Robotics and Autonomous Systems 97 (2017) 83–91

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Trajectory tracking control for a marine surface vessel with asymmetric saturation actuators

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ARTICLE INFO

Article history:
Received 23 November 2016
Received in revised form 30 May 2017
Accepted 7 August 2017
Available online 24 August 2017

Keywords:
Marine surface vessel
Trajectory tracking
Backstepping
Asymmetric saturation
Neural networks

ABSTRACT

This paper investigates the problem of trajectory tracking control for an unmanned marine surface vessel (MSV) with external disturbances and asymmetric saturation actuators. An adaptive radial basis function neural network (RBFNN) is constructed to provide an estimation of the unknown disturbances and is applied to design the trajectory tracking controller through a backstepping technique. To handle the effect of nonsmooth asymmetric saturation nonlinearity, a Gaussian error function-based continuous differentiable asymmetric saturation model is employed such that the backstepping technique can be used in the control design. It is proved that all the states in the closed-loop system are semiglobally uniformly ultimately bounded, and the tracking error converges to a small neighborhood of origin by appropriately choosing design parameters. Simulation results and comparisons illustrate the effectiveness of the proposed controller and its robustness to external disturbances and asymmetric saturation actuators.

1. Introduction

The past few years have witnessed an increased research effort in the motion control of marine surface vessel (MSV) [1–7]. A typical motion control problem is trajectory tracking, which is concerned with the design of control laws that force the MSV to track the desired time-referenced trajectory or virtual objects [8,9]. Trajectory tracking is of great significance for variety of scenarios, such as way-point navigation, reconnaissance, and surveillance. It has attracted a great deal of attention from the control community both in theory and in practice [10–23].

In [24], the paper concerns the robust tracking control problem for an underactuated surface vessel with parameter uncertainties by using sliding mode control method. An observer is constructed to provide an estimation of unknown disturbances and is applied to design a trajectory tracking robust controller through backstepping technique for MSV in [25]. Lekkas and Fossen present a guidance system for tracking applications of MSVs exposed to unknown ocean currents [26]. In addition, linear algebra approach [27], sampled-data method [28], and nonlinear model predictive control [29] are utilized to the trajectory tracking control design for MSV. Furthermore, these results have been extended to the spacial scenes for autonomous underwater vehicle recently [30,31].

Every input of a system is bounded by physical restriction of actuators. Actuator saturation causes performance degradation, lag, overshoot, undershoot as well as instability in the closed-loop response of practical systems. Therefore, actuator saturation must be taken into account in the control design [32]. Analysis and design of control systems with actuator saturation have been reported in [33,34] for tracking control of uncertain MIMO nonlinear systems, in [35] for position control of a MSV, and in [36] for global tracking control of underactuated ships. An adaptive steering law for asymptotically stable ship with saturation limits was proposed in [37], combined with a linear quadratic controller and a Riccati based anti-windup compensator. Ref. [38] considered the cooperative path following problem of multiple MSVs subject to actuator saturation, unknown dynamical uncertainty and unstructured ocean disturbances. It should be highlighted that one critical assumption made in all the above researches is that the actuator saturation is symmetric. However, the MSV propellers can only output positive force in surge direction while implementing the forward trajectory tracking task, and the asymmetric saturation situation may be encountered if the actuators have partial loss of effectiveness failures. Relatively, few results are available in the literature on the control of uncertain nonlinear systems with asymmetric saturation actuators except [39–41].

Learning-based adaptive control methodology using neural networks, with their strong approximate capacity, has received more and more attention. Some excellent researches on controlling nonlinear system have been made using adaptive neural network

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http://dx.doi.org/10.1016/j.robot.2017.08.005
0921-8890/

control [33,42]. Thus, the neural network can be introduced to handle the uncertainty and disturbance of MSVs [6,38,43,44]. The parameter update laws in the above neural networks all evolved from Lyapunov-based approaches.

In this paper, we present a trajectory tracking controller for an unmanned MSV with external disturbances and asymmetric saturation actuators. The contributions of this paper are summarized as follows: (1) By exploring a Gaussian error function, the asymmetric saturation nonlinearity is represented as a continuous differentiable formulation. (2) Based on the proposed smooth saturation model, backstepping is developed for the adaptive radial basis function neural network (RBFNN) control of MSV with disturbances and asymmetric saturation. (3) Stability analysis proves that all the states in the closed-loop systems are semiglobally uniformly ultimately bounded with tracking error converges to a small neighborhood of origin.

This paper is organized as follows. Some useful preliminaries and problem formulation are introduced in Section 2. Section 3 is devoted to designing the trajectory tracking control algorithm on the MSV. Section 4 simulates the proposed control approach, and finally, we conclude this paper and propose some further work in Section 5.

2. Preliminaries and problem formulation

2.1. Preliminaries

2.1.1. Notations

Throughout this paper, $|\cdot|$ represents the absolute value of a scalar or the absolute value of each components for a vector, i.e. for a vector $\boldsymbol{x} \in \mathbb{R}^n$, $|\boldsymbol{x}| = [|x_1|, |x_2|, \dots, |x_n|]^T$. In addition, $\|\cdot\|$ represents the Euclidean norm of a vector or the Frobenius norm of a matrix. For a matrix $\boldsymbol{X} \in \mathbb{R}^{n\times n}$, $\mathrm{tr}(\boldsymbol{X})$ denotes its trace with the property $\mathrm{tr}(\boldsymbol{X}^T\boldsymbol{X}) = \|\boldsymbol{X}\|^2$. For any vectors $\boldsymbol{a} \in \mathbb{R}^n$ and $\boldsymbol{b} \in \mathbb{R}^n$, $\boldsymbol{a} < \boldsymbol{b}$ means $a_i < b_i$, $i = 1, 2, \dots, n$.

