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Neural adaptive robust control of underactuated marine surface vehicles with input saturation

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ABSTRACT

This paper proposes a saturated tracking controller for underactuated autonomous marine surface vehicles with limited torque. First, a second-order open-loop error dynamic model is developed in the actuated degrees of freedom to simplify the design procedure. Then, a saturated tracking controller is designed by utilizing generalized saturation functions to reduce the risk of actuator saturation. This, in turn, improves the transient performance of the control system. A multi-layer neural network and adaptive robust control techniques are also employed to preserve the controller robustness against unmodeled dynamics and environmental disturbances induced by waves and ocean currents. A Lyapunov stability analysis shows that all signals of the closed-loop system are bounded and tracking errors are semi-globally uniformly ultimately bounded. Finally, simulation results are provided for a hovercraft vehicle to illustrate the effectiveness of the proposed controller as a qualified candidate for real implementations in offshore applications.

1. Introduction

The tracking control problem of underactuated autonomous surface vehicles has attracted a lot of attention from control, robotic and ocean engineering communities over past years. Search, rescue, surveillance, reconnaissance, exploration, oceanographic mapping, geological sampling, and minesweeping are potential applications of the motion control of surface vehicles. The interested reader is referred to reference [1] and references therein for an introduction to navigation, guidance, control and motion planning of such systems. In contrast to the motion control of fully actuated surface vehicles, the main concern in the design of controllers for underactuated ones is that number of their independent actuators is fewer than degrees of freedom. This restriction may be due to the actuator failure during an operation or may be a deliberate reduction to save the weight and cost of the system. This feature, in turn, increases the degree of complexity in the design of nonlinear tracking controllers for such systems.

Motivated by the challenging nature of motion control problems of underactuated marine surface vehicles and their offshore applications, many researchers proposed various controllers to solve the stabilization [2], path-following [3], point-to-point navigation [4], trajectory tracking control [5–9], formation and cooperative [10–12] control of underactuated surface vehicles. Li et al. [4] has proposed an adaptive tracking controller for point-to-point navigation of underactuated ships using backstepping method. In [5], an adaptive hierarchical sliding-mode technique is applied to solve stabilization and tracking of underactuated surface vessels. Wu et al. [7] has proposed a tracking controller for ships using nonlinear time series model. In [8], trajectory control of ships has been addressed by introducing a Target Path Iteration algorithm. Global smooth controllers are proposed in [9] for underactuated ships based on backstepping and Lyapunov direct methods. Recently, input–output feedback linearization technique has been applied to the control of surface vessels [13].

In spite of the existence of extensive researches, the main drawback of previous works is that they do not take the actuator saturation problem into account. In fact, they assume that vehicle actuators are able to accept every level of control signals which are generated by the controller. In practice, generated control signals may make the actuators go beyond their natural capabilities and their saturation may not be avoidable. This, in turn, may result in a poor tracking performance of the proposed controller. In [14], a global tracking controller is designed using *dynamic surface control* (DSC) method for underactuated ships with input and velocity constraints. In [15], the input saturation is incorporated in the design of trajectory tracking controller for surface vehicles by nonlinear model predictive control. Bounded feedback controllers are also proposed in [16] for global tracking of underactuated ships. However, such works neglect the effects of parametric

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uncertainties, unmodeled dynamics and environmental disturbances in the performance of the tracking system. Accordingly, the tracking control of surface vehicles in the presence of actuator constraints and model uncertainties has not been sufficiently addressed in the literature.

Based on above presented discussion, the main contribution of this paper is designing a saturated neural network-based adaptive robust controller to solve tracking control problem of underactuated marine surface vehicles in the presence of uncertainties under actuator saturation. For this purpose, a second-order open-loop error dynamic model is developed in the actuated degrees of freedom of the vehicle. Then, a saturated tracking controller is proposed by using generalized saturation functions which bound closed-loop error variables in the design of the controller. This technique reduces the amplitude of the generated control signals. As a result, the actuator saturation problem is alleviated which prevents a poor tracking performance in the transient response. A multi-layer neural network (NN) approximator is combined with an adaptive robust controller in order to compensate uncertain model parameters, unmodeled dynamics and environmental disturbances which are induced by waves, wind and ocean currents.

The rest of the paper is organized as follows. The problem formulation is presented in the next section. In Section 3, the design of a saturated neural adaptive robust tracking controller and a Lyapunov-based stability analysis are presented. In Section 4, simulation results are provided for a hovercraft vehicle to evaluate the effectiveness of the proposed controller. Conclusions are given in Section 5.

