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Neural network approximation-based nonsingular terminal sliding mode control for trajectory tracking of robotic airships

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ABSTRACT

This paper proposes a neural network approximation-based nonsingular terminal sliding mode control (NN-NTSMC) approach to address the problem of trajectory tracking for robotic airships. First, dynamics model of an airship and control problem of trajectory tracking are formulated. Second, a nonsingular terminal sliding mode controller (NTSMC) combined with neural network (NN) approximation is designed to track the commanded trajectory. Finally, the effectiveness and robustness of the designed controller are illustrated through simulation results. Simulation results indicate that NN-NTSMC reduces chattering effectively and ensures faster convergence and better tacking precision against linear hyperplane-based sliding mode control (LSMC).

1. Introduction

As a typical lighter-than-air vehicle, the robotic airship performs obvious advantages in more payload capacity, less energy consumption and longer time operation, comparing with unmanned aerial vehicles. It has received significant attention in the past few years because of its various applications, which require high-precise trajectory tracking. However, inherent dynamics nonlinearity makes robotic airships be a class of high coupled nonlinear MIMO systems. Moreover, a major difficulty in the control of robotic airships is well known for parameter variations and external disturbances, which hinders perfect tracking of a commanded trajectory.

In order to cope with the problem, there are many methodologies proposed in the literature, such as PID [1,2], state feedback [3], back-stepping control [4] and adaptive control [5]. The sliding mode control (SMC) represents an attractive alternative for aircraft control [6–8], due to its robustness to parametric uncertainties and external disturbances. It was the control approach employed in references [9–11] to design controller for airships. However, it has two obvious disadvantages: one is that the zero convergence of error dynamics is usually asymptotic; and the other is the chattering phenomenon in the control effort due to the use of a high-speed switching control law [12–14]. To overcome these drawbacks, terminal sliding mode control (TSMC) with intelligent control was recently proposed [15,16]. The NN was used to approximate the uncertain parameters or unknown model of the plant in these references.

Motivated by the published works, this paper proposes a NN-NTSMC approach, which combines both the merits of the NTSMC and NN, for trajectory tracking of robotic airships. A NTSMC approach is presented to ensure faster convergence, better tracking precision and, meanwhile, to weaken chattering phenomenon. Compared with LSMC, TSMC with a nonlinear terminal sliding surface offers some superior properties such as fast, finite time convergence [17]. However, dynamics of robotic airships are highly nonlinear and complicated, and the lumped uncertainty of the system, which includes unknown dynamics, parameter variations and external disturbances, are very difficult to obtain in practical applications. To cope with this problem, the radical basic function neural network (RBFNN) was employed to approximate the lump uncertainties of the robotic airship, due to its capability of universally approximating any unknown continuous function to arbitrary precision [15]. In addition, an adaptive law is designed to update the NN weight in the processing of approximation. Therefore, the proposed control approach, not only takes advantage of robustness of SMC, but also brings into full play NN's precise approximation to dynamics uncertainty of the robotic airship.

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The rest of this paper is organized as follows. In section 2, the dynamics model of the robotic airship and the problem of trajectory tracking are formulated. Section 3 designs the NN-NTSMC to address the problem of trajectory tracking. In section 4, simulation studies illustrate the performance of the proposed controller. Finally, conclusions are given in Section 5.

2. Modeling and formulation

A robotic airship consisting of an axis-symmetric, teardrop-shaped hull, propellers, tail fins, gondola and payload and equipped with actuators of 6-DOF [4,18] is investigated in this paper. According to references [19,20], the motion equations of an airship are expressed as follows:

$$\dot{\boldsymbol{\eta}} = \boldsymbol{J}(\boldsymbol{\eta})\boldsymbol{V} = \begin{bmatrix} \boldsymbol{J}_1 & \boldsymbol{0}_{3\times3} \\ \boldsymbol{0}_{3\times3} & \boldsymbol{J}_2 \end{bmatrix}\boldsymbol{V} \tag{1}$$

$$\boldsymbol{M}_\eta(\boldsymbol{\eta})\ddot{\boldsymbol{\eta}} + \boldsymbol{N}_\eta(\boldsymbol{\eta},\dot{\boldsymbol{\eta}})\dot{\boldsymbol{\eta}} + \boldsymbol{G}_\eta(\boldsymbol{\eta}) = \boldsymbol{\tau} \tag{2}$$

Considering the unknown dynamics, parameter variations and external disturbances of the robotic airship, the dynamic model (2) can be rewritten as follows:

$$(\boldsymbol{M}_\eta + \Delta\boldsymbol{M}_\eta)\ddot{\boldsymbol{\eta}} + (\boldsymbol{N}_\eta + \Delta\boldsymbol{N}_\eta)\dot{\boldsymbol{\eta}} + (\boldsymbol{G}_\eta + \Delta\boldsymbol{G}_\eta) = \boldsymbol{\tau} + \boldsymbol{\tau}_d \tag{3}$$

where $\Delta\boldsymbol{M}_\eta, \Delta\boldsymbol{N}_\eta$ and $\Delta\boldsymbol{G}_\eta$ denote the uncertainties of $\boldsymbol{M}_\eta, \boldsymbol{N}_\eta$ and $\boldsymbol{G}_\eta$, respectively, and $\boldsymbol{\tau}_d$ denotes the external disturbance.

