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Finite-time control of underactuated spacecraft hovering

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ABSTRACT

Finite-time controllers are proposed in this paper for underactuated spacecraft hovering in the absence of the radial or in-track thrust. The indirect method, which is generally adopted to solve the singularity problem in the conventional terminal sliding mode, is modified to ensure the continuity of the high-order time derivative of the sliding surface at the switch points. Rigorous proofs via the Lyapunov-based approaches verify the finite-time stability of the closed-loop system. By comparisons with the asymptotic controllers, the advantages of the finite-time ones in faster convergence rate and enhanced control precision have also been substantiated.

1. Introduction

Close proximity operations, such as on-orbit inspection, maintenance, and updating, have received growing research interest for decades (Dang, Wang, & Zhang, 2014). Spacecraft hovering, a new and less mature type of proximity operation (Zhang, Zhao, Zhang, & Zhai, 2015), can broadly be defined as maintaining a constant position relative to a target in space, whether it is a small asteroid or a satellite (Huang, Yan, & Zhou, 2014). To achieve hovering, a chaser generally needs continuous thrust to cancel the acceleration relative to the target, thus inducing an equilibrium state at a desired hovering position in the neighborhood of the target (Sawai, Scheeres, & Broschart, 2002). Hovering orbit is preferable in explorations of small bodies in space because it allows more high-resolution observations and measurements (Broschart & Scheeres, 2005). Also, a hovering tractor that hovers above an Earth-threatening asteroid can alter the trajectory of the asteroid by using the gravity as a towline, thus avoiding undesirable collisions with Earth (Lu & Love, 2005). Furthermore, hovering approach holds promise in on-orbit services because it enables more reliable and less complicated proximity operations when spacecraft are relatively static (Huang, Yan, & Zhou, 2014). Notably, due to the necessity of continuous thrust, most hovering orbits are therefore non-Keplerian ones. To solve the control problem of such non-Keplerian relative hovering orbits, several researches have been conducted. Sawai et al. (2002) proposed closed-loop control strategies for hovering over a rotating small body with altimetry measurements. Broschart and Scheeres (2005, 2007) presented a case study of hovering above an asteroid and analyzed the boundedness of spacecraft hovering under dead-band control. Recently, finite-time control schemes have been designed by Lee, Sanyal, Butcher, and Scheeres (2015) for hovering over an asteroid. Besides aforementioned works on control of hovering over an asteroid in space, several others dealt with the problem of hovering nearby a target spacecraft in Earth orbits. Wang, Zheng, Meng, and Tang (2011) proposed a sliding mode controller for hovering around elliptic orbits. Similar problem was addressed by Zhou, Yan, and Huang (2015) and Zhou, Yan, Huang, and Zhang (2015) via robust control technique. Furthermore, Huang, Yan, Zhou, and Xu (2015) and Huang, Yan, Zhou, and Zhang (2014) investigated the feasibility of spacecraft hovering controlled by the geomagnetic Lorentz force acting on an electrostatically charged spacecraft.

Despite that a variety of control schemes has been proposed for hovering, most of them are designed based on the assumption of a fully-actuated hovering system. That is, there exists an independent thruster in each of the radial, in-track, and normal directions. If one of the thrusters malfunctions, the system would be underactuated. Generally, an underactuated system refers to the system with fewer number of the control inputs than that of the degrees of freedom to be controlled (Huang, Yan, & Zhou, 2015a). Thus, if the underactuation happens, previous fully-actuated control methods may not accommodate any more, and it may lead to the hovering mission failure. A direct solution is to equip the spacecraft with redundant thrusters. However, in view of the mass and cost of spacecraft, a more economical and promising alternative is to design underactuated controllers (Godard, Kumar, & Zou, 2014).

Previous works on underactuated relative orbital control mainly concentrated on the application of underactuated spacecraft formation

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control (Bevilacqua & Romano, 2008; Huang, Yan, Zhou, & Hao, 2016; Kumar, Bang, & Tahk, 2007; Kumar, Ng, Yoshihara, & Ruiter, 2011; Leonard, Hollister, & Bergmann, 1989; Perez & Bevilacqua, 2014; Varma & Kumar, 2012). For spacecraft formation flying (SFF), the relative orbits between spacecraft are natural Keplerian ones, and barely no or little control effort is required to maintain the desired relative orbits. Differently, as aforementioned, the relative orbits between hovering spacecraft are non-Keplerian ones. Thus, despite that the existing underactuated control schemes for SFF could provide references, controllers for underactuated hovering remain to be designed. Huang, Yan, and Zhou (2016) designed asymptotic controllers for underactuated hovering without either the radial or in-track thrust. In Huang, Yan, and Zhou (2016), a linear transformation of the original state vector is firstly conducted to generate a new reduced-order state vector. Then, the asymptotic or finite-time convergence of the new state could be guaranteed by regular asymptotic or finite-time control method. Finally, once the new state converges to the equilibrium, due to the inherent linear coupling of the original states that consist of the newly-defined state, the original states will thereafter converge asymptotically to the equilibrium, too. As can be seen, these control schemes could only guarantee the finite-time convergence of the new states, but not those of the original states. In other words, as long as the new state vector is derived via a linear combination of the original states, the linear relationship could only provide asymptotic convergence for the original states. Therefore, if finite-time convergence is required, these traditional control schemes with linear transformation are not applicable.

