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Research article

Adaptive control for spacecraft rendezvous subject to actuator faults and saturations

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ABSTRACT

An adaptive saturated fault-tolerant controller is proposed for a spacecraft rendezvous maneuver with a cooperative target spacecraft. The six-degree-of-freedom (6-DOF) relative dynamics subject to unknown inertial parameters, external disturbances, actuator faults and saturations are formulated in the pursuer's body-fixed frame. To design controller satisfying asymmetric magnitude constraints, a modified smooth hyperbolic tangent function is applied to approximate the non-differentiable saturation function. Based on the augmented system technique, an adaptive fault-tolerant saturated controller is designed for the pursuer by using a Nussbaum function matrix compensating for the nonlinear term arising from the input saturations. In addition, a Levant differentiator is introduced to obtain the derivative of the virtual control in finite time that avoids the complicated calculation. It is proved via Lyapunov stability theory that all the signals in the closed-loop augmented system are bounded and the relative errors asymptotically converge to zero. Numerical simulations are performed to illustrate effectiveness of the proposed controller.

1. Introduction

Spacecraft autonomous rendezvous control problem has been studied by more and more researchers for recent years because of its widely applications in orbit missions, such as construction of space station, space debris removal, etc. In order to achieve these control objectives efficiently with high accuracy, attitude and position dynamics control of spacecraft should be operated simultaneously. Nevertheless, it is still a challenge to complete these control problems with unknown parameters and external disturbances.

A variety of nonlinear controllers have been developed to control attitude and position of spacecraft. For a 6-DOF spacecraft coordination control problem, three state feedback controllers are exploited in Ref. [1]. A disturbance observer based nonlinear controller is designed in Ref. [2] for a spacecraft formation control problem. With a pre-determined trajectory, a finite time controller is proposed in Ref. [3] for a 6-DOF spacecraft tracking problem. However, these results [1–3] are obtained with exact knowledge of model parameters and (bounds of) external disturbances.

As for the 6-DOF spacecraft control problem without exact knowledge of parameters and external disturbances, different kinds of adaptive robust controllers have been developed. For a spacecraft rendezvous and docking operation subject to uncertainties and measurement noises, an adaptive output feedback controller is developed in Ref. [4]. For a spacecraft proximity maneuver with model uncertainty, an integrated robust adaptive controller is designed in Ref. [5]. For a spacecraft formation flying tracking maneuver with inertial parameter uncertainty and periodic disturbances, an adaptive controller is designed in Ref. [6]. To solve spacecraft formation flying maneuver, a neural networks based sliding mode controller is developed in Ref. [7]. For a cooperative rendezvous and docking control problem, an adaptive switching controller consisting of a neural controller and a robust controller is proposed in Ref. [8].

Since spacecraft flies in orbit for a long time, some unexpected faults may arise in the aged actuators, which might result in unsatisfactory performance or make the control system unstable. In addition, the practical hardware limits the control output of actuators, which implies that control saturations should be considered in spacecraft controller design. For 6-DOF spacecraft operations with control constraints or actuator faults, saturated controllers [9–12] and fault-tolerant controllers [13–15] are designed. For the control problem of cooperative rendezvous and docking with actuator faults and saturation, a disturbance observer based saturated fault-tolerant controller is developed in Ref. [16]. Based on the modelling by dual-quaternion, a hybrid integral sliding mode based saturated fault-tolerant controller [17] are developed for the 6-DOF spacecraft control problem.

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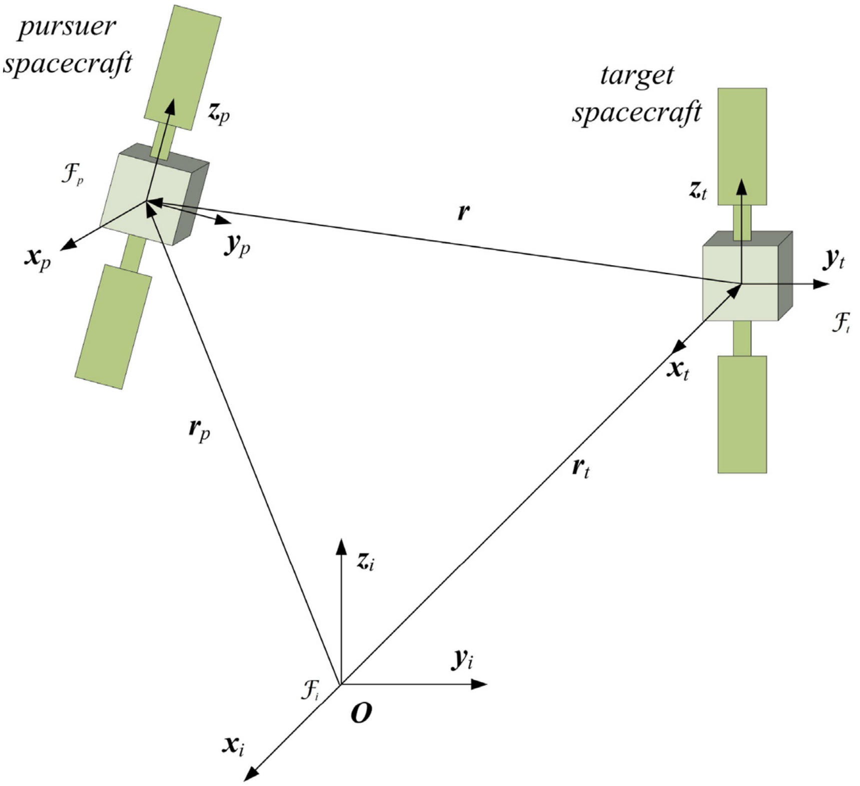

Fig. 1. Reference frames.

