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Attitude tracking control for spacecraft with robust adaptive RBFNN augmenting sliding mode control

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ABSTRACT

This paper investigates the attitude tracking problem for a rigid spacecraft subject to uncertain inertial parameters and external disturbances. A robust adaptive radial basis function neural network (RBFNN) augmenting sliding mode control strategy is developed. The classical sliding mode control serves as the main control framework, which is augmented by a robust adaptive RBFNN to approximate uncertain dynamics consisting of the inertial parameters and external disturbances. The robust adaptive RBFNN approximation combines a conventional RBFNN and a robust adaption, where the conventional RBFNN dominates in the neural active region, the robust adaptive control takes effect in the robust active region, and a smooth switching function is utilized to achieve a smooth transition between two regions. With this adaptive structure, the full-envelop attitude tracking can be realized. This systematic methodology is demonstrated to be able to accomplish the ultimately convergent attitude tracking of the spacecraft. Simulations verify and highlight the theoretical results.

1. Introduction

With the improvement of aerospace technology, more and more attention is paid to the development of spacecraft [1]. The attitude tracking, as a key issue for modern spacecraft systems, draws a growing interest among research communities. Nevertheless, high nonlinearity, uncertain inertial parameters and unexpected external disturbances make the attitude tracking control challenging [2]; and effective and flexible control approaches are imperative.

The sliding mode control is characterized by computational facilitation and in particular strong robustness against uncertainties and disturbances [3–6], which has been extensively studied for spacecraft attitude tracking controls [7–10]. Other approaches have also been developed to deal with the attitude control problem. An auxiliary unit-quaternion dynamics with the same structure as the actual one was introduced in [11] to design a controller for the almost globally asymptotic attitude tracking without taking uncertainty and disturbance into consideration. Based on the mini-max approach and the inverse optimal approach, a robust control was proposed in [12] to ensure the optical attitude tracking with disturbance attenuation. Furthermore, for uncertainties in the spacecraft attitude tracking problem, which include unknown inertial parameters and unexpected external disturbances, various adaptive algorithms have been studied to estimate and compensate them [2,7,13]; however, discontinuous control and high-frequency switching may lead to chattering phenomenon, which is unfavorable to practical applications [3].

Neural networks (NNs) are capable of approximating smooth functions to arbitrary accuracy over a compact set [14–16]. They are ideal implements for the system control approach exploitation, especially for systems subject to strong uncertainty and high nonlinearity. NNs have been widely applied to deal with the attitude tracking issue of the spacecraft (e.g. [17–20]). In [17] and [18], Chebyshev NNs (CNNs) were applied respectively for the finite-time and output–feedback attitude tracking of the spacecraft suffering from structured and unstructured uncertainties. In [19], a radial basis function NN (RBFNN) was used to synthesize controller and adaptive mechanisms for estimating unknown dynamics, which achieved the attitude tracking with the L_2-gain performance. In [20], a normalized input NN (NINN), estimating and removing unknown items, was augmented to a baseline controller, which realized the ultimately bounded attitude tracking. However, the NN approximation is valid only over an active region; once it transgresses this region, the tracking performance, even the stability of the system, may be destroyed [21,22]. To broaden the active

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region, a number of nodes of NNs are required, whereas massive nodes bring in calculation burden [16].

This paper develops a robust adaptive RBFNN augmenting sliding mode control strategy to autonomously accomplish the attitude tracking for a rigid spacecraft, which is subject to uncertain inertial parameters and unexpected external disturbances. Based on a decomposed model, a classical sliding mode control scheme is applied as the main framework, while a robust adaptive RBFNN is adopted to approximate and compensate the uncertain dynamics composed by the inertial parameters and external disturbances. It is demonstrated that the proposed control approach achieves the full-envelop attitude tracking of the spacecraft with boundedness. Simulations validate the theoretical analysis. Main contributions of this paper are enumerated as follows:

(1) A robust adaptive control strategy is developed to complete the full-envelop attitude tracking control in the presence of inertial parameter uncertainties and external disturbances.

(2) A novel robust adaptive RBFNN is developed to approximate and compensate the uncertain dynamics consisting of the uncertain inertial parameters and disturbances.

