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Disturbance observer based control for spacecraft proximity operations with path constraint

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ABSTRACT

This paper investigates the application of a nonlinear feedback control strategy for driving a chaser spacecraft to rendezvous and dock with a target spacecraft in space. The nonlinear coupled models are established to describe the relative position and relative attitude dynamics, while a nonlinear disturbance observer is employed to estimate and compensate the external disturbances. Furthermore, a specific potential function is designed to prevent the chaser from entering into the forbidden zone or colliding with the target during the final phase of rendezvous and docking. Within the Lyapunov framework, the ultimate boundedness of the closed-loop system is guaranteed in the existence of external disturbances. Numerical simulations are performed to illustrate the feasibility and effectiveness of the proposed control strategy for motion synchronization as well as collision avoidance.

1. Introduction

Along with the rapid increment of space activities worldwide, autonomous spacecraft proximity operations have become an increasingly prominent research topic in recent years. Typical practical-engineering missions that can be regarded as its application include removing space debris, servicing malfunctioning satellites, assembling large space structures, and so on [1,2]. To meet the requirements of these missions with high accuracy, both relative position tracking and attitude synchronization should be taken into account simultaneously.

A variety of research results related to autonomous proximity operations have been put forward for spacecraft over the past decades. Based on the state-dependent Riccati equation technique, an integrated controller is designed to control the position and attitude of the spacecraft and target [3]. In [4], three nonlinear controllers are developed for 6 degree-of-freedom spacecraft formation, and the asymptotic stability of the controllers are proved via Lyapunov theory. By using $\theta - D$ nonlinear optimal control technique, a closed-form feedback controller is presented to achieve the control of relative motion between two spacecraft and the suppression of flexible structure dynamics [5]. Then the proximity problem of a chaser spacecraft to rendezvous with a target accompanied by translational maneuver is studied, and a novel modified controller based on $\theta - D$ technique is proposed [6]. With the application of sliding mode approach [7], a relative position and attitude coupled controller based on super twisting algorithm is derived to solve finite-time position tracking and attitude synchronization problem subject to external disturbances and model uncertainties [8]. In [9], an adaptive output feedback controller is proposed for autonomous spacecraft proximity operations with consideration of measurement errors. Motivated by feedback linearization approach, a nonlinear state feedback controller is developed for motion synchronization of two spacecraft, and the globally ultimate boundedness of the closed-loop system is also derived [10]. Consider the input saturation and actuator faults, a fault-tolerant controller is derived in [11] for spacecraft rendezvous and docking (R&D) maneuver, in which a nonlinear disturbance observer is employed to compensate the lumped uncertainties [39]. By combining the conventional backstepping technology with neural networks, a robust adaptive switching controller is designed for spacecraft R&D problem [12]. Given different kinds of uncertainties in the close proximity phase, a class of robust adaptive controllers are designed for proximity maneuvers in the presence of model uncertainties [13], input saturation [14] and full-state constraint [15]. Besides, several compact and efficient tools for motion description are also applied in spacecraft R&D [16–19]. In [16,17], dual quaternion technique is employed to describe the coupled 6 DOF dynamics, and two controllers are then proposed to achieve asymptotic stability of the closed-loop system. By using exponential coordinates

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on the Lie group SE(3), a robust terminal sliding mode controller is proposed to ensure finite-time convergence of the relative pose tracking errors [18,19]. Although the abovementioned control algorithms have shown adequate reliability, the flight safety which is an indispensable requirement of close proximity phase is ignored. During the final phase of spacecraft rendezvous maneuver, the relative distance between the chaser spacecraft and target is very close, thus the chaser spacecraft may collide with target's large-scale components. A well-known representative event is the failure of NASA's Demonstration for Autonomous Rendezvous Technology (DART) mission, in which the active spacecraft collided with the target spacecraft MUBLCOM at its first approach due to the ineffectiveness of the collision-avoidance function [20].

As for the spacecraft R&D with the account of collision avoidance requirement, several techniques have been conducted. In [21], the minimum-energy optimal rendezvous problem is studied by employing Pontryagin minimum principle, and the collision avoidance is taken into consideration by imposing a keep-out sphere around the target. After that, in order to save space, a "sphere+ellipsoid" composite zone is used to describe the constrained zone [22]. A novel guidance control law based on artificial potential function (APF) and fuzzy logic is derived in [23], in which collision avoidance requirement is involved. Base on mixed-integer program approach, a proximity trajectory planning algorithm is developed for autonomous spacecraft proximity operations, and the keep-out zone is modeled as convex polygon [24]. In [25,26], an adaptive controller based on sliding mode technique in conjunction with the potential function is introduced to achieve safety rendezvous with the target. In addition, model predictive control approach as an alternative method is also introduced to guide the motion of a chaser spacecraft [27,28]. Nevertheless, it should be noted that these research work still reveal some significant drawbacks, such as the neglect of external disturbances and the coupling effect between the translational and rotational motions, the neglect of attitude synchronization requirement.

In the scope of this paper, we consider the problem of proposing a relative position tracking controller and an attitude synchronization controller for close proximity maneuvers while taking collision avoidance requirement into account. Firstly, a nonlinear and effective model is established. Then, a novel feedback control strategy is introduced by combining the core idea of the APF and feedback linearization technique, and Lyapunov method is employed to analyze the stability of the closed-loop system. The main contributions and unique features of this paper are as follows: (1) the external disturbances are estimated and compensated by a nonlinear disturbance observer, and the observer error can be made arbitrarily small by tuning observer gains; (2) a cardioid-based curve is used to represent the surface of the keep-out zone, which contains all the components of the target and describes the final approaching corridor; (3) the presented nonlinear control strategy can render the states of the closed-loop system ultimately bounded, and provide real-time collision-avoidance ability for the chaser spacecraft during close-proximity operations.

