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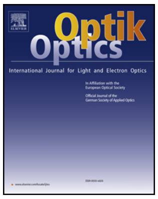

Original research article

A novel X-ray pulsar integrated navigation method for ballistic aircraft

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ABSTRACT

Since X-ray pulsar navigation system (XNAV) has better anti-interference and autonomy, a novel X-ray pulsar integrated navigation method combining celestial navigation system (CNS) and strapdown inertial navigation system (SINS) is proposed in this paper. Using XNAV and CNS to simultaneously correct the output of SINS not only solves the problem of error accumulation in SINS, but also ensures that the system has a high degree of autonomy and anti-interference. In order to further improve navigation accuracy, a suboptimal multiple fading extended Kalman filter (SMFEKF) is used for information fusion between XNAV and the other two navigation methods. Finally, numerical simulations show that the integrated navigation algorithm not only has higher accuracy than SINS and CNS/SINS, but also can output attitude information that XNAV cannot output. And navigation accuracy increases with the number of pulsars. Besides, the accuracy of XNAV/CNS/SINS using SMFEKF is significantly better than EKF.

1. Introduction

At present, the most basic navigation method for ballistic aircraft is inertial navigation system (INS). INS has the characteristics of fast update of navigation information, autonomy and strong anti-interference. However, due to industrial level restrictions, long-term operation will cause serious error accumulation due to device drift [1]. At the same time, the initial alignment requirements are also high. For this reason, the research on integrated navigation method related to INS has become a hotspot in this field. At present, navigation methods often combined with INS include celestial navigation system (CNS) [2,3] and global navigation satellite system (GNSS) [4–6].

CNS utilizes the characteristics that the star position in the inertial space remains unchanged and through the star sensor, high-accuracy attitude information can be directly obtained [7]. Taking as an example, CNS/SINS integrated navigation method can not only correct gyro drift in SINS, but also can estimate the velocity and position error caused by the initial misalignment angle by designing related algorithms, thereby reducing the initial alignment requirement [8]. However, CNS/SINS has the disadvantage of inaccurate estimation of accelerometer bias in ballistic aircraft applications. The aircraft still has an accumulation of position and velocity errors during that time. GNSS uses navigation satellites to achieve precise positioning and speeding of ballistic aircraft. However, GNSS/SINS cannot obtain high-precision attitude information, and navigation signals are susceptible to interference [9]. This is more deadly for ballistic aircraft with higher reliability requirements.

X-ray pulsar-based navigation system (XNAV) is an emerging autonomous navigation method. It can obtain spacecraft position and velocity information by measuring the Time-of-Arrival (TOA) of X-ray pulsar radiation signals in the universe [10]. XNAV has the

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advantages of high concealment, strong autonomy, good anti-interference, etc. It has received extensive attention from researchers in recent years [11–15]. However, due to the long observation period required for XNAV and the short flight time of ballistic aircraft, there are relatively few studies for ballistic aircraft.

Since XNAV has higher reliability than GNSS, some researchers have studied related integrated navigation methods for orbiting satellites. Liu et al. studied Doppler/XNAV integrated navigation method [16,17]. This method not only ensures the system's complete observability, but also reduces the area of the detectors for XNAV. However, this method cannot obtain attitude information. XNAV/SINS integrated navigation method was proposed in reference [18]. XNAV were used to reduce the long-term effects of the errors in SINS. However, the gyro drift cannot be eliminated in this method. Some scholars have also studied the integrated navigation method of XNAV with CNS and ultraviolet sensor-based satellite autonomous navigation system [19–21], but the update rate of these integrated navigation methods cannot meet the requirements of ballistic aircraft.

This paper presents a XNAV/CNS/SINS integrated navigation method for ballistic aircraft. XNAV can correct accelerometer bias while CNS can eliminate gyro drifts. SINS can compensate for the slower update rate of XNAV and CNS. In order to improve the correction effect of XNAV, a suboptimal multiple fading extended Kalman filter (SMFEKF) is used as the data fusion filter for XNAV and the other two navigation methods, which can increase the proportion of XNAV in data fusion.

The rest of the paper is organized as follows. Section 2 introduces the basic observation models of CNS and XNAV. Mathematical model of integrated navigation method is analyzed in Section 3. The basic steps of SMFEKF are explained in Section 4. Section 5 performs numerical simulation. Section 6 summarizes the paper.

2. Observation model

2.1. XNAV observation model

The basic principle of XNAV is shown in Fig. 1.

After a period of photon accumulation, X-ray pulse detector on the aircraft can recover the waveform of the pulse signal and obtain the TOA of the pulse t_{sat}. According to the position information $\tilde{\mathbf{r}}_{\text{sat}}$ output by SINS, the TOA at the aircraft can be converted to the TOA at the Solar System Barycenter (SSB) $\tilde{t}_{\text{SSB}}$ by Eq. (1) [22].

$$\begin{aligned}\tilde{t}_{\text{SSB}} &= t_{\text{sat}} + \frac{\mathbf{n}\cdot\tilde{\mathbf{r}}_{\text{sat}}}{c} + \frac{1}{2cD_0}\left[(\mathbf{n}\cdot\tilde{\mathbf{r}}_{sat})^2 - |\tilde{\mathbf{r}}_{sat}|^2 - 2\mathbf{b}\cdot\tilde{\mathbf{r}}_{sat} + 2(\mathbf{n}\cdot\mathbf{b})(\mathbf{n}\cdot\tilde{\mathbf{r}}_{sat})\right]\\ &\qquad + 2\frac{GM_{\text{sun}}}{c^3}\ln\left|1 + \frac{\mathbf{n}\cdot\tilde{\mathbf{r}}_{sat} + |\tilde{\mathbf{r}}_{sat}|}{\mathbf{n}\cdot\mathbf{b} + |\mathbf{b}|}\right|\end{aligned} \tag{1}$$

Where $\mathbf{n}$ is the unit direction vector of pulsar in Barycentric Celestial Reference System (BCRS); $\tilde{\mathbf{r}}_{\text{sat}}$ is the position of aircraft in BCRS output by SINS; c is the speed of light; D_0 is the distance between the pulsar and SSB; $\mathbf{b}$ is the position of SSB relative to the sun; G is the gravitational constant; M_{sun} is the quality of the sun.

At the same time, the real TOA of the pulse arriving at the SSB t_{SSB} can be predicted based on the phase-time model obtained by

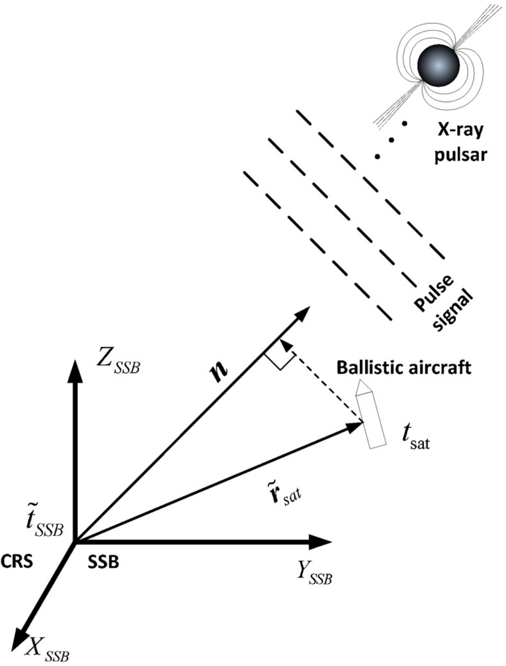

Fig. 1. The basic principle of XNAV.