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Research article

Adaptive nonlinear robust relative pose control of spacecraft autonomous rendezvous and proximity operations

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ABSTRACT

This paper studies relative pose control for a rigid spacecraft with parametric uncertainties approaching to an unknown tumbling target in disturbed space environment. State feedback controllers for relative translation and relative rotation are designed in an adaptive nonlinear robust control framework. The element-wise and norm-wise adaptive laws are utilized to compensate the parametric uncertainties of chaser and target spacecraft, respectively. External disturbances acting on two spacecraft are treated as a lumped and bounded perturbation input for system. To achieve the prescribed disturbance attenuation performance index, feedback gains of controllers are designed by solving linear matrix inequality problems so that lumped disturbance attenuation with respect to the controlled output is ensured in the L_2-gain sense. Moreover, in the absence of lumped disturbance input, asymptotical convergence of relative pose are proved by using the Lyapunov method. Numerical simulations are performed to show that position tracking and attitude synchronization are accomplished in spite of the presence of couplings and uncertainties.

1. Introduction

Many space programs such as rendezvous and docking, capturing, salvage and repair, refueling, and debris removal in orbit have been received increasing attention in recent years. A key enabling technology in these missions is autonomous rendezvous and proximity that requires precise relative pose control between two spacecraft. However, the spacecraft relative kinematics and dynamics are highly nonlinear and coupled, thus traditional linear control designs are unsuitable, especially when close distance and large angle relative maneuvers are required.

A robust controller based on state dependent Riccati equation technology was designed by [1] for spacecraft relative pose motion in rendezvous and proximity. Relative position control based on phase plane control technique and relative attitude control based on relative quaternion feedback scheme were described in [2], but the uncertainties of the pursue spacecraft were not considered. The integrated position and attitude control problem was considered for spacecraft rendezvous and proximity with parametric uncertainties, bounded disturbances, and measurement noises in [3], and ultimate boundedness of the errors was achieved. Liang and Ma [4] proposed a Lyapunov-based adaptive tracking control approach for tracking an arbitrary angular velocity of a tumbling satellite before docking and for stabilizing the rotation of the two-satellite compound system after docking. This method stabilizes the rotational motion only, but the coupled relative translational motion was not considered as in [5]. Singla et al. [6] proposed an output feedback adaptive control to solve the spacecraft autonomous rendezvous and docking problem under measurement uncertainties, but the coupling effect between relative translation and relative rotation was not considered. Xin and Pan [7] addressed a closed-form nonlinear optimal control solution of spacecraft to approach a target spacecraft by using θ-D technique. Although the translational and rotational dynamics coupled with the flexible structure motion were considered in one unified optimal control framework, but the parametric uncertainties and external disturbances were not considered. Then, they researched the same problem in [8,9] and redesigned new optimal controllers with considering modeling uncertainties. In [10], the relative position control problem in spacecraft rendezvous and proximity was converted into a model predictive control optimization problem with considering constraints on thrust magnitude, constraints on spacecraft positioning within line-of-sight cone, and constraints on approach velocity. A command filter based adaptive backstepping controller was developed for spacecraft rendezvous

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and proximity in [11], but the amount of online estimate parameters is large to increase the computational burden. The relative navigation, guidance and control algorithms of spacecraft rendezvous and proximity was designed based on the analytical closed-form solution of the Tschauner-Hempel equations in [12], where the methods are general and able to translate the chaser spacecraft in any direction and approach to the target spacecraft. In [13], a nonlinear adaptive position and attitude tracking controller was proposed for spacecraft rendezvous and proximity, and the dual quaternions were used to represent the absolute and relative attitude and position. In [14] and [15], the control problem of multiple spacecraft rendezvous and proximity were studied, and a linear quadratic optimal distributed controller was also formulated.

Motivated by aforementioned observations, we consider the problem of driving a chaser spacecraft to a fixed position with respect to the target and reorienting the chaser's attitude along with the attitude of target. The new contributions in this work are as follows.

