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A starlight refraction scheme with single star sensor used in autonomous satellite navigation system

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ABSTRACT

For autonomous satellite navigation, the method based on stellar refraction is studied in this paper. In the previous studies, two star sensors have been used for navigation. Actually, only one star sensor is sufficient for navigation. The additional sensor will result in an extra burden for the initial alignment process and design cost. In this paper, an autonomous satellite navigation scheme based on stellar refraction with a single star sensor is presented. The installed angle of star sensor is closely related with the navigation precision of satellite, and the refraction star identification is crucial in stellar refraction method. Hence the determination of installed angle and refraction star identification are also considered. Finally, to verify the feasibility of the proposed scheme, a simulation for low-Earth-orbit (LEO) satellite is carried out and its result indicates that the proposed method is practical with high-precision.

1. Introduction

Autonomous satellite navigation is of great interest among researchers. The celestial navigation system (CNS) plays an important role in autonomous satellite navigation system. It is accomplished via obtaining the positional or attitudinal information by on-board observation, an image taken from a field of view (FOV), which is manipulated by the star sensor. The CNS has become an effective autonomous navigation system with high-precision attitude measurement, moreover, the error does not accumulate with time, and independent wholly. Therefore it is widely applied to the spacecraft, lunar rover, ballistic missile and satellite [1–3]. For LEO satellite navigation, the Earth's horizon is an important reference. According to their mode of measurement acquisition, satellite celestial navigation methods fall into two main categories: the direct measuring method and the indirect measuring method by stellar refraction [4]. The first one has a problem that the high precision star sensor cannot match the low precision horizon indicator, resulting in a poor positioning accuracy. On the contrary, the second uses the star sensors to indirectly observe the position of Earth's horizon, achieving a high-precision positioning.

The first study of the refraction method dates back to the 1960s [5]. During Apollo plan, the Stark Draper Laboratory (CSDL) investigated many techniques for performing orbit navigation. The refraction method was one of them. Although it was very attractive, the technique was not adopted finally [6]. A significant step of the stellar refraction method was achieved when CSDL conducted a survey of existing satellites in late 1979 to determine if any could provide real data on stellar atmospheric refraction. Finally, the successful observations of refraction were obtained from OAO-3 (Orbiting Astronomical Observatory) in 1980 [7]. After that CSDL analyzed many observations and concluded that high accuracy navigation is possible by using the refraction method [8,9]. The refraction method in previous works was not applied in practice until the MADAN (multi-mission attitude determination and autonomous navigation) system of America was used in the

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decade of nineties in 20th century [10]. And now the refraction method has been successfully applied on an aircraft with high altitude of 30 km [11]. As a promising method, it has attracted many researchers so far.

In previous works, the stellar refraction program uses two star sensors. The first one observes the stars that never forms refraction, the other observes the refraction stars. Then the refraction star can be identified according to the differences between the refraction star and normal star. Actually, only one star sensor can achieve the above goal. The extra sensor will increase the design cost and burden the initial alignment process. In view of this situation, this paper presents an autonomous satellite navigation scheme based on stellar refraction with single star sensor. The installed angle of star sensor determines the number of observed refraction stars in a satellite orbit period, which affects the accuracy of the navigation. In this paper, a method on the basis of the principle of spherical geometry is presented to calculate the optimal installed angle. Moreover, the refraction star identification method uses only one star sensor is also given. Finally, a simulation is utilized to verify the feasibility of the proposed scheme.

2. Principle of stellar refraction

When starlight passes through the Earth's atmosphere, it will be refracted and bent inward. Viewed from the satellite, the apparent position of star will be higher than the actual one. The refracted rays appear to gaze at the horizon at an apparent height h_a but actually graze the horizon at a slightly lower height h_g. The angle R between the incident ray and refracted ray is the starlight refraction angle (see Fig. 1).

