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Autonomous positioning utilizing star sensor and inclinometer

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A B S T R A C T

An autonomous positioning method independent of satellites is introduced in this study. When the location of vehicles cannot be covered by navigation satellites or the signals of navigation satellites are denied or under disturbance, the presented method can offer accurate position information for the vehicles. The designed system contains two parts: a star sensor that determines the attitude of the vehicle through starlight imaging, and a dual-axis inclinometer that measures the tilt angle between the vehicle and the horizontal plane. In addition, a precision clock is needed to provide current time and synchronize the data from the star sensor and the inclinometer. Base on principle of star sensor and inclinometer, the measurement model of the system is established and error analysis is carried out. It is noticed that the systematic error caused by the misalignment of the star sensor and the inclinometer influences the positioning accuracy significantly. In order to eliminate this systematic error, a calibration method based on QUEST (QUaternion ESTimator) is proposed to obtain the misalignment matrix and refine measurement model. The night sky experiments prove the proposed calibration method is effective, and the autonomous positioning system can achieve accuracy of 20–70 m in distance by continuous measurement in several minutes.

1. Introduction

Generally speaking, the location of a vehicle is determined by its navigation system. In some cases, the system may lose its connection with the ground-support equipment; thereby a completely autonomous navigation system is needed. The two dominating methods of autonomous navigation are inertial navigation and celestial navigation. Though inertial navigation is of autonomy and good short-term accuracy, its usage as a stand-alone navigation system is limited due to the time-dependent growth of the inertial sensors imperfections [1]. Celestial navigation, which is based on astronomical observations, is becoming a preferable navigational choice [2]. It is characterized by its high navigation accuracy, no time accumulation error, and strong anti-interference ability. Over the past decades, celestial navigation has been developing rapidly due to its wide application. More and more vehicles, such as spacecraft, missile and vessel, tend to adopt celestial navigation to realize autonomous navigation. Therefore, many countries with developed military are investing a lot of human and material resources to research and develop celestial navigation owing to its irreplaceable applications in military affairs [3].

Celestial sensors are the core components of celestial navigation. Among all the celestial sensors, star sensors can supply the most accurate attitude information [4,5] and have been widely used to determine the attitudes of vehicles (e.g., spacecraft [6], missiles [7], and ships [8]). However, a star sensor could not accomplish location determination while used alone [9]. If there is a feasible method which can realize attitude determination and position localization simultaneously, the costs of volume, weight, and power consumption for navigation will be decreased significantly. Several efforts have been made in this field. Some researchers used an earth sensor or a magnetometer as horizon reference for star sensor, thus the location of the vehicle can be obtained by information fusion. In [10], an autonomous navigation method for high orbit satellite using star sensor and ultraviolet earth sensor were provided. The position accuracy of the method is within 300 m. In [11], an autonomous navigation scheme for small satellites based on geomagnetic and starlight is described. The simulation results show that the root mean square (RMS) of position errors reaches 1.3 km. It can be seen that these methods that adopt star sensor and earth sensor or magnetometer could not reach satisfactory accuracy. Some other researchers applied multi-FOV (Field Of View) star sensors to determine the position of space vehicles. In [12], a star sensor with two FOVs was utilized, with which the stellar starlight and the earth limb were imaged respectively. The accuracy of this method reaches 190 m (1σ).

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However, there are some other problems when adopting multiple FOVs. For instance, the fixing errors in equipment are difficult to be calibrated [13]. Other researchers employ occultation measurements to determine the position. In [14], star sensor I was used to take a photograph of the non-refracted stars, and star sensor II was used to capture the refracted starlight passing through the atmosphere. A positioning accuracy of better than 100 m can be achieved for a low-Earth-orbit (LEO) satellite. Though its precision is high, it is a method with less available observable objects and low robustness. Still, some researchers tend to adopt INS/CNS (Inertial Navigation System/Celestial Navigation System) integrated navigation algorithm, because of its higher accuracy compared with other methods. In [15], a two-mode INS/CNS navigation method for Lunar rovers was presented. The ground test showed that Lat/Long (abbreviation of latitude and longitude) errors within 50 m in distance can be achieved. In [16], an integrated navigation method of the strapdown inertial navigation system (SINS) using a star sensor was presented. The accuracy of the integrated navigation algorithm is obviously higher than other methods. However, the system needs strict calibration to correct the installation errors between INS and star sensors [17]. In addition, the method costs plenty of hardware and software resources because of its complicated system and algorithm.

