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Single Star Identification and Attitude Determination in Tracking Mode

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Abstract: The autonomous star trackers are among the most attractive attitude sensors, as they are capable to provide three-axis attitude information with high accuracy. Autonomous star tracker's basic software algorithms include Star image centroiding, Star Pattern Recognition (SPR) and attitude determination. In the last few decades many SPR algorithms have been presented, almost all of them need at least two or three stars in star image, for successful SPR. Similarly almost all of the existing attitude determination algorithms need at least two identified stars in the star image. In the worst case if there is only one star in the image then SPR and hence the attitude determination becomes a problem. Just star magnitude alone can not be used to identify one star reliably due to poor magnitude measurement accuracy. However the scheme of automatic pattern recognition based on predictive centroiding in tracking mode, can be used to identify a single star. The position information of this identified single star can be used to form one or more empirical image stars from the reference catalog stars, for attitude determination. In this paper the problem of single star identification and attitude determination is addressed. Simulation results show that the proposed method to calculate the attitude has good accuracy, and it depends on the star tracker calibration and centroiding accuracies. This scheme is particularly useful in case where single star is identified and no other scheme can be used.

Keywords: Star tracker, image centroiding, attitude determination, Pattern recognition, Autonomous navigation.

1. INTRODUCTION

Currently available star trackers are capable of providing very high accuracy (of few micro-radians) attitude determination without prior knowledge, recursive on-orbit calibration and rapid stellar update rate, thus making them devices of choice especially for small satellites. It is anticipated that a small, high performance star tracker could capture 80-percent of the world's market for satellite attitude and pointing sensors. This is primarily due to simple integration of the self-contained autonomous unit and low cost compared with other instruments for attitude determination. Typical star tracker hardware is composed of an electronic camera, connected to a microcomputer. Primary software algorithms include functions for image centroiding, SPR and attitude determination. Locating the positions of star centers in the star image is called image centroiding as in [1]. SPR involves matching the stars in the photograph to a data base of known stars, so that individual star can be identified. Usually star trackers are selected so that a sufficient number of stars fall with in the Field of View FOV of the camera, in any random boresight direction of the star tracker. At least three stars are necessary for any SPR scheme. About four to five stars are recommended for sufficiently reliable pattern recognition to suppress the false stars or spikes [2,12]. As stars are not distributed homogeneously on the sky; there are many stars in the galactic plane and relatively fewer at the galactic poles. Therefore, there are areas on the sky, where there are not enough stars for some star trackers to operate [3] and this leads to the possibility that there can be some chances that a star image may have less then three stars. In the worst case, if unfortunately there is only one star present in the star image, then no pattern recognition scheme exists to identify it. The only possibility is to match the magnitude of the observed star with catalog stars. But magnitude measured by a tracker is reliable to at best 0.2 M (visual magnitude), and more often 0.5 M. This is because the catalog magnitude system does not follow the spectral response of any star tracker [4]. The difficulty with matching magnitude is that near-perfect noise rejection is required. The number of stars of a given magnitude increase dramatically with magnitude and the fraction of stars with in a relatively small magnitude range increases as the magnitude increases. Thus visual magnitude can not be used as the sole parameter in matching star [5]. In initial acquisition mode, a single star in an image cannot be identified with a sufficiently reliable accuracy by any means. On the other hand, if initial attitude is known, as in tracking mode, it is easy to apply automatic SPR scheme to identify even a single star.

In normal tracking mode, the image frame rate, for active pixel sensor APS is relatively high, varying from a few frames per second (fps) to hundreds of fps. Therefore a typical star is imaged many times before it leaves the star tracker FOV. For virtually all anticipated missions change in angular position of star centers in sequential images is less than 10^{-3} radians. In view of these considerations a predictive centroiding scheme is suggested in [6]. In this paper, the angular positions of the stars are predicted from the rate gyro or by using previous star locations. In the fast predictive centroiding scheme, the information of boresight direction of the star tracker is used to predict the positions of the stars in the next image frame, for a calibrated camera in tracking mode. The process of single star identification is explained in the next section.