In this paper, we are aiming to design controller for the pursuer to rendezvous with a cooperative target, where the pursuer is subject to unknown inertial parameters, disturbances, actuator faults and saturations. To address this problem, the 6-DOF relative dynamics model is expressed in pursuer's body-fixed frame. In order to design the controller with asymmetric magnitude constraints, a modified smooth hyperbolic tangent function is applied instead of the non-differentiable saturation function. Based on the augmented system technique, a continuous adaptive fault-tolerant saturated controller is proposed for the pursuer, where a Nussbaum function matrix is applied to compensate for the nonlinear term arising from the input saturations. In addition, a Levant differentiator is employed to obtain the derivative of the virtual control in finite time that avoids the complicated calculation. The asymptotic stability of the closed-loop augmented system is proved via Lyapunov stability theory. Numerical simulations are carried out to verify the effectiveness of the proposed controller. Compared with the aforementioned results, the main contributions are listed as follows. i) The 6-DOF spacecraft rendezvous control problem subject to unknown inertial parameters, external disturbance, actuator faults and saturations is investigated in this work, a continuous controller is designed such that the asymptotic stability of the closed-loop system is achieved rather than the boundedness results obtained in Refs. [16,17]. ii) In contrast to the non-differentiable saturation function used in Refs. [9,11,16], a modified smooth hyperbolic tangent function [18] is applied in this work to approximate the non-differentiable asymmetric saturation function, with which not only the asymmetric magnitude constraints can be satisfied but also smoother control signals can be provided. iii) Furthermore, instead of the command filter estimating the derivative of virtual control in Refs. [9,18], a Levant differentiator is introduced to obtain the derivative of the virtual control in finite time that avoids the complicated calculation.

The layout of this paper is organised as follows. In Section 2, some mathematical preliminaries are provided. In Section 3, 6-DOF relative dynamics and the control objective are presented. In Section 4, detailed controller design procedure and stability proof are expressed. In Section 5, numerical simulations are performed. Finally, this paper is concluded in Section 6.

2. Preliminaries

In this paper, some useful definitions and lemmas are presented. For any scalar $a \in \mathbb{R}$ and any vector $\boldsymbol{x} = [x_1, x_2, \ldots, x_n]^T \in \mathbb{R}^n$, $|\boldsymbol{x}| = [|x_1|, |x_2|, \ldots, |x_n|]^T$ and $|\boldsymbol{x}|^a = [|x_1|^a, |x_2|^a, \ldots, |x_n|^a]^T$, $\|\boldsymbol{x}\|$ denotes its Euclidean norm. For any square matrix $\boldsymbol{X} \in \mathbb{R}^{n\times n}$, $\lambda_{\min}(\boldsymbol{X})$ and $\lambda_{\max}(\boldsymbol{X})$ denote its minimum and maximum eigenvalues, respectively. For any $\boldsymbol{x} = [x_1, x_2, \ldots, x_n]^T \in \mathbb{R}^n$, the diagonal matrix operator $\mathrm{diag}(\boldsymbol{x})$: $\mathbb{R}^n \to \mathbb{R}^{n\times n}$ is defined as $\mathrm{diag}(\boldsymbol{x}) = \mathrm{diag}(x_1, x_2, \ldots, x_n)$. For any vector $\boldsymbol{x} = [x_1, x_2, x_3]^T \in \mathbb{R}^3$, superscript × represents a transformation from $\boldsymbol{x}$ to a skew-symmetric matrix: $\boldsymbol{x}^{\times} = [0, -x_3, x_2; x_3, 0, -x_1; -x_2, x_1, 0]$.

Lemma 1. [19] *Let V and ψ be smooth functions defined on $[0, t_f)$ with $V(t) \geq 0$, $\forall t \in [0, t_f)$, and $\mathcal{N}(\psi)$ be an even smooth Nussbaum-type function. If the following inequality holds:*

$$V(t) \leq c_0 + e^{-ct} \sum_{i=1}^{n} \frac{1}{k_i} \int_0^t (g(y_i(\tau))\mathcal{N}(\psi_i)\dot{\psi}_i - \dot{\psi}_i) e^{c\tau} \mathrm{d}\tau,$$

where c, c_0, k_i are positive constants, $g(y_i(t))$ is a time-varying parameter which takes values in the unknown closed set $\mathcal{D}$ with $0 \notin \mathcal{D}$, then $V(t)$, $\psi(t)$ and $\sum_{i=1}^{n} k_i^{-1} \int_0^t (g(y_i(\tau))\mathcal{N}(\psi_i)\dot{\psi}_i - \dot{\psi}_i) e^{c\tau} \mathrm{d}\tau$ are bounded on $[0, t_f)$.

Lemma 2. [20] *(Barbalat's Lemma) Let $f\colon \mathbb{R} \to \mathbb{R}$ be a uniformly continuous function on $[0, \infty)$. Suppose that $\lim_{t\to\infty} \int_0^t f(\tau) d\tau$ exists and is finite, then,*

$f(t) \to 0$ as $t \to \infty$.