Among all the applications of star sensors in aerospace, the majority of near-earth navigation methods utilize star sensor to image starlight, use certain device as horizon reference to measure the information of geographic horizon, establish orbital dynamics model, and adopt advanced filtering technology to estimate the location of the vehicle. The applications in aviation, nautical navigation, and ground navigation, have always been suffering from the limitation of night-only operation. Nevertheless, with the development of the all-day star sensors [18,19], the autonomous positioning method based on star sensor has great development prospect in these fields. Equipment in aviation, nautical navigation, and ground navigation quite possibly has no certain orbits, which means that navigation methods based on orbit dynamics are no longer applicable and the devices used as horizon reference to measure the earth limb cannot work anymore. Consequently, some researchers attempt to utilize other devices to provide information of geocentric vector. Then position determination can be achieved through certain information fusion methods. These devices could be gravity pendulums [20], laser levelers [21], and inclinometers [22,23]. In these cases, the measurement accuracy of the star sensor and the geocentric vector sensor, along with the systematic error caused by the misalignment between the two sensors, will greatly influence the final positioning accuracy.

In this paper, an autonomous location determination method, which employs a star sensor and a dual-axis inclinometer, is proposed. By calibrating the misalignment matrix between the two sensors, the proposed method has the advantages of easy usability and high positioning accuracy. It can be used as the autonomous navigation system of aviation, nautical navigation, and ground navigation. In addition, it can be also used as the autonomous navigation system in cases of Lunar rover and Mars rover.

The remainder of this paper is organized as follows: In Section 2, the comprehensive measurement model establishment is outlined. To refine the model, a cone error model (CEM) and a calibration method based on QUEST (QUaternion ESTimator) are also proposed in Section 2. The experiment system configuration is described in Section 3. In Section 4, the night sky experiment is conducted and the results are presented. Conclusions and discussions are drawn in Section 5.

2. Measurement model & error analysis

2.1. Measurement model

Five reference frames are described in Fig. 1 to illustrate the positioning principle. F_E is Greenwich reference frame, origin O is at the geocenter, Z_E axis points to the North Pole, X_E axis points to the Greenwich Meridian; F_I is Earth Centered Inertial reference frame, origin O is at the geocenter, Z_I axis points to the North Pole, X_I axis points to the vernal equinox; F_B is star sensor measuring reference frame, origin O' is the intersection of the optical axis and the imaging plane, and the directions of X_B axis and Y_B axis depend on the position of the image sensors, the direction of the Z_B axis is the same as the star sensor's optical axis; F_Q is inclinometer measuring reference frame, X_Q axis and the Y_Q axis are the directions of two measuring axes; F_H is horizon reference frame

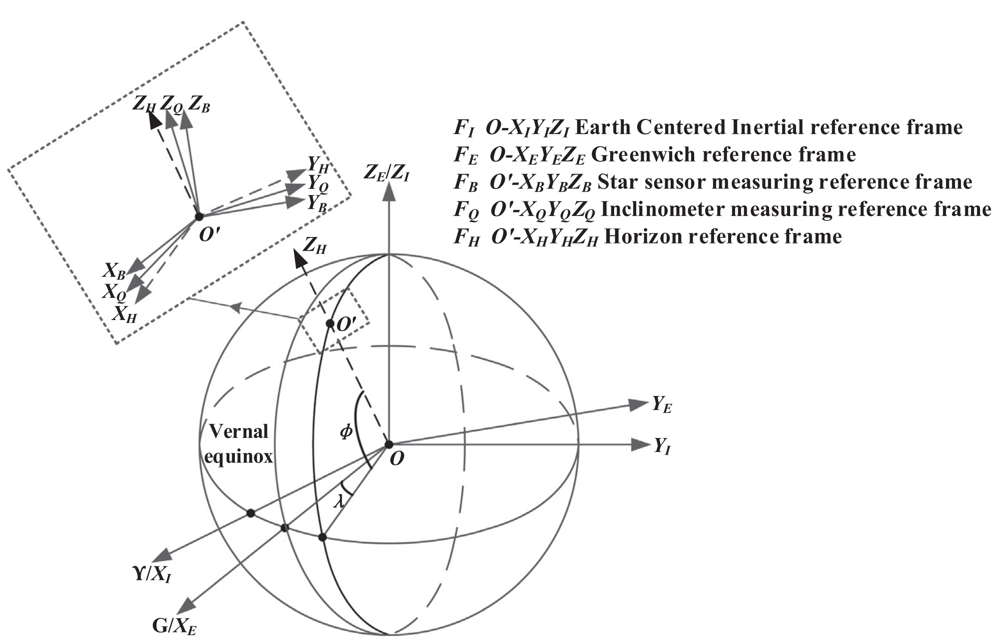

Fig. 1. Measurement model and reference frames.