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Integrated optical and X-ray pulsar methods for deep-space autonomous navigation based on an adaptive nonlinear filter

Sui Chen[1,a] *

[1]Politecnico di Milano, Department of Aerospace Science and Technology, Via La Masa 34, 20156, Milan, Italy

[a]sui.chen@polimi.it

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Abstract. Recent technological advancement and the commercialisation of the space sector have led to a significant surge in the development of space missions for deep-space exploration. Currently, deep-space missions mainly rely on ground-based Guidance, Navigation and Control (GNC) operations involving human-in-the-loop processes. Although being reliable, the ground-based navigation approach is prone to prolonged periods of communication delay, lacking real-time capabilities and autonomy. In addition, the booming growth of users in space will unavoidably lead to saturation of ground slots, hindering the progression of space exploration. Reducing the dependence on ground operation by developing on-board autonomous navigation methods represents a potential solution for future deep-space missions. Currently, navigation based on optical and X-ray pulsar measurements represents the two prominent methods for achieving autonomous deep-space navigation and will be investigated in this paper.

Literature Review

NASA Deep Space 1 was the first deep-space mission to use autonomous navigation throughout the entire mission phase, determining its orbit using optical images of distant asteroids [1]. Among the several autonomous navigation methods being proposed and developed, optical navigation represents the most mature and feasible solution for spacecraft autonomous navigation [2]. Using optical sensors, spacecraft's state is estimated by extracting the line-of-sight directions to several known navigation beacons in the Solar System which are subsequently fed into an orbit determination algorithm for state estimation. Optical navigation has been developed and tested extensively in current literature [3,4,5,6]. Several researchers [7,8,9] improved the state estimation accuracy by correcting the planetary light-time and light-aberration effects and by exploiting the optimal beacons selection strategy. Song and Yuan [10] enhanced the numerical stability and computation efficiency of the deep-space orbit determination problem by applying UD factorisation to the state estimator.

The innovative concept of X-ray pulsar navigation (XNAV) was first proposed in 1981 [11], after the first detection of pulsar in 1967. Pulsars are fast rotating neutron stars that can emit regular signals in both low and high energy bands. The pulse time of arrival (TOA) difference between observed pulse profile and standard pulse profile is used to estimate the spacecraft's state. In November 2016, as the first pulsar navigation mission, China launched an X-ray pulsar test satellite XPNAV-1 with a primary objective of detecting the details of X-ray signals emitted by 26 nearby pulsars and subsequently creating a pulsar navigation database. They utilised observation data obtained from the Crab Pulsar to validate the satellite's orbit determination, achieving an average positioning accuracy of 38.4 km [12]. In 2017, NASA demonstrated a fully autonomous, real-time pulsar navigation experiment in space for the first time, attaining an average accuracy of 16 km [13,14]. In general, although XNAV is a less mature and less established method, using pulsar navigation is typically expected to result in more accurate navigation solutions compared to optical navigation [15].

Since XNAV technology is still in the early development stage, it is believed that combining XNAV with other types of navigation methods is the way forward for future deep-space exploration navigation. In fact, a significant amount of work has been dedicated to investigating integrated navigation systems for deep-space exploration. Ning et al. 2017 [16] proposed combining XNAV with traditional celestial navigation, which involves measuring star angles, to create an integrated navigation method for the cruise phase of Mars exploration. Jiao et al. 2016 [17] integrated X-ray pulsar measurement with Mars optical measurement for Mars exploration orbiting phase, yielding an autonomous navigation accuracy of less than 1 km. Xiong et al. 2016 [18] incorporated an ultraviolet optical sensor to enhance the performance of XNAV system and demonstrated that the proposed XNAV/optical integrated navigation scheme can effectively scale down the spacecraft orbit error. However, in their work, an extended Kalman filter (EKF) was used which only works well with linear or slightly nonlinear problems and might produce unsatisfactory estimation results when dealing with highly nonlinear systems. Zhang et al. 2018 developed a novel orbit determination algorithm exploiting both the pulsar timing data and position vector to enhance the performance of XNAV. The Adaptive Divided Difference Filter (ADDF) adopted in their work has demonstrated to have a stronger system noise adaptive capacity and can handle unknown measurement noise and non-additive noise. However, navigation is solely relied on the information from pulsar sources which are still considered to be immature measurement techniques to date and might degrade the overall system reliability and performance. Gu et al. 2019 [19] proposed an optical/radio/pulsars integrated navigation algorithm with an adaptive extended Kalman filter (AEKF) for optimal state estimation, and illustrated that optical/radio/pulsars integrated navigation exhibits a higher level of estimation accuracy compared to both conventional optical navigation and optical/radio integrated navigation.

