Robotics and Autonomous Systems 78 (2016) 83–96

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

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

Observer-based neural adaptive formation control of autonomous surface vessels with limited torque

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HIGHLIGHTS

- A neural adaptive formation controller is proposed for surface vessels.
- A new formation model is proposed that inherits all properties of vessel dynamics.
- The controller reduces the risk of actuators saturation by saturation functions.
- Neural adaptive robust techniques compensate disturbances and unmodeled dynamics.
- The controller does not require velocity signals by using a velocity observer.

ARTICLE INFO

Article history:
Received 29 March 2015
Received in revised form
10 December 2015
Accepted 15 January 2016
Available online 1 February 2016

Keywords:
Actuator saturation
Autonomous surface vessels
Leader–follower formation
Model uncertainty
Neural adaptive control
Nonlinear observer

ABSTRACT

In this paper, the output feedback formation control of autonomous marine surface vessels with limited torque input is addressed. In order to successfully design a formation control system, a second order formation dynamic model is developed based on the leader-following strategy. The controller is designed by employing generalized saturation functions in order to reduce the risk of actuator saturation. A nonlinear saturated observer is also introduced to estimate velocities of the followers. Multi-layer neural network and adaptive robust techniques are also incorporated in the design of the control system to preserve its robustness against uncertain nonlinearities and environmental disturbances which are induced by waves and ocean currents. Lyapunov's direct method is used to show that all signals of the closed-loop system are bounded and tracking errors are semi-globally uniformly ultimately bounded. Finally, computer simulation results are provided to demonstrate the efficacy of the proposed formation controller for a number of surface vessels.

1. Introduction

The motion control of autonomous marine surface vessels is a challenging problem due to strong coupling and nonlinearities in their dynamics and environmental disturbances induced by waves, wind and ocean currents. Many researchers have proposed different solutions to the motion planning and control of a single surface vessel to increase the degree of autonomy in such systems for offshore applications [1–5]. However, cooperative and formation control of multiple surface vessels is more constructive for autonomous applications due to redundancy, robustness, and efficiency of vehicles teamwork with respect to a single-vehicle. There exist many practical examples for applications of the formation control of multiple autonomous surface vessels including autonomous exploration, oceanographic mapping, surveillance, reconnaissance, coverage, rescue operations and geological sampling. In fact, the formation control problem is related to the design of stabilizing, path-following and tracking controllers to force a group of autonomous vehicles to maintain or track desired positions and orientations with respect to one or more reference points. From a detailed review of the literature, there are many works on the formation control of surface vessels which are designed by either behavioral-based [6] virtual structure [7], or leader-following approaches [8,9]. By the investigation of available works, it is clarified that leader–follower approaches have been extensively used to design vehicles formation controllers due to their reliability and simplicity [8–13].

A dynamic surface leader-following formation controller has been proposed in [8] for underactuated surface vessels. Sliding-mode leader–follower formation controllers have been proposed for such systems in [9]. Ihle et al. [10] have utilized a Lagrangian approach for the formation control of marine surface crafts. Attractive results on the formation control of underactuated

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http://dx.doi.org/10.1016/j.robot.2016.01.005

surface vessels with limited sensing ranges have been presented in [14,15]. The problem of cooperative and path-following formation control has been addressed for marine surface vehicles in [16–24]. In spite of extensive researches, most of presented works need velocity measurements of all agents which are not easily measurable due to noise contamination and communication delays. Furthermore, velocity sensors increase the weight and cost of surface vessels. One useful solution to remove velocity sensors is the design of observer-based controllers. However, since the separation principle is not applicable for nonlinear systems, the development of observer-based controllers is still a challenging research area. This problem may be more demanding in the presence of parametric and nonparametric uncertainties in the kinematic and dynamic models of the system. The cooperative path-following and leader–follower rendezvous control of marine surface vehicles have been addressed in [16,18] using state and output-feedback. However, the main shortcoming of previous works including [16,18] is that they neglect the actuator saturation problem in the design of the controller. Essentially, they assume that vehicle actuators are capable to generate every arbitrary level of torque signals. In practice, large amplitudes of generated control signals may result in the actuator saturation problem. This may lead to poor tracking performance of the controller. One solution to relieve this problem is bounding of the closed-loop error variables by employing saturation functions in the design of the tracking controller.

To the best of author's knowledge, there is no work to address the observer-based formation control of marine surface vessels in the presence of the actuator saturation. Therefore, the main contributions and novelties of this paper are expressed as follows:

(i) A second-order formation dynamic model is introduced for the first time which inherits all properties of the vessel dynamics. Then, a saturated leader-following observer-based formation controller is proposed based on this model.

(ii) In contrast to the existing works [8–24], our proposed observer-based formation controller reduces the risk of the actuators saturation by bounding tracking and observation errors via generalized saturation functions. This technique effectively reduces the amplitude of generated control signals.

(iii) Compared with many previous works, a nonlinear saturated velocity observer is proposed to estimate unmeasured velocities in the surge, sway and yaw directions. In contrast to the existing output feedback controllers including [16,18], the observer is designed such that it does not involve system dynamics and the control input and it reduces unwanted peaks by using a saturated state in the observer design.

(iv) A multi-layer neural network and adaptive robust control technique are also incorporated in the design of the formation control system to compensate unmodeled dynamics and environmental disturbances induced by waves, wind and ocean currents.

