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Robust adaptive relative position tracking and attitude synchronization for spacecraft rendezvous

Liang Sun *, Wei Huo

Seventh Research Division, Science and Technology on Aircraft Control Laboratory, Beihang University, Beijing, 100191, PR China

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ABSTRACT

This paper studies the relative position tracking and attitude synchronization of non-cooperative spacecraft rendezvous with model uncertainty and external disturbance. The relative position vector between the chaser spacecraft and the non-cooperative target is required to direct towards the docking port of the target, while the attitude of the two spacecrafts must be synchronized. The coupled six degrees-of-freedom (6DOF) dynamics are modeled for spacecraft relative motion, where the modified Rodrigues attitude parameters are employed to describe relative attitude dynamics. In view of the thrust misalignment of the chaser spacecraft, an integrated robust adaptive controller for 6DOF relative motion is designed, where parametric uncertainties of the chaser spacecraft are estimated online by using gradient adaptive method, and dynamic coupling effect resulting from unknown inertial parameters of the target is handled with a norm-estimation-based adaptive method. It is proved via the Lyapunov theory that the closed-loop system errors asymptotically converge to zero. Numerical simulation example demonstrates theoretical results.

1. Introduction

Spacecraft rendezvous technology has become an important research area in recent years due to rapidly growing space activities. Many space missions such as capturing space object, removing space debris, repairing spacecraft in orbit, refueling satellite to extend its lifetime, and assembling space station have been identified as foreseeable applications of spacecraft rendezvous in the near future. A key enabling technology in autonomous spacecraft rendezvous is relative position tracking and attitude synchronization that requires precise position and attitude control. Without relative position tracking and attitude synchronization, the motion of chaser spacecraft cannot be coordinated with the target's motion, and above-mentioned space missions cannot be realized safely. Since space targets can be divided into active and passive objects in different space missions, thus spacecraft rendezvous missions have two manners, cooperative and non-cooperative, respectively. In general, the position and attitude information of controlled target is completely known for chaser spacecraft in cooperative rendezvous mission. However, non-cooperative rendezvous mission it is hard to achieve for the control system whose position and attitude information of uncontrolled target are assumed to be unaccessible for chaser spacecraft, thus the non-cooperative rendezvous is becoming a challenging problem for academicians and engineers.

Since the kinematics and dynamics of relative motion in autonomous rendezvous and docking are highly nonlinear and coupled, the effective controller designing methods are required to realize high control accuracy of relative position and relative attitude. Traditionally, the relative translational and relative rotational controllers are designed independently. For instance, some relative position controllers for spacecraft relative translational motion were designed by using artificial potential field [14], feedback linearization [10], sliding mode control [15], multi-pulse technology [7], parametric Lyapunov equation based control [34], robust control [28], H_∞ control [6], optimal control [5], adaptive control [23,29]. Meanwhile, the attitude synchronization control is mainly studied in the spacecraft formation problem, and many representative attitude synchronization controllers were proposed by using lead-follower scheme [22,8], behavior-based approach [12], virtual structure approach [16], neighborhood-based approach [4], passivity-based method [2]. However, due to modeling simplicity, the dynamic coupling effect between relative translation and relation rotation was neglected in above-mentioned works. Except for the dynamic coupling effect between relative translation and relation rotation, the control force and control torque are also coupled with unknown thrust misalignment on chaser spacecraft, thus the opinion of designing controllers for relative translation and relative rotation independently is not effective, and integrated control

* Corresponding author.
E-mail addresses: liangsun@buaa.edu.cn (L. Sun), weihuo@buaa.edu.cn (W. Huo).

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of 6DOF relative motion has gained attention in recent years. In view of the robustness property of the controller designing based on state dependent Riccati equation technology, a unified robust controller for relative position and relative attitude was designed in [20]. An output feedback adaptive controller was proposed in [19] to solve the autonomous spacecraft rendezvous and docking problem under measurement noises. An adaptive feedback linearization controller was presented in [21] for autonomous rendezvous and docking, and ultimate boundedness of the errors was also derived. A kind of nonlinear model for relative translational and rotational motions between two spacecrafts was established with considering the dynamic coupling effect in [11]. For the control problem of the spacecraft relative motion dynamics in the absence of parametric uncertainties and external disturbances, a suboptimal solution to the Hamilton–Jacobi–Bellman (HJB) equation with adding perturbations to the cost function was firstly addressed in [25] by using a novel θ-D technique. Then the autonomous spacecraft rendezvous and docking subject to model uncertainties were studied, and the suboptimal controller based on θ-D technique was extended in [27]. With constraints on thrust magnitude and spacecraft approach velocity in autonomous rendezvous, model predictive control problem for relative position motion was converted to a nonlinear optimization problem in [3]. By knowing the target's orbital and attitude information, a class of relative translational and rotational controllers was designed in [33,31,32] for chaser spacecraft. It should be pointed out that almost all research until now reveals some significant drawbacks, such as knowing non-cooperative target's motion information and inertial parameters, neglecting chaser's parametric uncertainties and thrust misalignment, ignoring external environment disturbances. To our best of knowledge, few of results are available in the literatures to deal with above significant problems simultaneously for the relative translational and rotational motions.

In the scope of this paper, we consider the problem of driving a chaser spacecraft at a fixed position with respect to a non-cooperative target spacecraft and synchronizing the chaser's attitude with target's attitude. Unique features and main advantages of the results in this paper are

- a novel and effective mechanical model for non-cooperative spacecraft rendezvous is presented without using target's motion information, where the modified Rodrigues attitude description is adopted for attitude synchronization controller design because it provides minimal parametrization and is singularity free as the rotation is less than 360° [24], while the uncertainties including unknown inertial parameters of two spacecrafts, unknown thrust misalignment and unknown external disturbances are considered simultaneously in the model;
- relative position tracking and attitude synchronization in non-cooperative rendezvous are achieved by using a 6DOF integrated controller, unknown inertial parameters of the target involved in 6DOF relative motion model are estimated by using a simple and effective norm-estimation-based adaptive method, and the amount of online estimated parameters is reduced to 12 in this work from 324 in [33], thus the computation burden of the controller is decreased largely;
- the presented controller can render the position and attitude tracking errors asymptotically stable rather than ultimately bounded in the face of model uncertainties and unexpected disturbances.