2. SINGLE STAR IDENTIFICATION USING AUTOMATIC SPR SCHEME

Automatic pattern recognition scheme, based on predictive centroiding in tracking mode, is founded on the fact that for high frame rate imagers, star centers move slowly between sequential image frames. This scheme makes use of the knowledge of boresight direction (α_0, δ_0) of the star tracker (right ascension and declination angles respectively) for predicting regions of star locations in next frame. For a given boresight direction of a calibrated camera, a suitable number of bright stars, with inertial coordinates (α_i, δ_i), are picked from the star catalog [7] with in the field of view FOV of star tracker. These coordinates (α_i, δ_i) are transformed into image coordinates as in [8] and rounded. These rounded coordinates predict the centers of candidate regions (masks), where stars are to be searched in the next image and centroided, with centroiding coordinates (x_i, y_i). By keeping track of the inertial coordinates (α_i, δ_i) and the respective centroided coordinates (x_i, y_i), SPR is automatically done. After attitude determination, the boresight direction is updated by using current attitude and above process is repeated for incoming frames.

3. ATTITUDE DERMINATION BY SINGLE STAR VECTOR OBSERVATION

Attitude determination uses unit vectors of the stars in body frame and the corresponding unit vectors in inertial frame. These unit vectors are used in one of several different algorithms to determine the attitude in the form of quaternion, Euler angles, or a rotation matrix. All the algorithms need at least two vectors to estimate the attitude; because it takes three independent parameters to determine the attitude and that a unit vector is actually only two parameters because of the unit vector constraint. Thus the system becomes underdetermined in case of one measurement [9].

To get rid of this worst case problem, the knowledge of one identified star position can be used to make one or more empirical image star measurements, under the assumption that star camera is well calibrated and the centroiding errors are small. The difference (Δx, Δy) between the image and catalog star coordinates of the identified star is calculated as shown in Fig. 1, where $C(x, y)$ and $I(x, y)$ represent the catalog star and image coordinates respectively. One or more stars from the star catalog are picked (from the list of inertial coordinates (α_i, δ_i) and transformed into image coordinates) within the FOV of the star tracker. This difference or shift (Δx, Δy) is added to the coordinates of these stars which can be regarded as the empirical image stars. Then these empirical image stars can be used, along with the one identified star, for the attitude determination. The small errors in the attitude matrix A introduced by empirical image stars can be compensated to some extent by using different weighting factors for observed star and the empirical stars, while using QUEST method[10].

4. SIMULATION AND RESULTS

Table. 1 shows the inertial coordinates, the transformed image coordinates and the coordinates of the centers of predicted regions or masks, for the next frame, where stars are to be searched. The empirical image formed by these transformed coordinates is shown in Fig. 2. The next star image taken by a star tracker simulator [11] is shown in the Fig. 3, and the same image with a single star is shown in Fig. 5. The results of the automatic pattern recognition scheme (as described above) are shown in Table. 2 and Fig. 3 shows the centroiding results. The process of attitude determination from this single identified star as defined in third section is explained here by the following example.

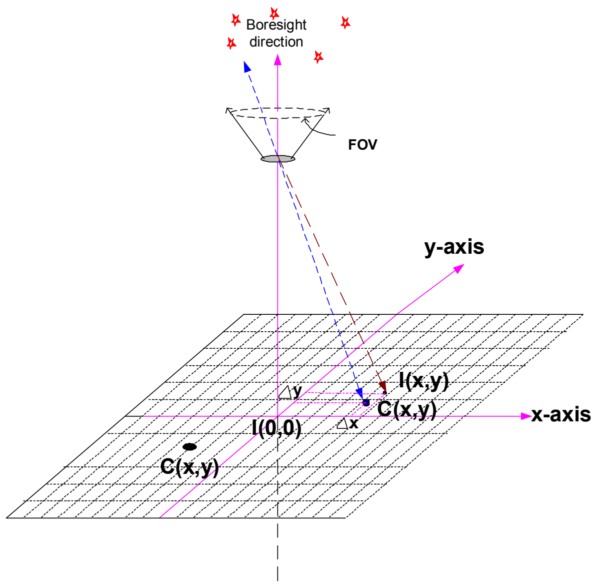

Fig. 1 Calculation of shift Δx and Δy

Table. 1 the inertial catalog coordinates, transformed image coordinates and predicted regions coordinates for six bright stars from the star catalog with in the FOV along a given boresight direction of star tracker