Objective

Achieving fully autonomous navigation for deep-space applications is a relatively new field of study. As illustrated in the literature review, although optical navigation represents the most mature technology for autonomous navigation, it typically results in low navigation accuracy when relying solely on optical measurements. For this reason, it becomes essential to incorporate other forms of measurement data to improve the performance of optical navigation. Considering the aforementioned limitations found in the current literature, this paper aims to fill in these gaps to advance the current technology for autonomous deep-space navigation. Specifically, information fusion will be performed by integrating optical and pulsar timing measurements and an adaptive nonlinear filter will be adopted to handle unknown measurement noise robustly. It is hoped that the contribution from this work will act as a stepping stone towards achieving fully autonomous deep-space navigation in the future.

Methodology

Measurement Models

Optical Measurement Model The spacecraft inertial position is defined as $\boldsymbol{r} = [x, y, z]^T$ and the beacon inertial position is $\boldsymbol{r}_p = [x_p, y_p, z_p]^T$ which is assumed to be known. The objective is to estimate $\boldsymbol{r}$ by obtaining the line-of-sight (LoS) directions to the beacons via celestial triangulation.

From geometry, the beacon position $\boldsymbol{\rho}$ and the LoS direction $\hat{\boldsymbol{\rho}}$ can be expressed as:

$$\boldsymbol{\rho} = \boldsymbol{r}_p - \boldsymbol{r} = \begin{bmatrix} x_p - x \\ y_p - y \\ z_p - z \end{bmatrix} \quad ; \quad \hat{\boldsymbol{\rho}} = \frac{\boldsymbol{\rho}}{\|\boldsymbol{\rho}\|} = \frac{1}{\|\boldsymbol{\rho}\|} \begin{bmatrix} x_p - x \\ y_p - y \\ z_p - z \end{bmatrix} \tag{1}$$

For optical navigation using the LoS directions to known navigation beacons, the measurements are the azimuth (Az) and elevation (El) to the beacons, defined by the following equation:

$$\boldsymbol{h} = \begin{bmatrix} Az \\ El \end{bmatrix} = \begin{bmatrix} \arctan(\frac{\hat{\rho}_y}{\hat{\rho}_x}) \\ \arcsin(\hat{\rho}_z) \end{bmatrix} = \begin{bmatrix} \arctan(\frac{y_p - y}{x_p - x}) \\ \arcsin(\frac{z_p - z}{\|\boldsymbol{\rho}\|}) \end{bmatrix} \tag{2}$$

Therefore, at each given epoch t_k, the optical measurement model is:

$$\boldsymbol{y}_{optical\_k} = \boldsymbol{h}_{\boldsymbol{optical}}(\boldsymbol{x}_k) + \boldsymbol{v}_{optical\_k} = \begin{bmatrix} \arctan(\frac{y_p - y}{x_p - x}) \\ \arcsin(\frac{z_p - z}{\|\boldsymbol{\rho}\|}) \end{bmatrix}_k + \boldsymbol{v}_{optical\_k} \tag{3}$$

where $\boldsymbol{v}_{optical\_k}$ is the measurement noise of the optical sensor.

X-ray Pulsar Measurement Model For X-ray pulsar-based navigation, the key measurement is the pulsar timing in the form of photon time of arrival (TOA) at the X-ray detector. Position error is corrected by finding the difference between the measured pulse TOA and the predicted pulse TOA. This pulse TOA difference can be determined by comparing the observed pulse profile and the standard pulse profile which is usually constructed in the solar system barycentre (SSB) inertial reference frame. For this reason, the measured photon is first transferred from the spacecraft moving frame to the SSB frame using the following time transfer equation [18]:

$$t_k^{(b)} = t_k^{(sc)} + \frac{1}{c}\boldsymbol{n} \cdot \boldsymbol{r}_{sc,k} + \frac{1}{2cD_0}\left[r_{sc,k}^2 - (\boldsymbol{n} \cdot \boldsymbol{r}_{sc,k})^2\right] - \frac{2\mu_{Sun}}{c^3}\ln\left|\frac{\boldsymbol{n}\cdot\boldsymbol{r}_{sc,k} + r_{sc,k}}{\boldsymbol{n}\cdot\boldsymbol{b} + b} + 1\right| \tag{4}$$

where k indicates the discrete time, $t_k^{(sc)}$ is the photon TOA measured at the spacecraft local frame, $t_k^{(b)}$ is the photon TOA at the SSB frame, $\boldsymbol{n}$ is the unit vector from the spacecraft to the pulsar, $\boldsymbol{r}_{sc,k}$ is the spacecraft position vector relative to the SSB origin, c is the speed of light, D_0 is the distance between the pulsar and the SSB, μ_{Sun} is the gravitational constant of the Sun and $\boldsymbol{b}$ is the position vector of the SSB relative to the centre of the Sun.
Therefore, for the X-ray pulsar navigation, the measurement model is defined as:

$$\boldsymbol{y}_{X-ray\_k} = \boldsymbol{h}_{\boldsymbol{X-ray}}(\boldsymbol{x}_k) + \boldsymbol{v}_{X-ray\_k} = \left(t_k^{(b)} - t_k^{(sc)}\right) + \boldsymbol{v}_{X-ray\_k} \tag{5}$$