The rest of this paper is organized as follows: In Sect. 2, the relative position and relative attitude dynamic models of the spacecraft are established, and the illustrations of potential function and control objective are also presented in this section. In Sect. 3, the designing procedure of a novel control strategy is proposed in detail, and the stability of the closed-loop system is proved. In Sect. 4, numerical simulation results applying the designed controller to meet control requirements are presented. Finally, conclusions are given in Sect. 5.

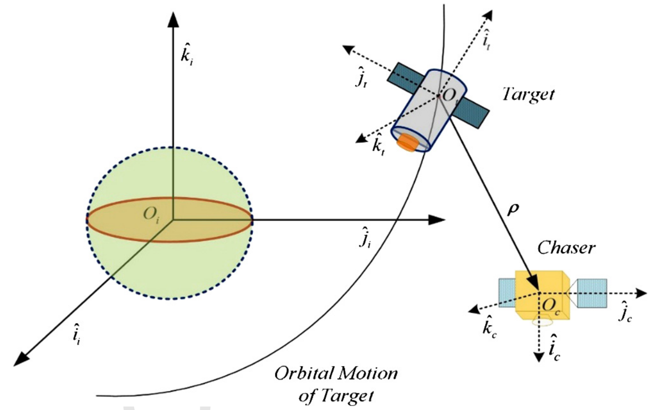

Fig. 1. Illustration of autonomous spacecraft rendezvous and docking.

2. Problem formulation

Throughout this paper, the following notations are adopted. The skew symmetric matrix $S(\boldsymbol{x}) \in \mathbb{R}^{3\times3}$ derived from a vector $\boldsymbol{x} = [x_1, x_2, x_3]^T \in \mathbb{R}^3$ is defined as

$$S(\boldsymbol{x}) = \begin{bmatrix} 0 & -x_3 & x_2 \\ x_3 & 0 & -x_1 \\ -x_2 & x_1 & 0 \end{bmatrix},$$

and it satisfies $S(\boldsymbol{x})\boldsymbol{y} = \boldsymbol{x} \times \boldsymbol{y}$, $S(\boldsymbol{x})\boldsymbol{y} = -S(\boldsymbol{y})\boldsymbol{x}$, $\boldsymbol{y}^T S(\boldsymbol{x})\boldsymbol{y} = 0$ for any $\boldsymbol{y} \in \mathbb{R}^3$. In the following, coordinate frames are denoted by $\mathcal{F}_{(\bullet)}$, and the transformation matrix from the fame $\mathcal{F}_i$ to $\mathcal{F}_j$ is represented by $R_i^j \in SO(3)$ satisfying $SO(3) = \{R \in \mathbb{R}^{3\times3} : R^T R = I_3, \det R = 1\}$. Moreover, according to [29], the time derivative of R_i^j can be written as $\dot{R}_i^j = S(\boldsymbol{\omega}_{j,i}^j)R_i^j = R_i^j S(\boldsymbol{\omega}_{j,i}^i)$, where $\boldsymbol{\omega}_{j,i}^k$ denotes the angular velocity of the frame $\mathcal{F}_i$ relative to $\mathcal{F}_j$, referenced in $\mathcal{F}_k$. $\lambda_{\min}(A)$ refers to the minimum eigenvalue of matrix $A \in \mathbb{R}^{n\times n}$. $\|\boldsymbol{x}\|$ and $\|A\|$ denote the Euclidean norm of vector $\boldsymbol{x}$ and the Frobenius norm of matrix A.

2.1. Cartesian coordinates frames

The relative coordinate frames used in this paper are shown in Fig. 1, defined as follows:

The Earth-centered inertial (ECI) frame, denoted $\mathcal{F}_i \triangleq \{O_i, \hat{i}_i, \hat{j}_i, \hat{k}_i\}$, has its origin located in the center of mass of the Earth, and $\hat{i}_i$ is along the direction of the vernal equinox, $\hat{k}_i$ points toward the north pole, in addition $\hat{j}_i$ completes the triad.

The body-fixed frames of the chaser and the target are denoted as $\mathcal{F}_c \triangleq \{O_c, \hat{i}_c, \hat{j}_c, \hat{k}_c\}$ and $\mathcal{F}_t \triangleq \{O_t, \hat{i}_t, \hat{j}_t, \hat{k}_t\}$, respectively. Without loss of generality, one can assume that the outward normal docking port on the target can be one of the unit vectors in the triad representing the frame $\mathcal{F}_t$. Likewise, in the frame $\mathcal{F}_c$, one of the unit vectors points toward the docking port on the chaser spacecraft and comprises the triad.

2.2. Relative motion dynamics

The relative position vector between the chaser and target spacecraft represented in the frame $\mathcal{F}_c$ is defined as

$$\boldsymbol{\rho} = \boldsymbol{r}_c - R_t^c \boldsymbol{r}_t \tag{1}$$

where $\boldsymbol{r}_c \in \mathbb{R}^3$ and $\boldsymbol{r}_t \in \mathbb{R}^3$ denote the inertial position vectors of the chaser and the target represented in the frames $\mathcal{F}_c$ and $\mathcal{F}_t$, respectively. According to the fundamental equation of the two-body problem, and by differentiating (1), we obtain [30]

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