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A novel decentralized relative navigation algorithm for spacecraft formation flying

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ABSTRACT

This paper presents a novel decentralized relative navigation algorithm. The relative motion equations are derived in the Earth-Centered-Inertial frame. The relative measurements contain not only the line of sight and range between the deputy and the chief, but also the ranges among different deputies. This helps to improve the redundancy and accuracy of the relative navigation for spacecraft formation flying. In decentralized estimation algorithm, it is necessary to transmit the global states in the formation to linearize the ranges among the deputies. A sigma-point method is used to account for the uncertainty in the estimated states of other spacecraft. The relative measurements are coupled with the relative motion equation in a novel decentralized filter to determine the relative position and velocity. Simulation shows that the proposed novel decentralized estimation algorithm provides better performance than the traditional iteration algorithm.

1. Introduction

Spacecraft formation flying (SFF) is an important technology for future missions, such as rendezvous and docking, long baseline interferometry, stereographic imaging and synthetic apertures. Many researches have been done with respect to spacecraft formation flying, such as relative dynamics, motion control and navigation [1–3]. Relative navigation [4–6] would be the topic in this paper.

In the past, researches on relative navigation of SFF have been focused on methods using GPS (Global Positioning System) [7,8]. However, this method is not suitable for high earth orbit (HEO) and deep-space formation flying because the GPS signal is not available in these cases. A GPS-like technology has been proposed for deep-space mission, however, this technique requires extensive hardware and is subject to some similar error sources to GPS [9]. Recently, vision-based navigation (VISNAV) system has been proposed by using an optical sensor with specific light sources [10,11]. The VISNAV provides multiple line-of-sight between the deputies and chief which could be coupled with gyro measurement and dynamic models in an extended Kalman filter to determine relative attitude, position and gyro biases. However, the VISNAV is not suitable for long distance application, in which case multiple line of sight will converge to single line of sight.

In this paper, the relative measurements contain both the line-of-sight and range between the deputy and the chief and the ranges between all deputies. By acquiring the ranges among the deputies, the relative navigation system improves both the redundancy and the accuracy. Moreover, the proposed relative system can also be applied to missions where GPS signal is not available, for example, high earth orbit and deep-space missions. There are three basic estimation architectures including centralized, decentralized and hierarchic. Generally, the centralized architecture could get the most accurate estimation result, but is subject to high computational burden in the chief and frequent communication demands among formation members. Therefore, it is desirable to select decentralized architecture. Because the computation of the ranges between the deputies requires the relative states of spacecraft in formation, the key issue to use decentralized estimation algorithm is to account for the uncertainty in the relative states of spacecrafts. Some papers presented several decentralized algorithms to compensate the uncertainty, including the Iterative Cascade Extended Kalman Filter, Schmidt Kalman Filter, Bump-up-R algorithm [12–14] and other decentralized filters [15–17]. In this paper, we propose to incorporate sigma-point method to account for the uncertainty.

The organization of this paper is as follows. Section 2 presents the system equations including relative motion equations and measurement equations. In Section 3, a novel decentralized estimation algorithm is developed and the decentralized filter is designed. To

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account for uncertainty, sigma-point method is employed. Simulations are conducted and the results are presented in Section 4 to verify the effectiveness. Finally, Section 5 concludes this paper with some conclusions.

2. System equations

In this section, we will derive the relative motion equations for formation flying and the measurement equations for both vision and range sensors.

2.1. Relative motion equations

The spacecrafts are identified as the "chief" and the "deputies". The spacecraft about which all other spacecrafts are orbiting is referred to as the chief. The remaining spacecrafts are referred to as the deputies. The inertial equations of the chief's motion could be given by the standard Newtonian relationship

$$\ddot{\mathbf{r}}_c = -\mu \frac{\mathbf{r}_c}{r_c^3} \tag{1}$$

where μ is the Earth gravitational constant, $\mathbf{r}_c = [x_c \ y_c \ z_c]^T$ is the position vector in ECI frame, the subscript c denotes the chief spacecraft, and

$$r_c = \|\mathbf{r}_c\| = \sqrt{x_c^2 + y_c^2 + z_c^2} \tag{2}$$

Similarly, the deputy inertial equations of motion are

$$\ddot{\mathbf{r}}_d = -\mu \frac{\mathbf{r}_d}{r_d^3} + \mathbf{v} + \mathbf{f}_c \tag{3}$$

where $\mathbf{r}_d = [x_d \ y_d \ z_d]^T$, the subscript d denotes the deputy spacecraft, the vector $\mathbf{v}$ is the perturbing force, $\mathbf{f}_c$ is the control force, and

$$r_d = \|\mathbf{r}_d\| = \sqrt{x_d^2 + y_d^2 + z_d^2} \tag{4}$$

The relative position vector $\mathbf{r}_{cd} = [x_{cd} \ y_{cd} \ z_{cd}]^T$ is defined as

$$\mathbf{r}_{cd} = \mathbf{r}_d - \mathbf{r}_c \tag{5}$$

So,

$$\mathbf{r}_d = \mathbf{r}_{cd} + \mathbf{r}_c \tag{6}$$

Combining Eqs. (1), (3), (4) and neglecting the control forces $\mathbf{f}_c$, it yields

$$\begin{aligned} \ddot{\mathbf{r}}_{cd} &= \ddot{\mathbf{r}}_d - \ddot{\mathbf{r}}_c \\ &= \mu \frac{\mathbf{r}_c}{r_c^3} - \mu \frac{\mathbf{r}_d}{r_d^3} + \mathbf{v} \end{aligned} \tag{7}$$