For an integrated system with both optical and X-ray pulsar measurement information, the combined navigation measurement equation can be written as follow, where $\boldsymbol{v}_k$ is the measurement noise with covariance $\boldsymbol{R}$:

$$\boldsymbol{y}_k = \begin{bmatrix} \boldsymbol{y}_{optical\_k} \\ \boldsymbol{y}_{X-ray\_k} \end{bmatrix} = \boldsymbol{h}(\boldsymbol{x}_k) + \boldsymbol{v}_k \tag{6}$$

Integrated Navigation Algorithms

System Dynamic Model The spacecraft state $\boldsymbol{x}$ in deep space is defined as $\boldsymbol{x} = [\boldsymbol{r} \quad \boldsymbol{v}]^T$, where $\boldsymbol{r}$ and $\boldsymbol{v}$ are the inertial position and velocity vectors of the spacecraft respectively. The dynamic model is described using the following equation of motion:

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}) + \boldsymbol{w} = \begin{bmatrix} \boldsymbol{v} \\ -\mu_{\boldsymbol{Sun}} \frac{\boldsymbol{r}}{r^3} + C_{\boldsymbol{R}} \frac{P_0 R_0^2}{c} \frac{A_s}{m_s} \frac{\boldsymbol{r}}{r^3} \end{bmatrix} + \boldsymbol{w} \tag{7}$$

where $\boldsymbol{f}$ is the system dynamics equation and $\boldsymbol{w}$ is the process noise with covariance $\boldsymbol{Q}$.

Adaptive nonlinear Filter For deep-space navigation problems, highly nonlinear models and time-varying measurement noise covariance are likely to be encountered, so using the traditional Kalman filters is likely to lead to unsatisfactory estimation results. In this paper, an adaptive nonlinear filter will be adopted instead in order to improve the overall navigation performance. Derived from the work of [20], a new recursive adaptive unscented Kalman filter (RAUKF) is implemented to estimate the spacecraft's state. Based on the measurement and dynamic models defined in Eq. 6 and Eq. 7, the RAUKF algorithm follows time update and measurement update steps similar to Kalman filters, but with the measurement noise covariance $\boldsymbol{R}$ being scaled by a scaling factor which is derived from current innovation recursively. The full RAUKF algorithm can be found in [20].

Expected Results

The proposed integrated deep-space navigation architecture in this paper has taken inspiration from [18], in which the feasibility of integrated optical and X-ray pulsar navigation systems is assessed and simulation results show that such an integrated system outperforms the ones based solely on either optical or X-ray pulsar measurements. In their work with an extended Kalman filter used for orbit determination, the position estimation mean root-mean-square (RMS) errors of the integrated system are found to be 1.59 km for an Earth-orbiting satellite and 1.73 km for a lunar-orbiting satellite. In Ning's work [20], the implementation of the new RAUKF algorithm in a purely optical-based navigation system has led to a reduction of 15% and 35% in the position and velocity estimation errors respectively as compared to UKF.

The novelty in this paper is the integration of optical and X-ray pulsar navigation methods combined with the implementation of an adaptive nonlinear filter, and this is expected to lead to both robustness to time-varying measurement noise and enhanced state estimation accuracy. Once the proposed algorithms described in this paper are implemented in computer-based codes with subsequent simulations being run, it is expected that the state estimation results will outperform those found in the existing literature given the aforementioned breakthrough of the system, leading to further improvements of the state estimation accuracy. In the long term, the integrated autonomous navigation system will ease the interplanetary exploration, improving our current knowledge of the Solar System and opening the doors to a new era of space exploitation.

Conclusion

This paper investigates an integrated deep-space navigation system using both optical and X-ray pulsar measurements. The proposed system is considered superior and innovative because it combines well-established optical measurement methods with less mature X-ray pulsar measurement techniques. The time-varying measurement noise is handled by the utilisation of an adaptive nonlinear filter instead of the conventional Kalman filters. Once implemented, the results are expected to lead to further improvements of the state estimation accuracy. It is hoped that the contribution from this work will serve as a foundational milestone for achieving fully autonomous deep-space navigation in the future.

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