Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research xxx (2017) xxx–xxx

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Research on navigation of satellite constellation based on an asynchronous observation model using X-ray pulsar

Pengbin Guo, Jian Sun [*], Shuling Hu, Ju Xue

State Key Laboratory for Strength and Vibration of Mechanical Structure, School of Aerospace, Xi'an Jiaotong University, PR China

Received 20 March 2017; received in revised form 27 October 2017; accepted 21 November 2017

Abstract

Pulsar navigation is a promising navigation method for high-altitude orbit space tasks or deep space exploration. At present, an important reason for restricting the development of pulsar navigation is that navigation accuracy is not high due to the slow update of the measurements. In order to improve the accuracy of pulsar navigation, an asynchronous observation model which can improve the update rate of the measurements is proposed on the basis of satellite constellation which has a broad space for development because of its visibility and reliability. The simulation results show that the asynchronous observation model improves the positioning accuracy by 31.48% and velocity accuracy by 24.75% than that of the synchronous observation model. With the new Doppler effects compensation method in the asynchronous observation model proposed in this paper, the positioning accuracy is improved by 32.27%, and the velocity accuracy is improved by 34.07% than that of the traditional method. The simulation results show that without considering the clock error will result in a filtering divergence.

Keywords: Pulsar navigation; Modified Kalman filtering; Asynchronous observation model; Doppler effects

1. Introduction

X-ray pulsar based navigation technology has already attracted extensive attention, and finding a high-accuracy and high-reliability X-ray pulsar based navigation method is a very urgent question for high-altitude orbit (orbit altitude greater than 20,000 km) tasks and deep space exploration because the main existing navigation methods cannot be fully applied to high-altitude orbit space tasks or deep space exploration.

The global positioning system (GPS) is designed for near-Earth (orbit altitude less than 20,000 km) space (Spilker and Parkinson, 1996), which clearly cannot be used for high-altitude orbit satellite or deep space exploration. The information of the inertial navigation system (INS) can only be relied upon during a short period of time because the INS errors accumulate with time (Gao et al., 2009). The performance of a general celestial navigation system degrades as the orbit altitude increases (Wang et al., 2013), and for high-orbit satellites, the best positioning accuracy achievable is of the order of around 1 km (Feng et al., 2014). The most common method to track spacecraft in deep-space exploration is to use deep space network (DSN) (Curkendall and Border, 2013). However, this method does not autonomously provide navigation information. With the increase in the distance between the ground station and spacecraft, the position-determination precision decreases (Deng et al., 2013).

X-ray pulsars are rapidly rotating neutron stars that emit pulsed radiation in the X-ray region of the electromagnetic spectrum (Ning et al., 2017). After a period of observation of stellar emissions in the X wavelengths, a stable X-ray pulse profile is acquired using the epoch

---

[*] Corresponding author.
E-mail address: sunjian10@mail.xjtu.edu.cn (J. Sun).

https://doi.org/10.1016/j.asr.2017.11.027
0273-1177/© 2017 COSPAR. Published by Elsevier Ltd.

Please cite this article in press as: Guo, P., et al. Research on navigation of satellite constellation based on an asynchronous observation model using X-ray pulsar. Adv. Space Res. (2017), https://doi.org/10.1016/j.asr.2017.11.027

folding (EF) procedure (Emadzadeh and Speyer, 2011). By comparing this profile with the standard one, the orientation, position, and time of the spacecraft can be determined.

Since Chester proposed the use of X-ray pulsars for navigation (Chester and Butman, 1981), researchers have studied many navigation methods based on X-ray pulsars. The unconventional stellar aspect experiment provided a platform for conducting pulsar-based spacecraft navigation experiment in 1999 (Wood et al., 2001). In 2004, the “X-ray source-based navigation for autonomous position determination” was proposed by the Defense Advanced Research Project Agency. In the same year, the European Space Agency studied the feasibility of pulsar navigation (Sala et al., 2004).

At present, the pulsar navigation accuracy is not high due to the weak signals that need a period of time to obtain an integrated profile. Most works in the literature (Liu et al., 2012, Wu et al., 2012, Xiong et al., 2012, Wang et al., 2013, Feng et al., 2014) adopted one integration time for different pulsars (i.e. the synchronous observation model), which resulted in a very long integration time for some pulsars. In fact, the improvement in the time-of-arrival (TOA) accuracy has become slower with the increase in the integration time. The cost of a very long integration time is that the update rate of the measurement is very slow, whereas the TOA accuracy does not improve much (Guo et al., 2016). So an asynchronous observation model is proposed to improve the update rate of the measurements in this article.

