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Robust adaptive backstepping neural networks control for spacecraft rendezvous and docking with input saturation

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ABSTRACT

This paper presents a robust adaptive neural networks control strategy for spacecraft rendezvous and docking with the coupled position and attitude dynamics under input saturation. Backstepping technique is applied to design a relative attitude controller and a relative position controller, respectively. The dynamics uncertainties are approximated by radial basis function neural networks (RBFNNs). A novel switching controller consists of an adaptive neural networks controller dominating in its active region combined with an extra robust controller to avoid invalidation of the RBFNNs destroying stability of the system outside the neural active region. An auxiliary signal is introduced to compensate the input saturation with anti-windup technique, and a command filter is employed to approximate derivative of the virtual control in the backstepping procedure. Globally uniformly ultimately bounded of the relative states is proved via Lyapunov theory. Simulation example demonstrates effectiveness of the proposed control scheme.

1. Introduction

With the continuous increase of orbit activity, autonomous rendezvous and docking has become an important research topic. Typical applications that could use this include collecting and removing space debris, servicing a malfunctioning satellite, refueling a powerless satellite, or installing improved technology. In order to achieve control requirements of these missions with high precision of position and attitude tracking, the six degrees-of-freedom (6-DOF) relative kinematics and relative dynamics between pursuer and target spacecrafts with highly nonlinear and strongly coupled should be taken into account.

Several research works dealing with both relative position and relative attitude motions of orbiting spacecrafts have been conducted over the past decade. An output feedback structured model reference adaptive control law has been developed for spacecraft rendezvous and docking problems with integrated position and attitude relative motions [1], ultimate boundedness of the tracking errors is achieved in spite of parametric uncertainties, bounded disturbances, and measurement noises. Subbarao et al. [2] consider the problem of motion synchronization of free-flying robotic spacecraft and serviceable floating objects in space with unknown but bounded disturbances and an adaptive control law is derived by feedback-linearization-based approaches to ensure asymptotic stability of the tracking errors. Based on the model presented in [3], several control schemes are proposed. Kristiansen et al. [4] utilize three nonlinear state feedback controllers, involving passivity-based PD+ controller, sliding surface controller, and integrator backstepping controller, to solve the problem of tracking relative 6-DOF motion in a leader–follower spacecraft formation. Zhang et al. [5] formulate a finite-time controller by using terminal sliding mode technique for spacecraft relative motion by designing a pre-determined trajectory, and the thruster installation misalignment is also modeled. Via backstepping theory, control input saturation problem [6] for spacecraft proximity operation with thruster installation misalignment [7] is solved by introducing a command filter. A problem of 6-DOF synchronized control of spacecraft formation flying in the presence of input constraint and parameter uncertainties is solved in [8], a command filter is used to overcome the control saturation. Shan [9] presents an adaptive synchronization control scheme for desired attitude and position tracking of spacecraft formation flying by introducing a synchronization error. Xin [10] presents a nonlinear optimal control solution of spacecraft to finish tumbling target approach by using the θ-D technique, and a further research [11] derives an optimal controller with considering the modeling uncertainties. A sliding mode control strategy with the adaptive gain and neural networks for a 6-DOF spacecraft formation flying control problem is solved in [12]. A composite control scheme for the same problem is proposed in

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[13] with a feedforward compensator based on a nonlinear disturbance observer technique.

In practical spacecraft rendezvous and docking maneuver, the inertial moments and mass cannot be known exactly, and the spacecraft is always subjected to external disturbances which arises from the unexpected environmental torques and forces. The presence of the external disturbances and the parameter uncertainties make the rendezvous and docking control problem more complicated [7]. The parameter uncertainties are not taken into account in [4,5,13], and the upper bound of the disturbance is known in [4,5]. Moreover, much literature has ignored a very important feature (actuator saturation), which always causes performance deterioration and even system instability in practical systems [14]. Only several research studies are concerned about the problem with control saturations due to the complicated nonlinear dynamics of the spacecraft systems [6–8]. In [8], the research work gives a control design based on the assumption that the uncertainties are bounded by known upper bounds. Actually, in practical spacecraft systems, the upper bound of the disturbance may not be easily obtained due to the complexity of the disturbance. Even if the bound can sometimes be obtained, it is usually very conservative.

In fact, it is not hard to only tackle one of the above problems with some control technique. However, the situation will get worse and be hard to deal with once all the above factors should be taken into account. Thus it is necessary and worthwhile to focus on the spacecraft rendezvous and docking control problems with the simultaneous consideration of external disturbance, unknown mass and inertial moments, and control saturation. Motivated by [15,16], a novel switching controller, which consists of a conventional adaptive neural networks controller dominating in the neural networks active region and an extra robust controller to pull back the transient outside the active region is used to overcome the parameter uncertainties and disturbance, and an auxiliary signal [7,8] is introduced to compensate for the control input saturation effect by using anti-windup technique.