Substituting Eq. (6) into Eq. (7) gives

$$\ddot{\mathbf{r}}_{cd} = \mu \frac{\mathbf{r}_c}{r_c^3} - \mu \frac{\mathbf{r}_{cd} + \mathbf{r}_c}{\|\mathbf{r}_{cd} + \mathbf{r}_c\|^3} + \mathbf{v} \tag{8}$$

where

$$\|\mathbf{r}_{cd} + \mathbf{r}_c\|^3 = \sqrt{(x_{cd} + x_c)^2 + (y_{cd} + y_c)^2 + (z_{cd} + z_c)^2}^{\,3} \tag{9}$$

Eqs. (8)–(9) are the relative motion equations used in this study, and the perfect orbit knowledge for the chief spacecraft is assumed.

2.2. Measurement equations

Vision sensor and range sensor are located on the deputy spacecraft. The vision sensor provides the line-of-sight between the deputy and the chief. The range sensors provide the range information from a deputy to the chief and to other deputies.

2.2.1. Vision sensor

The vision sensor provides the line-of-sight vector from the deputy to the chief in the deputy's body frame. The attitude of the deputy is assumed to be known exactly. Therefore, the elevation and azimuth angle can be expressed in the ECI as shown in Fig. 1. The line-of-sight vector $\mathbf{l}_{dc}$ can be expressed in the $O\mathbf{X}_I\mathbf{Y}_I\mathbf{Z}_I$ frame as

$$\mathbf{l}_{dc} = \cos\alpha \cos\beta \mathbf{I}_x + \cos\alpha \sin\beta \mathbf{I}_y + \sin\alpha \mathbf{I}_z \tag{10}$$

where α is the elevation angle, β is the azimuth angle. The line-of-sight vector $\mathbf{l}_{dc}$ and relative position vector $\mathbf{r}_{cd}$ are in an opposite direction, so

$$\alpha = -\arcsin \frac{z_{cd}}{r_{cd}} \tag{11}$$

$$\beta = \arctan \frac{y_{cd}}{x_{cd}} \tag{12}$$

where

$$r_{cd} = \sqrt{x_{cd}^2 + y_{cd}^2 + z_{cd}^2} \tag{13}$$

2.2.2. Range sensor

All deputies are equipped with range sensors to measure the ranges between a deputy and other spacecraft (chief and other deputies).

For example the deputy 1 shown in Fig. 2, the range ρ_{d1c} between it and the chief is

$$\rho_{d1c} = \sqrt{x_{cd1}^2 + y_{cd1}^2 + z_{cd1}^2} \tag{14}$$

where $\mathbf{r}_{cd1}$ is the relative position vector between the deputy 1 and the chief, and $x_{cd1}, y_{cd1}, z_{cd1}$ are the components of $\mathbf{r}_{cd1}$.

The range ρ_{d1di} between deputy 1 and the i-th deputy is

$$\rho_{d1di} = \sqrt{(x_{cd1} - x_{cdi})^2 + (y_{cd1} - y_{cdi})^2 + (z_{cd1} - z_{cdi})^2} \tag{15}$$

where $\mathbf{r}_{cdi}$, $(i = 2, \ldots, n)$ is the relative position vector between the deputy 1 and the i-th deputy, and $x_{cdi}, y_{cdi}, z_{cdi}$ are the components of $\mathbf{r}_{cdi}$. Therefore, there will be n ranges measured by the range sensor on the deputy 1.

3. Decentralized filter design

In this study, we define the states of each spacecraft as the local states. The global states are defined as the summation of all local states. In decentralized estimation algorithm, every spacecraft estimates its local states, and contributes equally to the estimation of the global states. Since all spacecrafts require the states of other spacecrafts to linearize the range between them, it is necessary to transmit the global states among the formation. Park presented several decentralized filters, and pointed out that the key issue during estimating the local state is to account for the uncertainty in the states of other spacecraft [13]. The filters developed in [13] include the Iterative Cascade Extended Kalman Filter, Schmidt Kalman Filter and Bump-up-R algorithm. In this paper, a novel decentralized estimation algorithm is proposed where the sigma-point [18] method is employed to account for the uncertainty in other spacecraft states.