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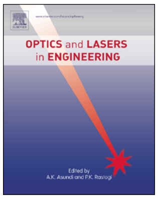

Review

Novel autonomous on-orbit calibration method for star sensors

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ABSTRACT

Autonomous on-orbit calibration is critical for the development of star sensors. However, simultaneous estimation of optical parameters and star sensor distortion are a challenging task. The existing methods either aim at estimating the optical parameters (the focal length and the principal point) and ignoring the lens distortion, or first estimating the optical parameters, and then estimating lens distortion. These methods ignore the mutual influence between the optical parameters and lens distortion. To solve this problem, we used a non-linear optimization technique to simultaneously obtain the optimal performance of different star sensor parameters. First, the initial estimation of the optical parameters was obtained by using the maximum likelihood estimation method. Then, the linear least-squares solution was adopted to the initial estimate of the star sensor lens distortion. Finally, a globally optimal solution was used to refine all of the star sensor camera parameters. Comparing with the least-squares method and Samaan's method under the same condition, the simulation results demonstrate that the proposed method is more robust and can achieve remarkable improvement in the star sensor calibration accuracy. In addition, the test results of the real nighttime images show that the calibration method can significantly improve the star identification performance.

Contents

1. Introduction

With fast development of autonomous spacecraft navigation technology, significant attention has been devoted to developing methods that use star sensors to determine the spacecraft attitude.

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A star sensor identifies the observable stars within its field of view (FOV) by employing several star identification algorithms [1,2]. It matches the direction vectors of stars within its FOV with the inertial cataloged vectors of stars to estimate the spacecraft attitude matrix [3,4]. The accuracy of attitude estimation mainly depends on the accuracy of the star sensor's optical parameters, including the focal length f and the principal point (x_0, y_0), which are used to calculate the direction vectors of stars within the sensor's FOV [5]. Moreover, the star sensor's optical system generates some inherent distortion, owing to which the star point image within its FOV has asymmetrical shape and heterogeneous energy distribution [6]. Consequently, the accuracy of the star centroid estimation is directly impacted, which in turn affects the accuracy of attitude determination and star identification [7]. Therefore, to implement the star identification algorithm and to determine the attitude accurately, it is essential to estimate the star sensor's optical parameters and correct the star image distortion. Ground-based testing has been widely used for initial calibration to estimate the star sensor's optical parameters [8,9]. However, instrument aging, intense vibration during the launching process, as well as temperature effects, are likely to change the sensor's parameters and yield systematic errors [8,10]. To obtain precise attitude estimations, star sensors should be recalibrated while orbiting. Therefore, on-orbit calibration algorithms are desired for achieving higher accuracy of the attitude estimation.

Two types of approaches (attitude-dependent and attitude-independent) have been developed for on-orbit calibration of star sensors. In the attitude-dependent approach, the estimated attitude matrix of a star sensor is used to estimate the star sensor's principal point and focal length [11]. However, the error in the star sensor's attitude estimation inevitably affects the calibration. In the attitude-independent approach, the inter-star angles are utilized to estimate the sensor's parameters. The attitude-independent approach depends on the calibration results while the attitude-dependent approach does not, indicating that the latter approach is apparently superior to the former approach [11]. Most attitude-independent methods utilize the star coordinates in the star image with the corresponding unit vector in the inertial coordinates system to estimate the sensor's parameters. However, using these methods [12,13] requires a large amount of information for the batch solution, which represents a burden for on-board implementation as a spacecraft should have large memory capacity for storing multiple images.

