. So the vector $S^{1-2}_{L_{t_0}}$ can be soluted from the equation (1). In the same way, the vector $S^{(2n)-(2n+1)}_{L_{t_{n-1}}}$ of $L_{t_{n-1}}$ in the star g_{2n}–g_{2n+1} coordinate system also can be get.

2.6 Establish the transfer matrix C^{1-2}_{4-5} between star g_1–g_2 coordinate system and star g_4–g_5 coordinate system

In the star g_1–g_2 coordinate system, the vector of star g_4 can be denoted as S^{1-2}_4 =(x_4, y_4, z_4) , as presented in Fig.6.

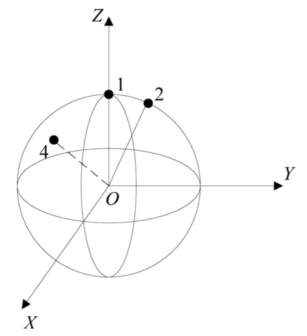

Fig.6 The coordinate of star g_4 in the g_1-g_2 coordinate system

The equations describing the vectors S^{1-2}_1, S^{1-2}_2, S^{1-2}_4 can be written as:

$$\begin{aligned} &S^{1-2}_1=(0,0,1),\ S^{1-2}_2=(0,\sin\theta_{12},\cos\theta_{12})\\ &S^{1-2}_4=(x_4,y_4,z_4),\sqrt{(x_4^2+y_4^2+z_4^2)}=1\\ &S^{1-2}_1\cdot S^{1-2}_4=\left|S^{1-2}_1\right|\left|S^{1-2}_4\right|\cos\theta_{14}\\ &S^{1-2}_2\cdot S^{1-2}_4=\left|S^{1-2}_2\right|\left|S^{1-2}_4\right|\cos\theta_{24}\end{aligned} \tag{2}$$

The angel $\theta_{12},\theta_{14},\theta_{24}$ can be measured by star sensor. So, the vector S^{1-2}_4 can be soluted from equation (2). In the same way, S^{1-2}_5 can be get. Thus, $S^{1-2}_4\times S^{1-2}_5$ can be soluted from S^{1-2}_4 and S^{1-2}_5. In star g_4–g_5 coordinate system, denote S^{4-5}_4=(0,0,1) , S^{4-5}_5= $(0,\sin\theta_{45},\cos\theta_{45})$ as the direction cosine vectors of stars g_4-g_5. Thus, $S^{4-5}_4\times S^{4-5}_5$ can be get from S^{4-5}_4 and S^{4-5}_5. Assume C^{1-2}_{4-5} be the transfer matrix from the star g_4–g_5 coordinate system to the star g_1–g_2 coordinate system, where C^{i-j}_{k-l} presents the transfer matrix from the star g_k–g_l coordinate system to the star g_i–g_j coordinate system. The equation decribing C^{1-2}_{4-5} can be written as:

$$\begin{bmatrix} S^{1-2}_4\\ S^{1-2}_5\\ S^{1-2}_4\times S^{1-2}_5\end{bmatrix}\begin{bmatrix} i\\ j\\ k\end{bmatrix}=\begin{bmatrix} S^{4-5}_4\\ S^{4-5}_5\\ S^{4-5}_4\times S^{4-5}_5\end{bmatrix}\begin{bmatrix} i'\\ j'\\ k'\end{bmatrix} \tag{3}$$

$$C^{1-2}_{4-5}=\begin{bmatrix} i\\ j\\ k\end{bmatrix}\begin{bmatrix} i'\\ j'\\ k'\end{bmatrix}^{\mathrm{T}}=\begin{bmatrix} S^{1-2}_4\\ S^{1-2}_5\\ S^{1-2}_4\times S^{1-2}_5\end{bmatrix}^{\mathrm{T}}\begin{bmatrix} S^{4-5}_4\\ S^{4-5}_5\\ S^{4-5}_4\times S^{4-5}_5\end{bmatrix} \tag{4}$$

Thus, through the transfer matrix C^{1-2}_{4-5}, the vector of L_{t_1} in the star g_1–g_2 coordinate system can be determined, which can be written as:

$$S^{1-2}_{L_{t_1}}=S^{4-5}_{L_{t_1}}C^{1-2}_{4-5} \tag{5}$$

2.7 After all-sky star pattern recognition is completed, determine the vector $S^E_{L_{t_n}}$ of boresight axis' projection in time t_n in the celestial sphere equatorial coordinate system

Firstly, step 2.6 is repeated until all-sky star pattern recognition is completed in time t_n. Thus the transfer matrixes $C^{(2n)-(2n+1)}_{(2n+2)-(2n+3)}$ are established , n=2,3, ···, where g_{2n+3} is the last star in the last overlapped area, as presented in Fig.7.

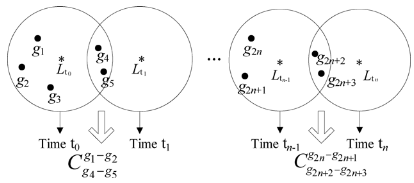

Fig.7 The transfer matrix $C^{g_{2n}-g_{2n+1}}_{g_{2n+2}-g_{2n+3}}$

Secondly, when all-sky star pattern recognition is completed, the vectors S^E_1 and S^E_2 are obtained by star sensor , where S^E_i presents the vector of star g_i in celestial sphere equatorial coordinate system, i=1,2,3,···. Thus, when the vectors S^E_1 and S^E_2 are obtained, use the method of step 2.6 and the transfer matrix C^E_{1-2} can be obtained.