Rest of this paper is arranged as follows. Section 2 describes a mechanical model of the spacecraft rendezvous and docking, and illustrates the objective of controller design. The designing procedure of a robust adaptive controller is given in detail, and the stability of the closed-loop system is proved in Section 3. Simulation example is then shown in Section 4. Section 5 concludes the paper.

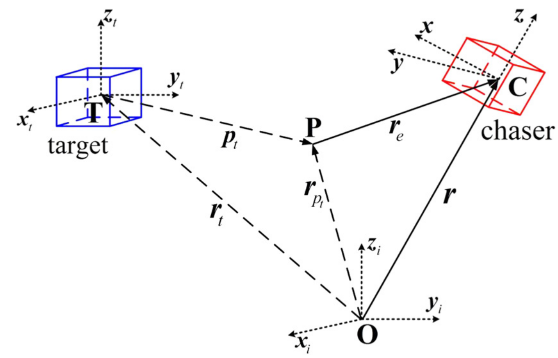

Fig. 1. The scenario of autonomous spacecraft rendezvous and docking.

2. Problem statement

The skew symmetric matrix $S(\boldsymbol{a}) \in \mathbb{R}^{3\times 3}$ derived from a vector $\boldsymbol{a} = [a_1, a_2, a_3]^{\mathrm{T}}$ is defined as

$$S(\boldsymbol{a}) = \begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{bmatrix}$$

and it satisfies $\|S(\boldsymbol{a})\| = \|\boldsymbol{a}\|$, $\boldsymbol{a}^{\mathrm{T}} S(\boldsymbol{a}) = \boldsymbol{0}$, $S(\boldsymbol{a})\boldsymbol{b} = -S(\boldsymbol{b})\boldsymbol{a}$, $\boldsymbol{b}^{\mathrm{T}} S(\boldsymbol{a})\boldsymbol{b} = 0$ for any $\boldsymbol{b} \in \mathbb{R}^3$. Moreover, $\|\boldsymbol{a}\| \le \|\boldsymbol{a}\|_1$, where $\|\boldsymbol{a}\|$ and $\|\boldsymbol{a}\|_1$ denote vector 2-norm and 1-norm, respectively. $A > 0$ denotes A is a positive definite matrix, and $\|A\|$ is its induced 2-norm of matrix. I_n and O_n are $n \times n$ unit and zero matrices, respectively. $\operatorname{sgn}(\boldsymbol{c}) \triangleq [\operatorname{sgn}(c_1), \cdots, \operatorname{sgn}(c_n)]^{\mathrm{T}}$ for any $\boldsymbol{c} = [c_1, \cdots, c_n]^{\mathrm{T}} \in \mathbb{R}^n$, where

$$\operatorname{sgn}(c_i) = \begin{cases} -1, & c_i < 0 \\ 0, & c_i = 0 \\ 1, & c_i > 0 \end{cases}$$

2.1. Dynamics for chaser and target

The scenario of autonomous spacecraft rendezvous and docking is depicted in Fig. 1, where $\mathscr{F}_i \triangleq \{\mathbf{O}x_i y_i z_i\}$ is the Earth-centered inertial frame, $\mathscr{F}_c \triangleq \{\mathbf{C}xyz\}$ and $\mathscr{F}_t \triangleq \{\mathbf{T}x_t y_t z_t\}$ are the body-fixed frames of the chaser and target, respectively; the origins $\mathbf{C}$ and $\mathbf{T}$ are centers of mass for the chaser and target, respectively, $\mathbf{P}$ is a fixed point relative to target and is the chaser's desired position along the direction of target's docking port; $\{\boldsymbol{r}, \boldsymbol{r}_e\}$ and $\{\boldsymbol{r}_t, \boldsymbol{r}_{pt}, \boldsymbol{p}_t\}$ are the vectors represented in frame $\mathscr{F}_c$ and frame $\mathscr{F}_t$, respectively. The aim is to control the chaser such that its center of mass $\mathbf{C}$ tracks point $\mathbf{P}$ and frame $\mathscr{F}_c$ tracks frame $\mathscr{F}_t$.

The position of point $\mathbf{C}$ and the attitude of frame $\mathscr{F}_c$ with respect to frame $\mathscr{F}_i$ can be described by following kinematics equations [26]:

$$\dot{\boldsymbol{r}} = \boldsymbol{v} - S(\boldsymbol{\omega})\boldsymbol{r} \tag{1}$$

$$\dot{\boldsymbol{\sigma}} = \frac{1}{4}\big[\big(1 - \boldsymbol{\sigma}^{\mathrm{T}}\boldsymbol{\sigma}\big)I_3 + 2S(\boldsymbol{\sigma}) + 2\boldsymbol{\sigma}\boldsymbol{\sigma}^{\mathrm{T}}\big]\boldsymbol{\omega} \tag{2}$$

where $\boldsymbol{r}, \boldsymbol{v}, \boldsymbol{\omega} \in \mathbb{R}^3$ are spacecraft position, velocity, and body angular velocity respectively. $\boldsymbol{\sigma}$ is the modified Rodrigues parameters (MRP) vector to describe the chaser's attitude with respect to frame $\mathscr{F}_i$. They are expressed in the frame $\mathscr{F}_c$.