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X-ray pulsar navigation method for spacecraft with pulsar direction error

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Abstract

In order to reduce the impact of the pulsar direction error on the navigation system performance, a novel X-ray pulsar navigation technique is proposed. Through analyzing the system bias caused by the pulsar direction error, it can be seen that the system bias is slowly time-varying. Based on the analysis result, the augmented state unscented Kalman filter (ASUKF), in which the system bias is treated as the augmented state, is designed here to deal with the system bias and estimate spacecraft's positions and velocities. The simulation results demonstrate the effectiveness and robustness of the proposed navigation method. The ASUKF-based navigation method for spacecraft is more accurate than the method based on unscented Kalman filter (UKF) in the presence of the pulsar direction error.

Keywords: Navigation; Performance; UKF; Pulsar; Error

1. Introduction

Currently, the orbit determination for spacecraft is supported by ground stations. However, the rapid increase in the number of spacecrafts has lead to a continuing increase in the cost of operating these spacecrafts (Ning and Fang, 2007, 2008). Consequently, autonomous navigation systems for spacecraft, which lead to a reduction in operating costs, are highly attractive.[1]

X-ray pulsar navigation (Hanson, 1996; Sheikh et al., 2005, 2006a,b; Shuai et al., 2007), which is a newly developed autonomous navigation technology for spacecraft, has been a hot subject of research. The Defense Advanced Research Projects Agency (United States government) has proposed "X-ray Source-based Navigation for Autonomous Position Determination" in 2004. In the same year, the European Space Agency has also studied the feasibility of a deep space navigation system based on pulsar timing information (Sala et al., 2004). The reason why so many countries attach great importance to X-ray pulsar navigation is that it has the following characteristics: (1) it is entirely passive; (2) its navigational accuracy does not decline with time; (3) it is robust to interference; (4) it is fit for the whole outer space.

X-ray pulsars emit pulsed electromagnetic radiation continually (Hewish et al., 1968), which can be detected by X-ray sensors placed onboard spacecraft. Through processing pulsed signals, a pulse time-of-arrival (TOA) at a spacecraft can be obtained after a period of observation usually lasts about 5–10 min. And its corresponding time at the solar system barycenter (SSB) can be predicted by the pulse timing model. Therefore, the offset of a pulse TOA at the spacecraft compared to its corresponding time at the SSB can be calculated (Sheikh et al., 2005, 2006a,b). It is the time offset that is used as the pulsar navigation measurement.

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The measurement errors of X-ray pulsar navigation (TOA errors) arise from the background radiation, the time resolution of the X-ray sensor and the system bias caused by the pulsar direction error. And they have significant impact on the navigational performance. We use the Taylor method to determine the pulse TOA, and the TOA accuracy is independent of the choice of the time resolution. And the TOA error caused by the background radiation is a type of random error, which can be dealt with an optimal state estimation technology, such as the Extended Kalman Filter (EKF) or the Unscented Kalman Filter (UKF) (Julier et al., 1995, 2000).

Under the condition of not considering the pulsar direction error, Sheikh uses the EKF and achieves 200 m or less (Sheikh et al., 2006a,b), Sun uses the central difference Kalman filter, whose accuracy is similar to the UKF, and achieves 117 m (Sun et al., 2008).

However, subjected to the current measurement technology (Very Long Baseline Interferometer), there is an unavoidable error in the pulsar direction information. Unfortunately, even the pulsar direction error of 0.001″ (″ denotes for arc s) will cause the system bias of several hundred meters, which the EKF and the UKF do not deal with effectively. Consequently, there is a sharp decline in the navigational performance. To eliminate the pulsar direction error, Xiong Kai has proposed a pulse time difference of arrival (TDOA) technology (Xiong et al., 2009). But, this technology requires the TOA measurements of several spacecrafts simultaneously. Thus, the TDOA technology is not good for single spacecraft.

In order to achieve 100 m with the pulsar direction error, we propose a pulsar navigation method for single spacecraft. In this paper, we analyze the system bias that arises from the pulsar direction error, and find that the variation of system bias is slow. Thus, the augmented state technology (Chmielewski and Kalata, 1995), in which the system bias is treated as the augmented component of the state vector, is adopted here. The augmented state method makes both the state model and measurement model include the system bias. Furthermore, the UKF is utilized for its good performance in nonlinear estimation. Therefore, we combine the augmented state technology with the UKF, and design the ASUKF to reduce the impact of the system bias.

2. Principle of pulsar navigation

X-ray pulsars can provide unique signals that can be detected by X-ray sensors. Upon sufficient detection, these signals are processed to obtain a pulse time-of-arrival. And its corresponding time-of-arrival at SSB can be predicted by the pulse timing model.