John Junkins has proposed an autonomous star sensor calibration method assuming that the angle between the unit vectors of two stars is invariant both in star image coordinates and in inertial coordinates systems [11,14]. Based on this assumption, Samaan et al. [15] has proposed a star sensor calibration algorithm that combines the least squares algorithm with a recursive Kalman filter. In this approach, the least-squares method is used to estimate the initial values of the principal point and the focal length. Then, the initial estimates are used as an input to the Kalman filter for optimization. Finally, the optimized parameters are used to obtain the lens distortion of a star sensor. However, in Samaan's algorithm a star sensor's optical parameters are estimated assuming that the star sensor has no lens distortion. Obviously, errors arise in the optical parameters estimation. Moreover, the lens distortion estimation is not accurate because it uses the optical parameters that contain errors. The method ignores the mutual influence between the optical parameters and the lens distortion. Woodbury and Junkins [16] proposed a recursive least squares algorithm to estimate the pinhole model parameters by using the dot product method and the scalar product method. This method only estimates the pinhole parameters of star sensors and ignores the lens distortion estimation, which reduces the position accuracy of the star centroids.

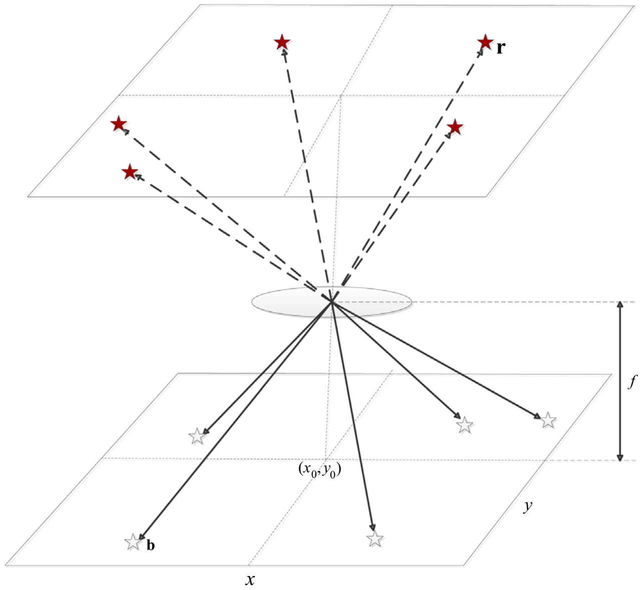

Fig. 1. Stars projection model in the CCD plane.

Based on John Junkins's assumption, a novel optimization method for autonomous on-orbit calibration of a star sensor using an non-linear optimization technique is developed in this paper. The initial estimations of the principal point and the focal length are conducted by using the maximum likelihood estimation method. By using the initial estimates of the optical parameters, we adopt the linear least squares solution to treat the star sensor distortion. Because the initial estimates of the optical parameters and the distortion are given, a globally optimal solution is used to refine all of the star sensor parameters. Unlike Samaan's and the least squares algorithm, our method takes into account the mutual influence between the optical parameters and the lens distortion. Our proposed method allows simultaneously estimating the optical parameters and the distortion of a star sensor, which can yield more accurate parameter estimation for star sensors. The results of the mutual influence tests demonstrate that our proposed method yields significantly improved star sensor's calibration accuracy. Moreover, the simulation results show that much better star sensor calibration can be realized by using our algorithm compared with the other two algorithms.

The paper is organized as follows. In Section 2, the algorithm is described in detail, including the initial estimation of the principal point and the focal length, the treatment of radial distortion, the maximum likelihood estimation for refining all parameters, and the summary of our calibration algorithm. In Section 3, the five stages of the simulation and analysis of the results are described. First, the star sensor calibration procedure is simulated. Second, the mutual influence between the optical parameters and the lens distortion is tested. Third, we compare the estimation results of the different algorithms (the least-squares algorithm, Samaan's algorithm, and our proposed algorithm) with different initial values of the star sensor parameters. Then, the residual distortion estimations of the three algorithms are analyzed. Finally, the robustness of the calibration results of the three algorithms with respect to the centroid noise is tested. Because it is currently difficult to obtain space images, we describe the acquisition of nighttime sky images that we used to test our calibration algorithm in Section 4. The paper ends with some concluding remarks in Section 5.