(3) The conventional RBFNN is enhanced with a robust adaption through a smooth switching function, so that a global-scope approximation is achieved.

The remaining sections of this paper are organized as follows: Section 2 provides some mathematical preliminaries; Section 3 states the problem to be solved; Section 4 streamlines the main control strategy and presents the stability analysis; Section 5 performs simulations to verify and highlight the proposed control approach; and Section 6 draws conclusions.

2. Mathematical preliminaries

In the following discussion, $\mathbb{R}^{m\times n}$ denotes the Euclidean space of dimension $m\times n$, $|\cdot|$ denotes the absolute value of a scalar, $\|\cdot\|$ denotes the Euclidean norm of a vector or the Frobenius norm of a matrix, and $\boldsymbol{I}_3\in\mathbb{R}^{3\times 3}$ denotes a 3×3 identity matrix. For a square matrix $\boldsymbol{X}\in\mathbb{R}^{n\times n}$, $\mathrm{tr}(\boldsymbol{X})$ denotes its trace satisfying the property $\mathrm{tr}(\boldsymbol{X}^T\boldsymbol{X})=\|\boldsymbol{X}\|^2$. The superscript "$\times$" denotes an operation which transforms a vector $\boldsymbol{x}=[x_1,x_2,x_3]^T\in\mathbb{R}^3$ to the following skew-symmetric matrix:

$$\boldsymbol{x}^\times=\begin{bmatrix}0 & -x_3 & x_2\\ x_3 & 0 & -x_1\\ -x_2 & x_1 & 0\end{bmatrix}.$$

Suppose that $f(\boldsymbol{x}):\mathbb{R}^n\to\mathbb{R}$ is an unknown smooth nonlinear function. It can be approximated over a compact set $\Omega\subseteq\mathbb{R}^n$ with the following l-node RBFNN [23]:

$$f(\boldsymbol{x})=\boldsymbol{w}^{*T}\boldsymbol{\Phi}(\boldsymbol{x})+\varepsilon, \tag{1}$$

where $\boldsymbol{w}^*\in\mathbb{R}^l$ denotes the optimal weight vector and is defined as

$$\boldsymbol{w}^*=\arg\min_{\hat{\boldsymbol{w}}}\{\sup_{\boldsymbol{x}\in\Omega}|f(\boldsymbol{x})-\hat{\boldsymbol{w}}^T\boldsymbol{\Phi}(\boldsymbol{x})|\}, \tag{2}$$

with $\hat{\boldsymbol{w}}$ as the estimate of $\boldsymbol{w}^*$, $\boldsymbol{\Phi}(\boldsymbol{x})=[\phi_1(\boldsymbol{x}),\phi_2(\boldsymbol{x}),\dots,\phi_l(\boldsymbol{x})]^T:\Omega\to\mathbb{R}^l$ denotes the radial basis function vector and its components are chosen as the Gaussian function:

$$\phi_i(\boldsymbol{x})=\exp(\frac{\|\boldsymbol{x}-\mu_i\|^2}{\sigma_i^2}),\ i=1,\dots,l, \tag{3}$$

with $\mu_i\in\mathbb{R}^m$ and $\sigma_i\in\mathbb{R}$ as the center and spread, and ε is the approximation error and is bounded over Ω.

Moreover, based on the RBFNN approximation theory [16], more nodes mean more approximation accuracy; however, a number of nodes increase calculation burden, which may cause programs to crash. To obviate such dilemma, a robust adaption is augmented to the RBFNN. The RBFNN takes effect within the neural active region Ω, while the robust adaptive control works outside Ω (defined as the robust active region). In terms of this adaptive framework, the approximation accuracy can be warranted without massive nodes. In addition, to ensure a smooth transition between two regions, the RBFNN and the robust adaption are connected with the following switching function.