Thirdly, use the method of step 2.5 and the vector $S^{(2n+2)-(2n+3)}_{L_{t_n}}$ can be obtained. So, the vector $S^E_{L_{t_n}}$ can be written as

$$S^E_{L_{t_n}}=C^E_{1-2}C^{1-2}_{4-5}C^{4-5}_{6-7}\cdots C^{(2n)-(2n+1)}_{(2n+2)-(2n+3)}S^{(2n+2)-(2n+3)}_{L_{t_n}} \tag{6}$$

Thus, the coordinate of boresight axis' projection in time t_n in celestial sphere equatorial coordinate system can be obtained.

2.8 Start localized star pattern recognition in the circle area $G_{L_{t_n}}$ of sky. The circle area $G_{L_{t_n}}$ centred at $S^E_{L_{t_n}}$ whose radius is 2R, where R is the radius of the star sensor's lens

Firstly, the Stars g_A, g_B, g_C can be captured in time t_n by the star sensor. And all candidate stars in the circle area $G_{L_{t_n}}$ are extracted from the star catalog stored in the computer of the space vehicle.

Secondly, the localized star pattern recognition is started to recognize the Stars g_A, g_B, g_C from the candidate stars in the circle area $G_{L_{t_n}}$, as presented in Fig.8.

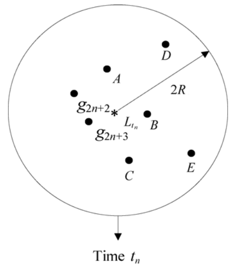

Fig.8 The stars g_A, g_B,g_C in time t_n

Because the localized star pattern recognition is completed in very short time, the attitude obtained by the localized-sky star pattern recognition is more precise than by the all-sky star pattern recognition.

3 SIMULATION RESULTS

In the course of simulation, standard celestial star catalog 'Skycharts' and a software are used to simulate the space vehicle's flight are selected. The stars in Skycharts are brighter than 6.5 magnitude. The number of the stars in Skycharts is 13332. In the simulation, the algorithm reducing delay time is compared with all-sky triangle star pattern recognition algorithm. The results of the simulation are presented in Fig.9~12.

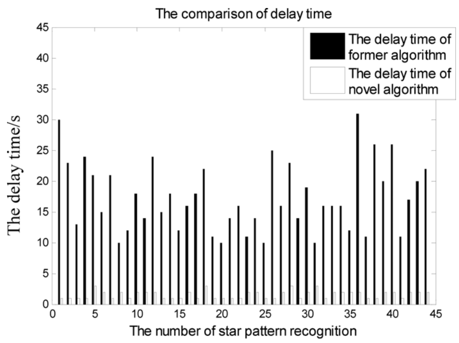

Fig.9 The comparison of delay time

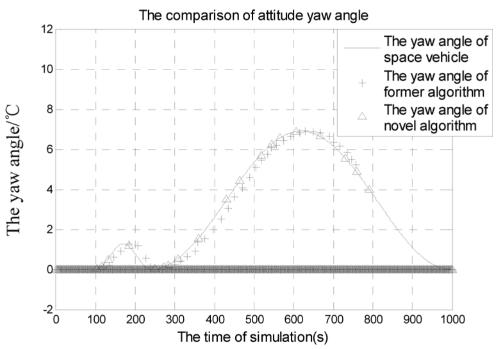

Fig.10 The comparison of attitude yaw angles

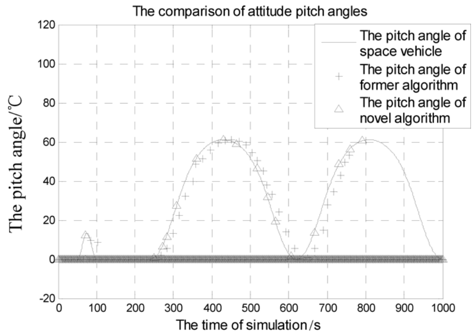

Fig.11 The comparison of attitude pitch angles

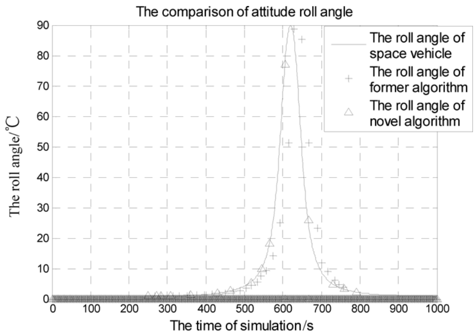

Fig.12 The comparison of attitude roll angles

From the above Fig. 9~12, we can conclude that the novel algorithm needs less time to complete recognition than traditional all-sky triangle star pattern recognition algorithm. And the attitude measured by the novel algorithm has more precision than traditional all-sky triangle star pattern recognition algorithm.

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