The pulse TOA measured at the spacecraft, t_{SC}^i, can be transferred into its corresponding time at the SSB, t_b^i (Sheikh et al., 2005, 2006a,b). The transferring equation is given by,

$$t_b^i = t_{SC}^i + \frac{1}{c}\boldsymbol{n}^i \cdot \boldsymbol{r}_{SC} + \frac{1}{2cD_0^i}\left[-r_{SC}^2 + (\boldsymbol{n}^i \cdot \boldsymbol{r}_{SC})^2 - 2\boldsymbol{b}\cdot\boldsymbol{r}_{SC} + 2(\boldsymbol{n}^i\cdot\boldsymbol{b})(\boldsymbol{n}^i\cdot\boldsymbol{r}_{SC})\right] + \frac{2\mu_{Sun}}{c^3}\ln\left|\frac{\boldsymbol{n}^i\cdot\boldsymbol{r}_{SC} + r_{SC}}{\boldsymbol{n}^i\cdot\boldsymbol{b} + b} + 1\right| \quad (1)$$

where c is the speed of light, D_0^i is the range from the ith pulsar to the SSB, $\boldsymbol{b}$ is the position of the SSB relative to the sun, μ_{Sun} is the gravitational constant of the sun, $\boldsymbol{n}^i$ is the real direction vector of the ith pulsar, the superscript (i) is used to distinguish different pulsars. $\boldsymbol{r}_{SC}$ is the position vector of spacecraft with respect to SSB. For Earth orbiting spacecraft, $\boldsymbol{r}_{SC}$ can be transferred to the position vector of spacecraft with respect to Earth $\boldsymbol{r}$, using the known position of the Earth $\boldsymbol{r}_E$, which can be provided by standard ephemeris tables.

$$\boldsymbol{r} = \boldsymbol{r}_{SC} - \boldsymbol{r}_E \quad (2)$$

The second term on the right-hand side of Eq. (1) is the first-order Doppler delay, which is determined by the distance between the spacecraft and the SSB in the pulsar direction. And the third term is due to the effects of annual parallax, which is caused by the light-curve change resulting from the Earth's motion. Together, these two terms are referred to as Roemer delay. The fourth term is the Shapiro delay effect, which is the bending effect on the path due to the Sun's gravitational field.

3. System bias caused by pulsar direction error

3.1. Review of system bias

In fact, the real direction vector of the ith pulsar, $\boldsymbol{n}^i$, could not be obtained. And we can only get a measured value, $\hat{\boldsymbol{n}}^i$.

Replacing $\boldsymbol{n}^i$ with $\hat{\boldsymbol{n}}^i$, Eq. (1) is transformed into

$$t_b^i = t_{SC}^i + \frac{1}{c}\hat{\boldsymbol{n}}^i \cdot \boldsymbol{r}_{SC} + \frac{1}{2cD_0}\left[-r_{SC}^2 + (\hat{\boldsymbol{n}}^i \cdot \boldsymbol{r}_{SC})^2 - 2\boldsymbol{b}\cdot\boldsymbol{r}_{SC} + 2(\hat{\boldsymbol{n}}^i\cdot\boldsymbol{b})(\hat{\boldsymbol{n}}^i\cdot\boldsymbol{r}_{SC})\right] + \frac{2\mu_{Sun}}{c^3}\ln\left|\frac{\hat{\boldsymbol{n}}^i\cdot\boldsymbol{r}_{SC} + r_{SC}}{\hat{\boldsymbol{n}}^i\cdot\boldsymbol{b} + b} + 1\right| + \frac{1}{c}B^i \quad (3)$$

where B^i is the system bias caused by the direction error of the ith pulsar.

According to Eqs. (1) and (3), B^i can be represented as follows:

$$B^i = (\boldsymbol{n}^i - \hat{\boldsymbol{n}}^i)\cdot\boldsymbol{r}_{SC} + \frac{1}{2D_0}\left[(\boldsymbol{n}^i\cdot\boldsymbol{r}_{SC})^2 - (\hat{\boldsymbol{n}}^i\cdot\boldsymbol{r}_{SC})^2 + 2(\boldsymbol{n}^i\cdot\boldsymbol{b})(\boldsymbol{n}^i\cdot\boldsymbol{r}_{SC}) - 2(\hat{\boldsymbol{n}}^i\cdot\boldsymbol{b})(\hat{\boldsymbol{n}}^i\cdot\boldsymbol{r}_{SC})\right] + \frac{2\mu_{Sun}}{c^2}\left(\ln\left|\frac{\boldsymbol{n}^i\cdot\boldsymbol{r}_{SC} + r_{SC}}{\boldsymbol{n}^i\cdot\boldsymbol{b} + b} + 1\right| - \ln\left|\frac{\hat{\boldsymbol{n}}^i\cdot\boldsymbol{r}_{SC} + r_{SC}}{\hat{\boldsymbol{n}}^i\cdot\boldsymbol{b} + b} + 1\right|\right) \quad (4)$$