Lemma 1 *([22,24]). The function $h(\boldsymbol{x}):\mathbb{R}^m\to\mathbb{R}$ defined by*

$$h(\boldsymbol{x})=\begin{cases}0, & \|\boldsymbol{x}\|\le a,\\ 1-\cos^n(\frac{\pi}{2}\sin^n(\frac{\pi}{2}\frac{\|\boldsymbol{x}\|^2-a^2}{b^2-a^2})), & a<\|\boldsymbol{x}\|<b,\\ 1, & \|\boldsymbol{x}\|\ge b\end{cases} \tag{4}$$

is n-order smooth:

Lemma 2 *([24,25]). Given $\eta>0$, the following inequality holds for $x\in\mathbb{R}$:*

$$0\le|x|-x\tanh(\frac{x}{\eta})\le\kappa\eta, \tag{5}$$

where κ satisfies $\kappa=e^{-(\kappa+1)}$, i.e., $\kappa=0.2785$.

3. Spacecraft attitude model

3.1. Attitude kinematics and dynamics

There are three kinds of coordinate frames to describe the rigid spacecraft attitude: body frame, orbital frame and inertial frame; their definitions are in accordance with the ones in [17]. According to [26], the attitude kinematics and dynamics of a rigid spacecraft can be established as

$$\dot{\boldsymbol{q}}_{\boldsymbol{v}}=\frac{1}{2}(q_4\boldsymbol{I}_3+\boldsymbol{q}_{\boldsymbol{v}}^\times)\boldsymbol{\omega},\quad \dot{q}_4=-\frac{1}{2}\boldsymbol{q}_{\boldsymbol{v}}^T\boldsymbol{\omega}, \tag{6}$$

$$\boldsymbol{J}\dot{\boldsymbol{\omega}}=-\boldsymbol{\omega}^\times\boldsymbol{J}\boldsymbol{\omega}+\boldsymbol{\tau}+\boldsymbol{d}, \tag{7}$$

where the unit quaternion $\boldsymbol{q}=[\boldsymbol{q}_{\boldsymbol{v}}^T,q_4]^T\in\mathbb{Q}=\{\boldsymbol{q}\in\mathbb{R}^3\times\mathbb{R}\mid\boldsymbol{q}_{\boldsymbol{v}}^T\boldsymbol{q}_{\boldsymbol{v}}+q_4^2=1\}$ represents the relative attitude between the body and inertial frames, with $\boldsymbol{q}_{\boldsymbol{v}}=[q_{v1},q_{v2},q_{v3}]^T$ and q_4 as the vector and scalar components, respectively; $\boldsymbol{\omega}=[\omega_1,\omega_2,\omega_3]^T\in\mathbb{R}^3$ denotes the angular velocity of the spacecraft with respect to the inertial frame expressed in the body frame; $\boldsymbol{J}\in\mathbb{R}^{3\times 3}$ denotes the symmetric inertial matrix of the spacecraft expressed in the body frame; $\boldsymbol{\tau}=[\tau_1,\tau_2,\tau_3]^T\in\mathbb{R}^3$ denotes the total torque vector exerted by actuators; and $\boldsymbol{d}\in\mathbb{R}^3$ is the external disturbance arising from undesired environmental torques.

3.2. Attitude error kinematics and dynamics

The control objective is to make the attitude of the spacecraft track a desired attitude generated by

$$\dot{\boldsymbol{q}}_{\boldsymbol{dv}}=\frac{1}{2}(q_{d4}\boldsymbol{I}_3+\boldsymbol{q}_{\boldsymbol{dv}}^\times)\boldsymbol{\omega}_{\boldsymbol{d}},\quad \dot{q}_{d4}=-\frac{1}{2}\boldsymbol{q}_{\boldsymbol{dv}}^T\boldsymbol{\omega}_{\boldsymbol{d}}, \tag{8}$$

where the unit quaternion $\boldsymbol{q}_{\boldsymbol{d}}=[\boldsymbol{q}_{\boldsymbol{dv}}^T,q_{d4}]^T\in\mathbb{Q}$ denotes the attitude of the orbital frame with respect to the inertial frame, and $\boldsymbol{\omega}_{\boldsymbol{d}}\in\mathbb{R}^3$ denotes the desired angular velocity.

Let $\boldsymbol{q}_{\boldsymbol{e}}=[\boldsymbol{e}_{\boldsymbol{v}}^T,e_4]^T\in\mathbb{Q}$ with $\boldsymbol{e}_{\boldsymbol{v}}=[e_1,e_2,e_3]^T$ denote the attitude error between the body frame and the orbital frame, which, according to [7], can be derived as