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Study on command attitude law for refracted starlight observation in SINS/RCNS integrated navigation

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Abstract

To ensure the validity of refracted starlight observation, a command attitude law for maneuver is built for strapdown star sensor. The constraint relations between the relative attitude angles and the constant boresight apparent height are first established, by which attitude control command is generated, and the following attitude maneuver enables the star sensor FOV (Field of View) to keep covering the stratosphere during the midcourse. The simulating environment is set up, which involves the schema trajectory designing, the simulating algorithm of refracted star map and the modeling of the complete autonomous SINS/RCNS (Strapdown Inertial Navigation System/Refraction Celestial Navigation System) integrated navigation system. In the SINS/RCNS integrated navigation, the star sensor boresight is directed to the stratosphere in a suitable height with the command attitude law. The test simulation results show that the SINS/RCNS system prominently increases the precision of position and velocity at reentry point by 87.8% and 39.5% respectively than the sole SINS, and using of wide FOV helps to increase the positioning accuracy.

Keywords: Star sensor; Stellar refraction; Command attitude; Attitude maneuver; Starlight positioning

1. Introduction

The SINS/RCNS (Strapdown Inertial Navigation System/Refraction Celestial Navigation System) integrated navigation device is composed of an IMU (Inertial Measurement Unit) and a star sensor. The sole star sensor undertakes two roles: one is the normal starlight attitude determination that is used to compensate for gyro drift, the other is the refracted starlight observation to realize spacecraft positioning through information fusion technology, so it is autonomous and complete. The research on RCNS can be traced to the Apollo plan in the 1960s (Lillestrand and Carroll, 1963). Then in the 1980s, Draper Laboratory proposed the starlight refraction model and proved the feasibility of starlight refraction autonomous navigation in theory (Gounley et al., 1984; White et al., 1985). It was not until the 1990s that engineering application of RCNS technology came true in the MADAN (Multi-mission Attitude Determination and Autonomous Navigation) system in America, with a positioning accuracy better than 100 m (Anthony, 1992).

Atmospheric refraction modeling is a key problem. The primitive United States Standard Atmosphere 1976 was derived from the observation data of a sky-cruising experimental satellite. Since then some improved empirical models such as NRLMSISE-00 came into being with increased precision on the atmospheric modeling (Picone et al., 2002). However, NRLMSISE-00, which is mainly about thermosphere, is not suitable for refracted starlight positioning. The most practical refraction model used in RCNS so far is still the one from the atmosphere model 1976 (Guoquan et al., 2005). And later, an atmosphere refraction model with a rather high accuracy for the 20–50 km

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stratosphere was put forward (Xinlong and Shan, 2009; Xinlong et al., 2010).

As for filtering algorithms, unscented Kalman Filter (UKF) is generally used to solve the non-linear system problem (Xiaolin and Jiancheng, 2007). An implicit UKF (IUKF) and the method of observability analysis on the implicit measurement model were proposed (Xiaolin et al., 2016). A fault-tolerant federated unscented Kalman filtering (FFUKF) algorithm was constructed, which improved the navigation accuracy, reliability, information utilizing efficiency and the applicable scope of the integrated model, though systematic complexity is increased (Shujie et al., 2016).

In system scheme design, Ning proposed a double star sensor configuration. Star sensor A observes direct starlight and complete attitude determination, while star sensor B observes the stratosphere (Xiaolin et al., 2012, 2013), whose attitude can be transferred from the former's by the installing matrix. Taking the calculated attitude of sensor B as a reference, the star map and its projected centroids regarding sensor B can be simulated assuming that there is no refraction effect. Then the refraction angle can be finally calculated according to the deviation of each pair (the refracted real star spot and the non-refracted projected one). Though this scheme sounds reasonable, it is of high cost and complexity. To overcome this shortcoming, Qian put forward a sole star sensor configuration scheme. Both the refracted and the direct stars share the common FOV (Field of View) (Huaming et al., 2014). The non-refracting zone of FOV is used to determine the attitude, while the refracting zone, virtually a mapped stripe of the stratosphere in FOV, is used to capture the refracted stars. Although Qian's scheme is simple, it has to rely on the attitude control system, which operates to keep the star sensor to stare at the stratosphere, so is Ning's scheme.