It is assumed that system (3) satisfies the following assumptions.

Assumption 1. Introduce $\Delta\boldsymbol{f}$ to represent a lumped term and define it as

$$\Delta\boldsymbol{f} = -(\Delta\boldsymbol{M}_\eta\ddot{\boldsymbol{\eta}} + \Delta\boldsymbol{N}_\eta\dot{\boldsymbol{\eta}} + \Delta\boldsymbol{G}_\eta - \boldsymbol{\tau}_d) \tag{4}$$

There exists a finite positive constant γ such that the following inequalities hold for all $\boldsymbol{\eta}$ in the domain of interest

$$\|\Delta\boldsymbol{f}\| \le \gamma \tag{5}$$

Substituting (4) into (3) yields

$$\boldsymbol{M}_\eta\ddot{\boldsymbol{\eta}} + \boldsymbol{N}_\eta\dot{\boldsymbol{\eta}} + \boldsymbol{G}_\eta = \boldsymbol{\tau} + \Delta\boldsymbol{f} \tag{6}$$

The problem of trajectory tracking is the design of a controller that stabilizes the tracking error dynamics in the presence of model uncertainties, parameter variations and external disturbances [11]. The commanded time-varying trajectory, expressed by generalized coordinates, is assumed to be $\boldsymbol{\eta}_c = [x_c, y_c, z_c, \theta_c, \psi_c, \phi_c]^T$, and the true state of the airship is $\boldsymbol{\eta} = [x_E, y_E, z_E, \theta, \psi, \phi]^T$. Design a proper controller so that the robotic airship converges to and track the commanded trajectory, i.e. $\lim_{t_0\to t_f} |\boldsymbol{\eta} - \boldsymbol{\eta}_c| = 0$.

3. Trajectory tracking control design

3.1. NTSMC

Define the tracking error

$$\boldsymbol{e} = \boldsymbol{\eta} - \boldsymbol{\eta}_c \tag{7}$$

A nonsingular terminal sliding manifold is chosen as follows [14]

$$\boldsymbol{s}(t) = \boldsymbol{e}(t) + \boldsymbol{\lambda}\dot{\boldsymbol{e}}(t)^{p/q} \tag{8}$$

where $\boldsymbol{\lambda} = \mathrm{diag}(\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6)$ is a constant matrix, $\lambda_i > 0$, $i = 1, 2, 3, 4, 5, 6$, p and q are positive odd integers satisfying $1 < p/q < 2$.

The NTSMC is designed as follows:

$$\begin{aligned}\boldsymbol{\tau} = {} & \boldsymbol{M}_\eta\ddot{\boldsymbol{\eta}}_c + \boldsymbol{N}_\eta\dot{\boldsymbol{\eta}} + \boldsymbol{G}_\eta - \frac{q}{p}\boldsymbol{M}_\eta\boldsymbol{\lambda}^{-1}\,\mathrm{diag}(\dot{\boldsymbol{e}}^{2-p/q}) \\ & - \frac{[\boldsymbol{s}^T\boldsymbol{\lambda}\,\mathrm{diag}(\dot{\boldsymbol{e}}^{p/q-1})\boldsymbol{M}_\eta^{-1}]^T}{\|\boldsymbol{s}^T\boldsymbol{\lambda}\,\mathrm{diag}(\dot{\boldsymbol{e}}^{p/q-1})\boldsymbol{M}_\eta^{-1}\|^2} \\ & \cdot\gamma\|\boldsymbol{s}\|\,\|\boldsymbol{\lambda}\,\mathrm{diag}(\dot{\boldsymbol{e}}^{p/q-1})\boldsymbol{M}_\eta^{-1}\|\end{aligned} \tag{9}$$

Theorem 1. *For the system (3), if the terminal sliding manifold is chosen as (8), and the controller is designed as (9), then it guarantees the stability of the closed-loop system and the tracking error will converge to zero in a finite time.*

Proof. Select the following Lyapunov function candidate:

$$V = \frac{1}{2}\boldsymbol{s}^T\boldsymbol{s} \tag{10}$$

Differentiating (10) with respect to time and using (8), it is obtained that

$$\dot{V} = \boldsymbol{s}^T\dot{\boldsymbol{s}} = \boldsymbol{s}^T\left[\dot{\boldsymbol{e}} + \frac{p}{q}\boldsymbol{\lambda}\,\mathrm{diag}(\dot{\boldsymbol{e}}^{p/q-1})\ddot{\boldsymbol{e}}\right] \tag{11}$$