Obviously, compared to asymptotic convergence, finite-time convergence is more desirable in practice, especially for critical real-time missions (Hu, Jiang, & Friswell, 2014). Given that finite-time control technique could offer a faster convergence rate, higher control accuracy, and better disturbances rejection property (Du, He, & Cheng, 2014; Du, Li, & Qian, 2011; Du, Qian, Yang, & Li, 2013; Du, Wen, Yu, Li, & Chen, 2015; Zou, 2014), this paper aims to design finite-time control schemes for underactuated hovering in the absence of either the radial or in-track thrust by using terminal sliding mode (TSM) control method (Liu & Wang, 2012). In view of the drawback of the linear transformation as discussed above, the nonlinear transformation is conducted in this paper in combination with the TSM control technique. A major drawback of the initial TSM is the singularity problem (Huang, Yan, & Zhou, 2015b; Zou, Kumar, Hou, & Liu, 2011). Both direct and indirect methods have been proposed to remove the singularity. The direct way is to use the nonsingular terminal sliding mode (NTSM) controller developed by Feng, Yu, and Man (2002). By contrast, in the indirect method, the singularity is avoided by switching from the terminal to general sliding manifold, as that proposed by Wang, Chai, and Zhai (2009). In this paper, the indirect method is adopted and modified. Notably, the indirect method developed by Wang et al. could guarantee the continuity of the first order time derivative of the sliding manifold. However, due to the necessity of controller design, this indirect method is further improved in this paper to ensure the continuity of higher or even arbitrary order time derivative of the sliding manifold. Meanwhile, this paper also explains the reason why the direct method is not used. Also, the continuous reaching law developed by Yu, Yu, Shirinzadeh, and Man (2005) is introduced to eliminate the chattering problem existing in regular sliding mode control.

To the authors' best knowledge, this is the first paper proposing finite-time control strategies for underactuated hovering, in which two separate controllers are designed. One is for the case without radial thrust, and the other is for the case without in-track thrust. In comparison with existing works on related topics, the main enhancements of this paper are summarized as follows:

(1) Compared with the fully-actuated hovering control schemes (Broschart & Scheeres, 2005, 2007; Dang et al., 2014; Huang, Yan, & Zhou, 2014; Huang, Yan, Zhou, & Xu, 2015; Huang, Yan, Zhou, & Zhang, 2014; Lee et al., 2015; Lu & Love, 2005; Sawai et al., 2002; Wang et al., 2011; Yan, Huang, & Yang, 2017; Zhang et al., 2015; Zhou, Yan, & Huang, 2015; Zhou, Yan, Huang, & Zhang, 2015), the underactuated hovering controllers proposed in this paper could accommodate the underactuated cases, thus avoiding the hovering mission failure arising from the thruster malfunction;

(2) As a similar underactuated relative orbital control mission, the control problem of underactuated spacecraft formation reconfiguration was addressed in Bevilacqua and Romano (2008), Godard et al. (2014), Huang et al. (2015a), Huang, Yan, Zhou, and Hao (2016), Kumar et al. (2007, 2011), Leonard et al. (1989), Perez and Bevilacqua (2014) and Varma and Kumar (2012). Notably, the relative orbits between spacecraft in formation are natural Keplerian ones, whereas those between the hovering spacecraft are generally non-Keplerian ones. Thus, compared with the underactuated control schemes for Keplerian relative orbits, the underactuated controllers proposed in this paper are applicable to non-Keplerian relative orbits;

(3) The existing underactuated hovering controllers are all asymptotic ones due to the linear transformation of system states (Huang & Yan, 2016; Huang, Yan, & Zhou, 2016; Huang, Yan, Zhou, & Hao, 2017). Instead, novel nonlinear transformations of system states are adopted in this paper to ensure finite-time stability. Thus, the controllers inherit the advantages of finite-time controllers over asymptotic ones, including faster convergence rate, enhanced control accuracy, and better disturbance rejection property;

(4) Furthermore, the indirect approach to eliminate the singularity in TSM is also improved. Compared with the original indirect method in Wang et al. (2009), the modified one in this paper could guarantee the continuity of the arbitrary order time derivative of the sliding surface at the switch points by using the hyperbolic functions.

The organization of this paper proceeds as follows. The dynamical model of underactuated spacecraft hovering is introduced in Section 2, based on which the analysis on the feasibility and controllability of underactuated hovering is conducted for either underactuated case. Sections 3 and 4 elaborate the finite-time control scheme and the corresponding stability analysis for the case without radial and in-track thrust, respectively. Numerical simulations are presented in Section 5 to validate the theoretical analyses and the advantages of the finite-time controllers. Finally, Section 6 concludes the paper.

2. Dynamical analysis of underactuated spacecraft hovering

2.1. Dynamical model

Spacecraft hovering refers to a relative equilibrium state that a chaser spacecraft thrusts continuously to maintain a constant position with respect to some target in space. The spacecraft involved in a hovering configuration are referred to as the chaser and target spacecraft. As shown in Fig. 1, $O_E X_I Y_I Z_I$ is an Earth-centered inertial (ECI) frame, and O_E is the center of Earth. The dynamics of underactuated spacecraft hovering is represented in a local-vertical–local-horizontal (LVLH) frame located at the center of mass (c.m.) of the target, as denoted by $O_T xyz$ in Fig. 1, where x axis is along the radial direction, z axis is normal to target's orbital plane, and y axis completes the right-handed Cartesian frame. O_C is the c.m. of the chaser. Define the position and velocity vector of the chaser with respect to the target as $\boldsymbol{\rho} = \begin{bmatrix} x & y & z \end{bmatrix}^{\mathrm{T}}$ and $\boldsymbol{v} = \begin{bmatrix} \dot{x} & \dot{y} & \dot{z} \end{bmatrix}^{\mathrm{T}}$, the dynamical model of underactuated spacecraft hovering can be described in the LVLH frame as (Huang, Yan, & Zhou, 2016)

$$\ddot{\boldsymbol{\rho}} = \boldsymbol{f}(\boldsymbol{\rho}, \boldsymbol{v}) + \overline{\boldsymbol{U}} \tag{1}$$