It has been proved that in the case of the same total detector area, the navigation accuracy of using multiple detectors is higher than that of using a single detector (Wang et al., 2013). For a single satellite, while observing multiple pulsars, you must install multiple detectors, which will increase the weight and volume of the satellite. In addition, the visibility for a single satellite is also an important issue. A satellite constellation contains multiple satellites, and each satellite observes a different pulsar. Even though some of the satellites cannot receive the signals from pulsars due to the block of Earth or some satellites are out of order, there are still many satellites on work. It is easy to ensure that at least four pulsars are observed, so the visibility and reliability of a constellation are much better than those of a single satellite. In addition, considering that each satellite is only equipped with one detector, the satellite in a constellation can be much smaller than the single satellite.

Clock error and Doppler effects are two other factors that affect the accuracy of pulsar navigation. A clock error of 1 μs would cause a systematic bias of 200 m (Wang et al., 2014). Usually the Doppler effect is compensated by the predicted velocity, but the Doppler effects cannot be removed completely by the predicted velocity information with error (Liu et al., 2015). Although Liu et al. (2015) proposed a method to compensate the Doppler effects, the method is not suitable for a constellation. The Doppler compensation was in the form of velocity in Liu et al. (2015), for a constellation it is complicated to convert both the velocity and position of different satellites to a satellite at the same time. In this article a new Doppler effects compensation method is presented. By introducing the Doppler effect into an expression about the position, the derivation process is much easier than that proposed in Liu et al. (2015).

In order to improve the accuracy of pulsar navigation, an asynchronous observation model that considers the clock error and Doppler effects is proposed on the basis of satellite constellation in this paper. This paper is organized as follows: in Section 2, the model of the X-ray pulsar navigation is proposed; Section 3 presents the filtering algorithm. Simulations are presented in Section 4, and the conclusion is drawn in the final section.

2. Navigation model of satellite constellation using X-ray pulsar

2.1. State model

The Earth-centric celestial reference system is selected, and the orbit dynamic model is expressed as:

$$\begin{cases} \dot{x} = v_x \\ \dot{y} = v_y \\ \dot{z} = v_z \\ \dot{v}_x = -\frac{\mu r_x}{r^3}\left[1 + \frac{3}{2}J_2\left(\frac{Re}{r}\right)^2\left(1 - 5\frac{r_z^2}{r^2}\right)\right] + \omega_{vx} \cdot \\ \dot{v}_y = -\frac{\mu r_y}{r^3}\left[1 + \frac{3}{2}J_2\left(\frac{Re}{r}\right)^2\left(1 - 5\frac{r_z^2}{r^2}\right)\right] + \omega_{vy} \\ \dot{v}_z = -\frac{\mu r_z}{r^3}\left[1 + \frac{3}{2}J_2\left(\frac{Re}{r}\right)^2\left(3 - 5\frac{r_z^2}{r^2}\right)\right] + \omega_{vz} \end{cases} \tag{1}$$

Eq. (1) can be rewritten in a general state equation as

$$\dot{\mathbf{x}}(t) = f(\mathbf{x}, t) + \mathbf{w}(t) \tag{2}$$

where $\mathbf{x} = [x \quad y \quad z \quad v_x \quad v_y \quad v_z]^T$ is the state vector. $\mathbf{r} = [x \quad y \quad z]^T$ and $\mathbf{v} = [v_x \quad v_y \quad v_z]^T$ are the position and velocity vectors of the spacecraft, respectively. μ is the gravitational constant of the Earth. Re is the radius of the Earth, and J_2 is the second order harmonic coefficient. ω_{vx}, ω_{vy} and ω_{vz} are the disturbance items, $\mathbf{w}(t) = [0 \quad 0 \quad 0 \quad \omega_{vx} \quad \omega_{vy} \quad \omega_{vz}]^T$.

2.2. Measurement model

Satellite constellation can effectively reduce system operation and management costs; thus, it has attracted wide attention. The time-transfer equation can be expressed as (Sheikh et al., 2005)

Please cite this article in press as: Guo, P., et al. Research on navigation of satellite constellation based on an asynchronous observation model using X-ray pulsar. Adv. Space Res. (2017), https://doi.org/10.1016/j.asr.2017.11.027