From the geometric relationship shown in Fig. 1, the following equation can be derrived

$$h_a = \sqrt{r^2 - u^2} + u \tan R - R_e - c \tag{1}$$

where

$$\begin{cases} r = |\boldsymbol{r}| = \sqrt{x^2 + y^2 + z^2} \\ u = |\boldsymbol{r} \cdot \boldsymbol{u}| = |x s_x + y s_y + z s_z| \end{cases} \tag{2}$$

$\boldsymbol{r} = [x \quad y \quad z]$ is the position vector from Earth's core to satellite, $\boldsymbol{u} = [s_x \quad s_y \quad s_z]^T$ is the starlight vector before refraction which can be obtained from the star catalog after the star is identified, R_e is the Earth radius and c is very small and can be ignored.

According to the atmospheric refraction model we can also obtain the relationship between h_a and R. The

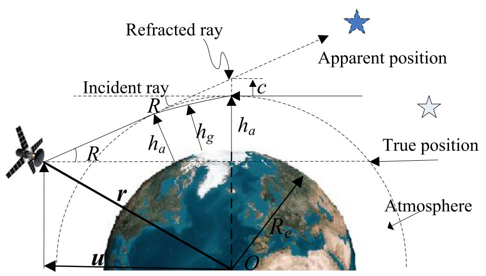

Fig. 1. Geometric illustration of stellar atmospheric refraction.

development of autonomous navigation based on stellar refraction result in a lot of interest in the study of the atmospheric refraction model [12–14]. Where, the literature [12] improved the observation model. Compared with the existing model, it establishes an continuous range of altitudes (CRA) from 20 km to 50 km on the basis of the data provided by U.S. Standard Atmosphere

$$\begin{cases} h_a = h_g + k(\lambda)\rho(R_e + h_g) \\ h_g = 57.081 - 6.441 \ln(R) \\ \rho = 1.762\exp(-0.152 h_g) \end{cases} \tag{3}$$

where h_a is the apparent ray altitude; $\lambda = 0.7$ μm is the wavelength of starlight; $k(\lambda) = 2.2517 \times 10^{-7}$ is the scattering parameter; h_g is the tangent height; R is starlight refraction angle, R and h_g are measured in second (″) and km respectively; ρ is the atmospheric density and its unit is kg/m^3. Because $R_e \gg h_g$ and $k(\lambda)\rho < 2 \times 10^{-3}$ for the atmosphere altitude higher than 20 km [15], so $h_{ac} \approx h_g + k(\lambda)\rho R_e$, then the relationship between h_a and R can be derrived as follows

$$h_a = 57.081 + 2.531\exp[0.981 \ln(R) - 8.689] - 6.441 \ln(R) \tag{4}$$

where h_a is measured in kilometer. If the starlight refraction angle R can be obtained, the apparent height h_a can be calculated by (4). According to (1), h_a is a function of position. so, if we let h_a as the measurement data, the satellite's position and velocity can be calculated by combining the dynamics equation of orbits and using the reasonable filtering algorithm.

3. Scheme design

3.1. Workflow of the new scheme

The star sensor is used to observe the refraction star and the normal star. Its optical axis is installed on the satellite's orbit plane. In general, to calculate the refraction angle and to identify the refraction star require two star sensors as shown in Fig. 2. Star sensor A observes the normal star, and then outputs the satellite's attitude and its optic axis's direction after the star identification process. According to the installation matrix between A and B, the direction of B star sensor's optic axis can be obtained. We choose the stars fall into Field of View (FOV) of B from the star catalog, henceforth generating a simulated star image. Using this star image and the actual one can identify the refraction star. Then the refraction angle can be calculated.

As a matter of fact, both the refraction stars and the normal stars exist in the image captured by sensor B. If the traditional star identification method is utilized to deal with this star image, only the normal stars can be identified successfully. The rest is the refraction star. If the number of the normal stars is larger than 3, we can still successfully identify these stars. It means that we can also obtain the satellite's attitude and the direction of sensor's optic axis. Utilizing the differences between the refraction star and the normal stars can identify the refraction star and calculate the refraction angle. Finally,