A Lyapunov-based stability analysis is used to show that all signals in the resulting closed-loop system are bounded and tracking and state estimation errors are semi-globally uniformly ultimately bounded. Finally, simulation results are provided for a number of marine surface vessels to illustrate the effectiveness of the proposed formation controller in real offshore applications.

The rest of the paper is organized as follows. The problem formulation and preliminaries are presented in the next section. A variable transformation is introduced to develop a second-order formation model of surface vehicles. In Section 3, the design of a saturated output feedback formation controller is given. Section 4 presents the main result of this paper. In Section 5, simulation results are provided to evaluate the effectiveness of the proposed controller. Conclusions are given in Section 6.

2. Problem formulation

The following notations are employed throughout this paper: $\|x\| := \sqrt{x^T x}$ is used as Euclidean norm of a vector $x \in \Re^n$. The norm of a matrix A is defined as the induced norm $\|A\| := \sqrt{\lambda_{\max}(A^T A)}$, or the Frobenius norm, i.e. $\|A\|_F := \sqrt{\mathrm{tr}\{A^T A\}}$, where $\mathrm{tr}\{\bullet\}$ represents the trace operator. $\lambda_{\max}(\bullet)$ $(\lambda_{\min}(\bullet))$ denotes the largest (smallest) eigenvalue of a matrix. $\{\alpha_j\}_{j=1}^n := \{\alpha_1, \alpha_2, \ldots, \alpha_n\}$ denotes a set of α_j, $j = 1, \ldots, n$. The matrix I_n is n-dimensional identity matrix and $\mathrm{diag}[\bullet]$ denotes a diagonal matrix. To simplify the subsequent control design and its stability analysis, the following notations are also used: $s(x) := [s_1(x_1),\ s_2(x_2), \ldots, s_n(x_n)]^T$ and $s'(x) = \mathrm{diag}[s'_1(x_1), \ldots, s'_n(x_n)]$ with $x = [x_1, x_2, \ldots, x_n]^T \in \Re^n$ where $s_j(\bullet)$, $j = 1, \ldots, n$ and $s'_j(\bullet)$, $j = 1, \ldots, n$ are generalized saturation functions and their derivatives, respectively, which are defined in the next subsection.

2.1. Surface vessel model description

Consider a group of N autonomous marine surface vessels whose kinematic and dynamic models are described as follows [25,26]:

$$\dot{\eta}_i = T_i(\psi_i)\upsilon_i, \quad i = 1, 2, \ldots, N, \tag{1}$$

$$M_{1i}\dot{\upsilon}_i + C_{1i}(\upsilon_i)\upsilon_i + D_{1i}\upsilon_i + \tau_{w1i}(t) = \tau_{ai}(t), \tag{2}$$

where $\eta_i := [x_i,\ y_i,\ \psi_i]^T$, x_i, y_i and ψ_i denote the position and orientation (i.e. yaw angle), respectively, in the earth-fixed frame, $\upsilon_i := [u_i,\ v_i, r_i]^T$ where $u_i,\ v_i$ and r_i represent the surge, sway and yaw velocities in the body-fixed frame, M_{1i} is a symmetric positive-definite inertia matrix, $C_{1i}(\upsilon_i)$ is a matrix of centripetal and Coriolis terms, D_{1i} is the hydrodynamic damping matrix which is also symmetric and positive-definite, $\tau_{ai} := [\tau_{ui},\ \tau_{vi}, \tau_{ri}]^T$ where $\tau_{ui},\ \tau_{vi}$ and τ_{ri} are the torque signals which are provided by the vessel actuators, $\tau_{w1i}(t) = [\tau_{wui}(t),\ \tau_{wvi}(t),\ \tau_{wri}(t)]^T$ is a vector of unmodeled dynamics and bounded time-varying disturbances which are induced by waves and ocean currents [25,26]. The rotation matrix $T_i(\psi_i)$, with the property $T_i^{-1}(\psi_i) = T_i^T(\psi_i)$, and dynamic matrices are defined as follows:

$$T_i(\psi_i) = \begin{bmatrix} \cos(\psi_i) & -\sin(\psi_i) & 0 \\ \sin(\psi_i) & \cos(\psi_i) & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$$M_{1i} = \begin{bmatrix} m_{11i} & 0 & 0 \\ 0 & m_{22i} & 0 \\ 0 & 0 & m_{33i} \end{bmatrix},$$

$$C_{1i}(\upsilon_i) = \begin{bmatrix} 0 & 0 & -m_{22i}v_{ii} \\ 0 & 0 & m_{11i}u_i \\ m_{22i}v_i & -m_{11i}u_i & 0 \end{bmatrix},$$

$$D_{1i} = \begin{bmatrix} d_{11i} & 0 & 0 \\ 0 & d_{22i} & 0 \\ 0 & 0 & d_{33i} \end{bmatrix}.$$

Remark 1. In order to simplify the controller–observer design in the next section, it is assumed that nonlinear damping terms in the dynamic model (2) and off-diagonal terms of the inertia and damping matrices are very small and they are ignored in this paper. These assumptions hold when the vessel has three planes of symmetry. The interested readers are referred to [26] for a detailed discussion.

2.2. Mathematical preliminaries

Definition 1. Given a positive constant M_k, a function $s_k : \Re \to \Re : \xi \to s_k(\xi)$ is said to be a generalized saturation with bound