Differentiating (7) with respect to time twice and using (3) and (4), it is obtained that

$$\begin{aligned}\ddot{\boldsymbol{e}} & = \ddot{\boldsymbol{\eta}} - \ddot{\boldsymbol{\eta}}_c = \boldsymbol{M}_\eta^{-1}(\boldsymbol{\tau} + \Delta\boldsymbol{f} - \boldsymbol{N}_\eta\dot{\boldsymbol{\eta}} - \boldsymbol{G}_\eta) \\ & = \boldsymbol{M}_\eta^{-1}\left[-\frac{q}{p}\boldsymbol{M}_\eta\boldsymbol{\lambda}^{-1}\,\mathrm{diag}(\dot{\boldsymbol{e}}^{2-p/q}) + \Delta\boldsymbol{f}\right] \\ & \quad + \boldsymbol{M}_\eta^{-1}\left[-\frac{[\boldsymbol{s}^T\boldsymbol{\lambda}\,\mathrm{diag}(\dot{\boldsymbol{e}}^{p/q-1})\boldsymbol{M}_\eta^{-1}]^T}{\|\boldsymbol{s}^T\boldsymbol{\lambda}\,\mathrm{diag}(\dot{\boldsymbol{e}}^{p/q-1})\boldsymbol{M}_\eta^{-1}\|^2}\right. \\ & \quad \left.\cdot\gamma\|\boldsymbol{s}\|\|\boldsymbol{\lambda}\,\mathrm{diag}(\dot{\boldsymbol{e}}^{p/q-1})\boldsymbol{M}_\eta^{-1}\|\right]\end{aligned} \tag{12}$$

Substituting (12) into (21) yields

$$\begin{aligned}\dot{V} & = -\frac{p}{q}\gamma\|\boldsymbol{s}\|\,\|\boldsymbol{\lambda}\,\mathrm{diag}(\dot{\boldsymbol{e}}^{p/q-1})\boldsymbol{M}_\eta^{-1}\| \\ & \quad + \frac{p}{q}\boldsymbol{s}^T\boldsymbol{\lambda}\,\mathrm{diag}(\dot{\boldsymbol{e}}^{p/q-1})\boldsymbol{M}_\eta^{-1}\Delta\boldsymbol{f} \\ & \le -\frac{p}{q}\gamma\|\boldsymbol{s}\|\,\|\boldsymbol{\lambda}\,\mathrm{diag}(\dot{\boldsymbol{e}}^{p/q-1})\boldsymbol{M}_\eta^{-1}\| \\ & \quad + \frac{p}{q}\|\boldsymbol{s}\|\,\|\boldsymbol{\lambda}\,\mathrm{diag}(\dot{\boldsymbol{e}}^{p/q-1})\boldsymbol{M}_\eta^{-1}\|\|\Delta\boldsymbol{f}\| \\ & = \frac{p}{q}\|\boldsymbol{s}\|\,\|\boldsymbol{\lambda}\,\mathrm{diag}(\dot{\boldsymbol{e}}^{p/q-1})\boldsymbol{M}_\eta^{-1}\|\big(\|\Delta\boldsymbol{f}\| - \gamma\big)\end{aligned} \tag{13}$$

The inequation $\|\Delta\boldsymbol{f}\| - \gamma < 0$ exists according to Assumption 1, and then it is obtained that

$$\dot{V} \le \frac{p}{q}\|\boldsymbol{s}\|\,\|\boldsymbol{\lambda}\,\mathrm{diag}(\dot{\boldsymbol{e}}^{p/q-1})\boldsymbol{M}_\eta^{-1}\|\big(\|\Delta\boldsymbol{f}\| - \gamma\big) < 0, \quad \big(s(t) \ne 0\big) \tag{14}$$

According to eq. (13), it is known that if $\boldsymbol{s} = 0$ then $\dot{V} = 0$. The following equation is derived

$$\lim_{t\to t_f}\boldsymbol{s} = \lim_{t\to t_f}\left[\boldsymbol{e} + \boldsymbol{\lambda}\dot{\boldsymbol{e}}^{p/q}\right] = \lim_{t\to t_f}\left[(\boldsymbol{\eta} - \boldsymbol{\eta}_c) + \boldsymbol{\lambda}(\dot{\boldsymbol{\eta}} - \dot{\boldsymbol{\eta}}_c)^{p/q}\right] = 0 \tag{15}$$

where $t_f = t_r + t_s$, t_r is the time when $\boldsymbol{s}(t)$ reaches zero, and t_s is the finite time which can be expressed as

$$t_s = -\lambda_i^{q/p}\int_{e_i(t_r)}^{0}\frac{de}{e_i^{-q/p}(t)} = \frac{p\lambda_i^{q/p}}{p-q}\big[e_i(t_r)\big]^{1-q/p} \tag{16}$$