S/No	(α_i, δ_i)	(x_i, y_i)	Predicted(x_i, y)$_i$
1	(89.7066, 0.55297)	(254.82, 344.44)	(255, 344)
2	(89.3553, 0.02754)	(219.65, 289.04)	(220, 289)
3	(93.1858, -2.5048)	(610.23, 26.297)	(220, 289)
4	(87.6250, 2.0247)	(42.545, 498.05)	(610, 26)
5	(88.6834, 0.9686)	(150.77, 387.45)	(43, 498)
6	(89.4771, 1.22431)	(231.02, 414.77)	(151, 387)

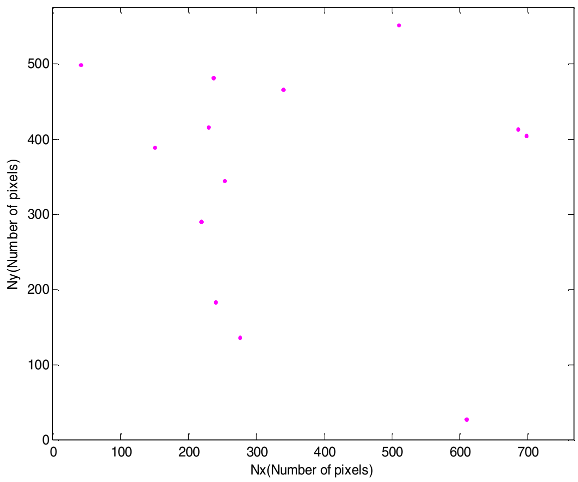

Fig. 2 Empirical star image formed from catalog stars with in FOV in the given boresight direction

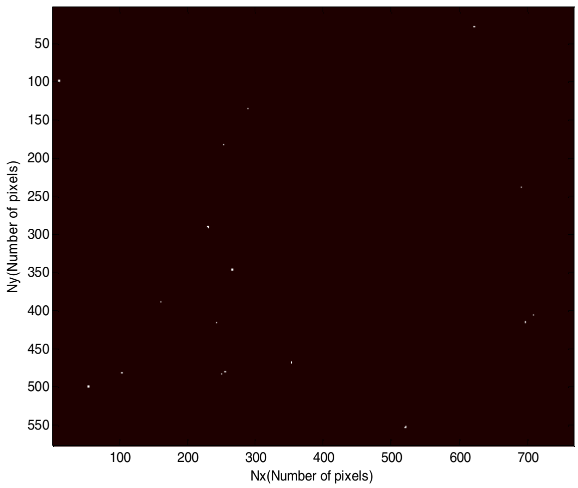

Fig. 3 star image taken by a star tracker simulator

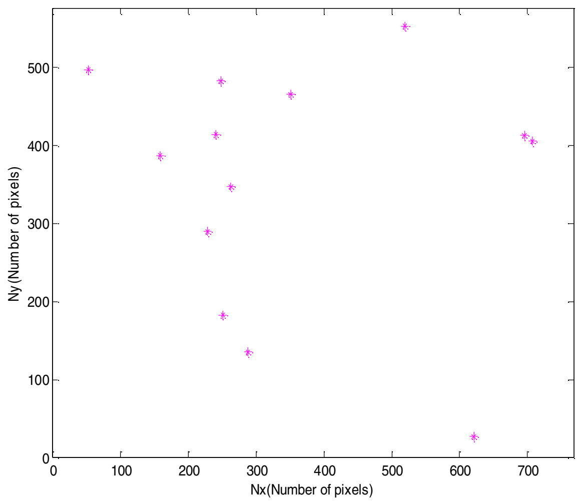

Fig. 4 Centroiding results of the given star image

Table. 2 Results of automatic SPR algorithm showing inertial coordinates and the corresponding centroidded coordinates

S/No	Inertial coordinates (α_i, δ_i)	Centroiding results (x_i, y_i)
1	(89.7066, 0.55297)	(264.11, 345.19)
2	(89.3553, 0.02754)	(229.16, 289.42)
3	(93.18585, -2.50481)	(620.99, 27)
4	(87.62505, 2.02472)	(52.756, 497.83)
5	(88.68345, 0.96861)	(159.97, 387.32)
6	(89.4771, 1.22431)	(241.62, 414.63)