So far, studies related to RCNS, including the theories, the modeling and the algorithms, have been almost fully developed. The next focus should be shifted to the application research. The first thing or the precondition is that only when the star sensor FOV contains the stratosphere will the target refracted stars be captured, which is the necessity for attitude control or maneuver. Perhaps it seems to be difficult for a satellite with designated orbit and nadir pointing attitude, but to the other types of spacecraft like a maneuverable ballistic missile in the midcourse, the attitude maneuver is precisely a typical operating condition (Weiguo et al., 2006). Therefore, how to satisfy this precondition is worthy of further research. In this paper, a command attitude law is presented to ensure valid observation of refracted starlight for strapdown star sensor. Then the SINS/RCNS integrated system can be executed by UKF. In addition, the refracted star map processing and simulating methods are proposed.

This paper is divided into seven parts. Section 1 introduces the development of RCNS and especially the obstacle to its engineering implementation. Section 2 presents the starlight atmospheric refraction model. Section 3 puts forward the command attitude law for refracted starlight observation according to space geometry analysis. In Section 4, both refracted star map processing and its simulating methods are given. Section 5 presents the SINS/RCNS integrated navigation system model and the unscented Kalman Filtering method. Section 6 shows simulation and verification results. Section 7 is the conclusion.

2. Starlight atmospheric refraction modeling

When passing through the atmosphere, starlight will be refracted and bent inward to the geocentre, therefore the apparent position of a star will be a little higher than its actual one. The angle between the incident starlight before the atmosphere and the refracted starlight on to the star sensor is defined as starlight refraction angle R. Its relation with refraction tangent height h_g is shown as follow in Fig. 1 (Xinlong and Shan, 2009).

$$R = k(\lambda_w)\rho_g\sqrt{\frac{2\pi(R_e + h_g)}{H_g}} \tag{1}$$

where $k(\lambda_w)$ is the scattering coefficient determined by the wavelength of the starlight λ_w. When $\lambda_w = 0.7\ \mu\text{m}$, $k(\lambda_w) = 2.25 \times 10^{-7}\ \text{m}^3/\text{g}$ (Xiaolin et al., 2013); H_g is the density scale height at h_g in unit of km; R_e is the radius of the earth; ρ_g is the atmospheric density at h_g in unit of g/m^3, an empirical function with regard to h_g is given as follow:

$$\rho_g = 1.762162e^{-0.1522204h_g} \tag{2}$$

The stratosphere atmospheric condition of the altitude range from 20 to 50 km is stable, fit for refracted starlight observation. The following two equations are also empirical formulae:

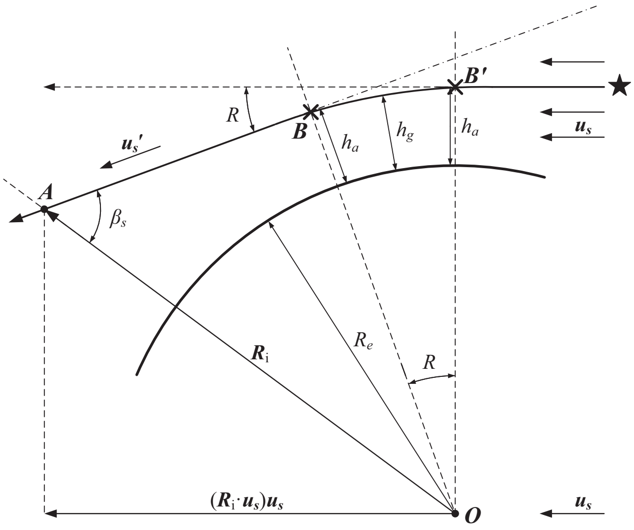

Fig. 1. Geometric relationship of the parameters in starlight refraction (variable scale).