In this paper, we consider the problem of driving a pursuer spacecraft to approximate a cooperative target spacecraft and synchronizing the spacecraft attitude with the attitude of the target. A nonlinear and coupled mechanical model for 6-DOF relative motion is expressed in the pursuer body-fixed frame. The uncertainties of the dynamics are compensated by using RBFNNs. A novel switching controller is developed by combining direct adaptive control approach and backstepping technique, which consists of a conventional adaptive neural controller dominating in the neural active region and an extra robust controller to pull back the transient outside the neural active region. The controllers work together not only improving the control accuracy, but also reducing real-time computing burden of the controller. A command filter is introduced to estimate the derivative of a virtual control input and two auxiliary signals are used to overcome control saturation via anti-wind up technique. Globally uniformly ultimately bounded stability for the closed-loop system is proved, and the performance of the proposed controller is demonstrated via a numerical example.

Through this paper, the main contributions are as follows: (1) robust RBFNNs are utilized to estimate and compensate for the uncertainties, so that the control accuracy is improved than only the robust method is used; (2) the traditional RBFNNs is enhanced with a robust control via an nth-order smooth switching function, which consists of a conventional adaptive neural controller dominating in the neural active region and an extra robust controller to pull back the transient outside the neural active region, the controllers work together not only improving the control accuracy, but also reducing real-time computing burden of the controller; (3) a command filter is introduced to estimate the derivative of a virtual control input and two auxiliary signals are used to overcome control saturation via anti-wind up technique.

This paper is organized as follows. In Section 2, some preliminaries used throughout this paper are presented. The relative dynamic model and control problem are stated in Section 3. Then, a novel controller is developed in Section 4. Section 5 proposes a numerical simulation scenario. Finally, the conclusions are summarized in Section 6.

2. Preliminaries

2.1. Notations

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

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

For any vector $\boldsymbol{x} = [x_1, x_2, \ldots, x_n]^T$, $|\boldsymbol{x}|$ is defined as $|\boldsymbol{x}| = [|x_1|, |x_2|, \ldots, |x_n|]^T$; $|\cdot|$ denotes the absolute value of a scalar; $\|\cdot\|$ denotes the Euclidean norm of a vector or the Frobenius norm of a matrix; $\lambda_{min}(\boldsymbol{A})$ and $\lambda_{max}(\boldsymbol{A})$ denote the smallest and largest eigenvalues of a square matrix $\boldsymbol{A}$, respectively. For a matrix $\boldsymbol{X} \in R^{n\times n}$, $\mathrm{tr}(\boldsymbol{X})$ denotes its trace with the property $\mathrm{tr}(\boldsymbol{X}^T\boldsymbol{X}) = \|X\|^2$.

2.2. RBFNNs approximation

Suppose $f(\boldsymbol{x}): \mathbb{R}^m \to \mathbb{R}$ is an unknown smooth nonlinear functions and it can be approximated on a compact set $\Omega \subseteq \mathbb{R}^m$ by the following RBFNNs:

$$f(\boldsymbol{x}) = \boldsymbol{w}^T \Phi(\boldsymbol{x}) + \epsilon$$

where ϵ is the approximation error which is bounded over, namely $|\epsilon| \le \overline{\epsilon}$, where $\overline{\epsilon}$ is an unknown constant. $\boldsymbol{w} \subseteq \mathbb{R}^l$ represents the weight vector, where the node number of the neural networks is l. More nodes means more accurate approximation [15]. $\boldsymbol{w}$ is defined by

$$\boldsymbol{w} = \arg\min_{\hat{\boldsymbol{w}}} \left\{ \sup_{\boldsymbol{x}\in\Omega} |f(\boldsymbol{x}) - \hat{\boldsymbol{w}}^T \Phi(\boldsymbol{x})| \right\}$$

where $\hat{\boldsymbol{w}}$ is the estimate of $\boldsymbol{w}$, $\Phi(\boldsymbol{x}) = [\phi_1(\boldsymbol{x}), \phi_2(\boldsymbol{x}), \ldots, \phi_l(\boldsymbol{x})]^T : \Omega \to \mathbb{R}^l$ represents the radial basis function vector, its elements are selected as the Gaussian functions

$$\phi_i(\boldsymbol{x}) = \exp\left(-\frac{\|\boldsymbol{x} - \boldsymbol{\mu_i}\|^2}{\eta_i^2} \right), \quad i = 1, 2, \cdots, l$$

where $\boldsymbol{\mu_i} \in \mathbb{R}^m$ are the centers and $\eta_i > 0$ are the spreads of the Gaussian functions.

2.3. Definitions and lemmas

Definition 1 (*Wu et al. [16]*). For all $\boldsymbol{x} \in \mathbb{R}^m$ and given constants a and b satisfying $0 < a < b$, the following nonlinear switching

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