- Compared with the models presented in [16,17], the external disturbances in uncontrolled target dynamics are considered in this paper, and unknown external disturbances in two spacecraft dynamics are regarded as a lumped and bounded perturbation in system model. Relative position and relative attitude controllers are developed based on an adaptive robust control method, where the controllers have classical proportional-integral-derivative structure, and adaptive laws are used to estimate the uncertain mass and inertia parameters of the chaser spacecraft and the unknown inertia of the target spacecraft.
- Compared with the controllers in [1–15], a simple six-degrees-of-freedom adaptive robust relative motion controller is designed to achieve spacecraft rendezvous and proximity, and the performance of relative position tracking and attitude synchronization is evaluated by L_2-gain from lumped perturbation to controlled output. The proposed robust state feedback controller has positive definite gain matrices whose condition to be satisfied is given by a linear matrix inequality. The closed-loop system is uniformly ultimately bounded stable with the L_2-gain less than any given small level. Meanwhile, in the absence of lumped perturbation, asymptotic stability of the closed-loop system is also proved in the Lyapunov framework.

The rest of this paper is arranged as following. In Section 2, mathematical model of the spacecraft proximity maneuvers is derived, and objective of controller design is stated. A detailed designing procedure of adaptive robust controllers and stability analysis are presented in Section 3. Simulation results are displayed in Section 4. Finally, Section 5 concludes the work.

Notations Skew symmetric matrix derived from vector $\boldsymbol{a} = [a_1, a_2, a_3]^{\mathrm{T}} \in \mathbb{R}^3$ is defined by

$$S(\boldsymbol{a}) = \begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{bmatrix} \in \mathbb{R}^{3\times 3}.$$

it satisfies $\| S(\boldsymbol{a})\| = \| \boldsymbol{a} \|$, $\boldsymbol{a}^{\mathrm{T}} S(\boldsymbol{a}) = \boldsymbol{0}$, and $S(\boldsymbol{a})\boldsymbol{b} = -S(\boldsymbol{b})\boldsymbol{a}$, $\boldsymbol{b}^{\mathrm{T}} S(\boldsymbol{a})\boldsymbol{b} = 0$ for any $\boldsymbol{b} \in \mathbb{R}^3$. $\| \boldsymbol{a} \| \le \| \boldsymbol{a} \|_1$, where $\| \boldsymbol{a} \|$ and $\| \boldsymbol{a} \|_1$ denote vector 2-norm and 1-norm, respectively. $A > 0$ denotes A being positive definite, and $\| A \|$ is the induced matrix 2-norm. I_3 and O_3 are 3×3 unitary and zero matrices, respectively. $\mathrm{sgn}(\boldsymbol{a}) \triangleq [\mathrm{sgn}(a_1), \mathrm{sgn}(a_2), \mathrm{sgn}(a_3)]^{\mathrm{T}}$ for any $\boldsymbol{a} \in \mathbb{R}^3$, where the standard signum function is defined by

$$\mathrm{sgn}(a_i) = \begin{cases} -1, & a_i < 0 \\ 0, & a_i = 0, \quad i = 1, 2, 3. \\ 1, & a_i > 0 \end{cases}$$

2. Problem statement

2.1. Dynamics of the chaser and target

We investigate a control problem in which a chaser spacecraft tracks a tumbling space target under the influence of disturbances. Frames and vectors are defined in Fig. 1, where $\mathcal{F}_i \triangleq \{\mathbf{O}x_i y_i z_i\}$ denotes the Earth-centered inertial frame, $\mathcal{F}_c \triangleq \{\mathbf{C}xyz\}$ and $\mathcal{F}_t \triangleq \{\mathbf{T}x_t y_t z_t\}$ are chaser and target spacecraft body-fixed frames, respectively. The objective of controller design is to control the chaser so that its mass center $\mathbf{C}$ tracks point $\mathbf{P}$ and frame $\mathcal{F}_c$ tracks frame $\mathcal{F}_t$.

The position of mass center $\mathbf{C}$ and the attitude of $\mathcal{F}_c$ with respect to $\mathcal{F}_i$ are given by following kinematics and dynamics expressed in frame $\mathcal{F}_c$, if the modified Rodrigues parameters(MRP) are used for attitude parametrization [18].

$$\begin{cases} \dot{\boldsymbol{r}} = \boldsymbol{v} - S(\boldsymbol{\omega})\boldsymbol{r} \\ m\dot{\boldsymbol{v}} + mS(\boldsymbol{\omega})\boldsymbol{v} + m\mu\boldsymbol{r} = \boldsymbol{f} + \boldsymbol{d}_c \\ \dot{\boldsymbol{\sigma}} = G(\boldsymbol{\sigma})\boldsymbol{\omega} \\ J\dot{\boldsymbol{\omega}} + S(\boldsymbol{\omega})J\boldsymbol{\omega} = \boldsymbol{\tau} + \boldsymbol{w}_c \end{cases} \tag{1}$$