2.1.2. RBFNN approximation

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

$$f(\boldsymbol{x}) = \boldsymbol{\omega}^{*T}\Phi(\boldsymbol{x}) + \epsilon \tag{1}$$

where the node number of the NN is l. More nodes mean more accurate approximation [45]. $\boldsymbol{\omega}^* \in \mathbb{R}^l$ represents the optimal weight vector, which is defined by

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

where $\hat{\boldsymbol{\omega}}$ is the estimation of $\boldsymbol{\omega}^*$. $\boldsymbol{\Phi}(\boldsymbol{x}) = [\phi_1(\boldsymbol{x}), \dots, \phi_l(\boldsymbol{x})]^T$: $\Omega \to \mathbb{R}^l$ represents the radial basis function vector, the element of which is chosen as the Gaussian function

$$\phi_i(\boldsymbol{x}) = \exp\left(-\frac{\|\boldsymbol{x} - \boldsymbol{\mu}_i\|^2}{\varepsilon_i^2}\right), \quad i = 1, \dots, l \tag{3}$$

where $\boldsymbol{\mu}_i \in \mathbb{R}^m$ and $\varepsilon_i \in \mathbb{R}$, are the center and spread. ϵ is the approximation error that is bounded over Ω, namely, $|\epsilon| \le \bar{\epsilon}$, where $\bar{\epsilon}$ is an unknown constant.

2.1.3. Definitions and lemmas

Definition 1 ([46]). Given a nonlinear system

$$\dot{x} = f(x, t), \; x \in \mathbb{R}^n, \; t \ge t_0$$

the solution of the above system is semiglobally uniformly ultimately bounded if for any Ω_0, a compact subset of $\mathbb{R}^n$ and all $x(t_0) = x_0 \in \Omega_0$, there exists $S > 0$ and a number $T(S, X(t_0))$ such that $\|X(t)\| \le S$ for all $t \ge t_0 + T$.

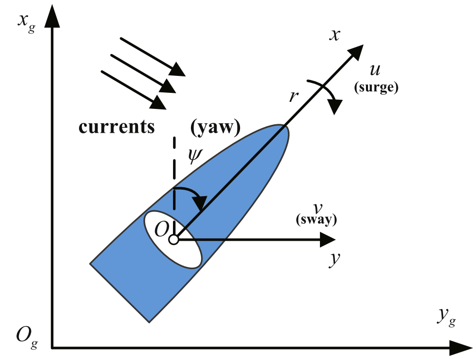

Fig. 1. Motion of the MSV.

Lemma 1 ([46]). *For bounded initial conditions, if there exists a $\mathcal{C}^1$ continuous and positive definite Lyapunov function $V(x)$ satisfying $k_1(\|x\|) \le V(x) \le k_2(\|x\|)$, such that $\dot{V}(x) \le -\gamma V(x) + \nu$, where $k_1, k_2 : \mathbb{R}^n \to \mathbb{R}$ are class $\mathcal{K}$ functions and γ, ν are positive constants, then the solution $x(t)$ is uniformly bounded.*

Lemma 2 ([33]). *The following inequality holds for any $\varrho \in \mathbb{R}^+$ and $x \in \mathbb{R}$:*

$$0 \le |x| - x\tanh\left(\frac{x}{\varrho}\right) \le \kappa\varrho \tag{4}$$

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

Definition 2. For any $\boldsymbol{x} \in \mathbb{R}^n$, the hyperbolic tangent function matrix $\tanh(\boldsymbol{x}) : \mathbb{R}^n \to \mathbb{R}^{n\times n}$ is defined as

$$\tanh(\boldsymbol{x}) = \mathrm{diag}(\tanh(x_1), \tanh(x_2), \dots, \tanh(x_n))$$

2.2. MSV model

Motion of the MSV in horizontal plane is illustrated in Fig. 1 [47]. We define the inertial and body-fixed frames firstly. The inertial frame (IF) is fixed to the earth with its origin O_g locating at a fix point. The $O_g x_g$-axis points to north, and the $O_g y_g$-axis points to east. The coordinate origin O of the body-fixed frame (BF) is taken as the geometric center point of the MSV structure as shown in Fig. 1. The Ox-axis points to head of the MSV. The Oy-axis is perpendicular to the Ox-axis and points to right.

Neglecting the motions in heave, pitch and roll, the three degrees-of-freedom nonlinear equations of the MSV in the presence of disturbances can be expressed as [25,48]:

$$\dot{\boldsymbol{\eta}} = \boldsymbol{R}(\psi)\boldsymbol{v} \tag{5}$$

$$\boldsymbol{M}\dot{\boldsymbol{v}} + \boldsymbol{C}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{D}\boldsymbol{v} = \boldsymbol{\tau}(\boldsymbol{\varphi}) + \boldsymbol{b} \tag{6}$$

In the above expressions, $\boldsymbol{\eta} = [x, y, \psi]^T$ is the actual track of the ship in IF, consisting of the position (x, y) and yaw angle ψ. $\boldsymbol{v} = [u, v, r]^T$ is the velocity vector of the MSV in BF, where u, v, and r are the forward velocity (surge), the transverse velocity (sway), and the angular velocity in yaw, respectively. The matrix $\boldsymbol{R}(\psi)$ is rotation matrix defined as

$$\boldsymbol{R}(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{7}$$

with the property $\boldsymbol{R}^{-1}(\psi) = \boldsymbol{R}^T(\psi)$. Here, $\boldsymbol{M}$ is nonsingular, symmetric, and positive definite inertia matrix, $\boldsymbol{C}(\boldsymbol{v})$ is the matrix