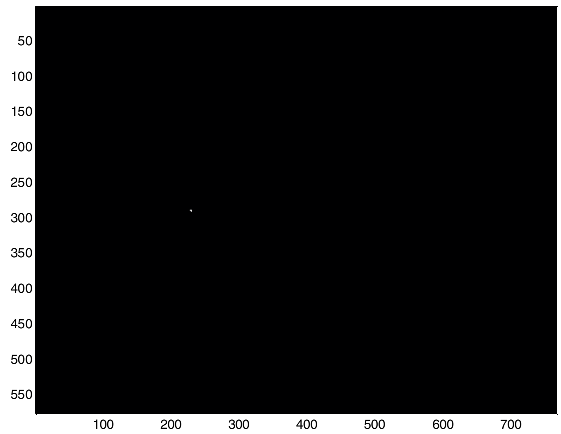

Fig. 5 Single star image taken by star tracker simulator

Example:-

Case 1: Attitude determination from two identified stars

Consider the first two identified stars as given in table 2 and their corresponding unit vectors are given bellow.

$$r_1 = \begin{bmatrix} 0.005121 \\ 0.999940 \\ 0.009651 \end{bmatrix} \quad b_1 = \begin{bmatrix} 0.011976 \\ -0.02364 \\ 0.999613 \end{bmatrix}$$

$$r_2 = \begin{bmatrix} 0.011252 \\ 0.999937 \\ 0.000481 \end{bmatrix} \quad b_2 = \begin{bmatrix} 0.0002935 \\ -0.038253 \\ 0.9994907 \end{bmatrix}$$

Where r_1, r_2 are unit vectors in reference and b_1, b_2 are unit vectors in body frame. Using QUEST [10] method, the attitude matrix is given bellow.

$$A = \begin{bmatrix} -0.99628 & 0.013861 & 0.085026 \\ 0.084471 & -0.03668 & 0.99575 \\ 0.016921 & 0.99923 & 0.035372 \end{bmatrix}$$

Case 2: Attitude determination from a single identified star

Consider star 1 is identified from the Fig. 4. The shift of the identified star center from the corresponding reference star center in image coordinates is calculated as bellow.

$$\Delta x = 264.1069 - 254.823628 \approx 9.28328$$

$$\Delta y = 345.19025 - 344.43765 \approx 0.752600$$

Now to form one or more empirical image stars, one can pick one or more of reference stars from Table. 2 and transform into image coordinates and add the above shift. Consider second star is taken from the Table. 2 then the body or image coordinates of the second empirical star are calculated as bellow.

$$x_b = 219.6527 + \Delta x$$

$$y_b = 289.0390 + \Delta y$$

The unit vectors of the first identified star and the second empirical image star, are given bellow.

$$r_1 = \begin{bmatrix} 0.005121 \\ 0.999940 \\ 0.009651 \end{bmatrix} \quad b_1 = \begin{bmatrix} 0.011976 \\ -0.02364 \\ 0.999613 \end{bmatrix}$$

$$r_2 = \begin{bmatrix} 0.011252 \\ 0.999937 \\ 0.000481 \end{bmatrix} \quad b_2 = \begin{bmatrix} 0.0003692 \\ -0.038245 \\ 0.9994892 \end{bmatrix}$$

Again using QUEST method the attitude matrix is calcu lated as given bellow.

$$A' = \begin{bmatrix} -0.99652 & 0.013915 & 0.082138 \\ 0.081583 & -0.036653 & 0.99599 \\ 0.01687 & 0.99923 & 0.03539 \end{bmatrix}$$

The Euclidian norm of the error matrix is

$$\left| A' - A \right| = 0.00289$$

It can be shown that this error stems from the centroiding errors and the star tracker calibration errors. Thus errors in the attitude matrix calculated by this scheme can be minimized by good calibration and centroiding accuracies.

5. CONCLUSION

Usually for SPR at least two or three stars are required to match the observed stars with the reference catalog stars. In the worst case, if single star is observed then automatic pattern recognition scheme in tracking mode, can be used to identify it. Almost all the attitude determination algorithms need at least two identified stars for attitude determination. This paper describes a novel method to calculate the attitude when only a single star is observed. Simulation results show that calculated attitude has good accuracy and depends on the star tracker calibration and centroiding accuracy. For moderately calibrated camera with high centroiding accuracy this scheme can be used particularly when a single star is observed in tracking mode.

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