where $G(\boldsymbol{\sigma}) = \frac{1}{4}[(1 - \boldsymbol{\sigma}^{\mathrm{T}}\boldsymbol{\sigma})I_3 + 2S(\boldsymbol{\sigma}) + 2\boldsymbol{\sigma}\boldsymbol{\sigma}^{\mathrm{T}}]$, $\mu = \mu_g / \| \boldsymbol{r} \|^3$; $\boldsymbol{r} \in \mathbb{R}^3$ is the position and $\boldsymbol{\sigma}$ is the MRP attitude; $\boldsymbol{v}, \boldsymbol{\omega} \in \mathbb{R}^3$ are linear and angular velocities; μ_g is the gravitational constant of the Earth, $\boldsymbol{f}, \boldsymbol{\tau} \in \mathbb{R}^3$ are the control force and torque; $\boldsymbol{d}_c, \boldsymbol{w}_c \in \mathbb{R}^3$ are the disturbance force and torque; $m \in \mathbb{R}$ and $J \in \mathbb{R}^{3\times 3}$ are the chaser mass and the positive definite symmetric inertia matrix, respectively.

With ignoring the control forces and torques, kinematics and dynamics of a tumbling target can be described in frame $\mathcal{F}_t$ as

$$\begin{cases} \dot{\boldsymbol{r}}_t = \boldsymbol{v}_t - S(\boldsymbol{\omega}_t)\boldsymbol{r}_t \\ m_t\dot{\boldsymbol{v}}_t + m_t S(\boldsymbol{\omega}_t)\boldsymbol{v}_t + m_t\mu_t\boldsymbol{r}_t = \boldsymbol{d}_t \\ \dot{\boldsymbol{\sigma}}_t = G(\boldsymbol{\sigma}_t)\boldsymbol{\omega}_t \\ J_t\dot{\boldsymbol{\omega}}_t + S(\boldsymbol{\omega}_t)J_t\boldsymbol{\omega}_t = \boldsymbol{w}_t \end{cases} \tag{2}$$

where $G(\boldsymbol{\sigma}_t) = \frac{1}{4}[(1 - \boldsymbol{\sigma}_t^{\mathrm{T}}\boldsymbol{\sigma}_t)I_3 + 2S(\boldsymbol{\sigma}_t) + 2\boldsymbol{\sigma}_t\boldsymbol{\sigma}_t^{\mathrm{T}}]$, $\mu_t = \mu_g / \| \boldsymbol{r}_t \|^3$; $\boldsymbol{r}_t \in \mathbb{R}^3$ and $\boldsymbol{\sigma}_t$ are position and attitude of the target; $\boldsymbol{v}_t, \boldsymbol{\omega}_t \in \mathbb{R}^3$ are linear and angular velocities of the target; $\boldsymbol{d}_t, \boldsymbol{w}_t \in \mathbb{R}^3$ are the disturbance force and torque; $m_t \in \mathbb{R}$ and $J_t \in \mathbb{R}^{3\times 3}$ are mass and inertial matrix of the target, respectively.

Remark 1. When the external disturbances $\boldsymbol{d}_t = \boldsymbol{0}$, and $\boldsymbol{w}_t = \boldsymbol{0}$ in (2), then the undisturbed dynamics of the target can be written as $\dot{\boldsymbol{v}}_t = -S(\boldsymbol{\omega}_t)\boldsymbol{v}_t - \mu_t\boldsymbol{r}_t$ and $J_t\dot{\boldsymbol{\omega}}_t = -S(\boldsymbol{\omega}_t)J_t\boldsymbol{\omega}_t$. The target's orbit

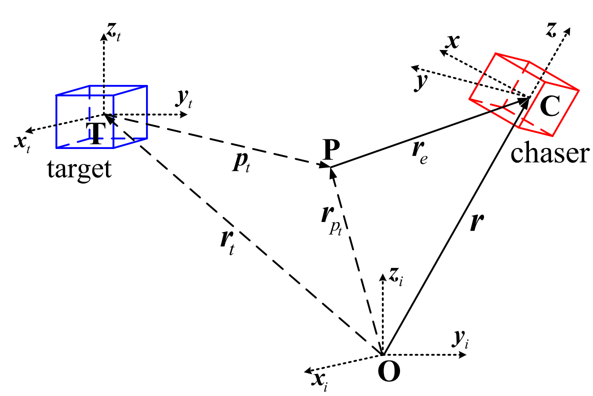

Fig. 1. Definitions of frames and vectors.