2. Problem formulation

2.1. Notations

The following notations are used throughout this paper. $\lambda_{\max}(\cdot)$ ($\lambda_{\min}(\cdot)$) denotes the largest (smallest) eigenvalue of a matrix. $\|x\| := \sqrt{x^T x}$ is used as Euclidean norm of a vector $x \in \Re^n$, while 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 $\mathrm{tr}\{\cdot\}$ denotes the trace operator. The function f belongs to class C^k, if derivatives $f, f', \ldots, f^{(k)}$ exist and are continuous. The matrix I_n denotes n-dimensional identity matrix and $\mathrm{diag}[\cdot]$ denotes a diagonal matrix. $\{\alpha_j\}_{j=1}^n := \{\alpha_1, \alpha_2, \ldots, \alpha_n\}$ denotes a set of α_j, $j = 1, \ldots, n$. To facilitate the subsequent control design and stability analysis, the following notations are 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 $s_j(\cdot)$, $j = 1, \ldots, n$ and $s'_j(\cdot)$, $j = 1, \ldots, n$ are generalized saturation functions and their derivatives, respectively, which are defined in [17].

2.2. Kinematic and dynamic models

Consider a class of underactuated autonomous surface vehicles whose mathematical models are described as follows [18]:

$$\begin{aligned} \dot{x} &= u\cos(\psi) - v\sin(\psi), \\ \dot{y} &= u\sin(\psi) + v\cos(\psi), \\ \dot{\psi} &= r, \end{aligned} \tag{1}$$

$$\begin{aligned} m_{11}\dot{u} &= m_{22}vr - d_{11}u + \tau_u - \tau_{wu}(t), \\ m_{22}\dot{v} &= -m_{11}ur - d_{22}v - \tau_{wv}(t), \\ m_{33}\dot{r} &= (m_{11} - m_{22})uv - d_{33}r + \tau_r - \tau_{wr}(t), \end{aligned} \tag{2}$$

where x, y and ψ denote the position and orientation (i.e. yaw angle), respectively, in the earth-fixed frame which are represented by $\eta := [x,\ y,\ \psi]^T$, the signals u, v and r represent the surge, sway and yaw velocities in the body-fixed frame and τ_u and τ_r are the torque signals which are provided by the actuators, $\tau_{wu}(t)$, $\tau_{wv}(t)$, $\tau_{wr}(t) \in \Re$ are bounded time-varying disturbances and unmodeled dynamics. Furthermore, $m_{11} = m - X_{\dot{u}}$, $m_{22} = m - Y_{\dot{v}}$, $m_{33} = I_z - N_{\dot{r}}$, $d_{11} = -X_u$, $d_{22} = -Y_v$ and $d_{33} = -N_r$ where m is the mass of the ship, I_z denotes the moment of inertia about the yaw rotation, and other symbols represent hydrodynamic derivatives [19]. In order to facilitate controller design in the next section, the dynamic of the vehicle is re-written in the actuated directions as follows:

$$M_1\dot{\upsilon} + C_1(v)\upsilon + D_1\upsilon + \tau_{w1}(t) = \tau_a(t), \tag{3}$$

where M_1 is a symmetric positive-definite matrix, $C_1(v)$ is the centripetal and Coriolis matrix, D_1 is the hydrodynamic damping matrix which is also symmetric and positive-definite, $\tau_{w1}(t) = [\tau_{wu}(t), \tau_{wr}(t)]^T$ is the vector of forces and moments induced by environmental disturbances, $\tau_a(t) = [\tau_u(t), \tau_r(t)]^T$ is the vector of actuators inputs, and

$$M_1 = \begin{bmatrix} m_{11} & 0 \\ 0 & m_{33} \end{bmatrix}, \quad C_1(v) = \begin{bmatrix} 0 & -m_{22}v \\ (m_{22} - m_{11})v & 0 \end{bmatrix}, \quad D_1 = \begin{bmatrix} d_{11} & 0 \\ 0 & d_{33} \end{bmatrix}. \tag{4}$$

2.3. Control objectives and mathematical preliminaries

Definition 1 *(**(Passive-boundedness)** [4])*. Given a system $\dot{x}_i = f(x) + d$, where $x = [x_1, \ldots, x_i, \ldots, x_n]^T$, $f: \Re^n \to \Re$, and d is a disturbance term. For all bounded x_j, $j \neq i$, and d, if there exists a scalar function $V(x_i) \in C^1$ such that (i) $V(x_i)$ is globally positive-definite and radially unbounded, (ii) $\dot{V}(x_i) < 0$ if $|x_i| > b$, where b is a positive constant and its magnitude is related to the bounds of x_j, $j \neq i$ and d, then, we say the variable x_i is passive-bounded.

Assumption 1 *([4])*. The sway velocity of the vehicle in (2) is passive-bounded in the sense that $\sup_{t\geq 0} \|v(t)\| < B_v$ where B_v is an unknown positive constant.

Remark 1. By considering the literature [4,11,18], it is easy to systematically analyze the passive-boundedness of sway velocity of ocean vehicles. Since in practice the hydrodynamic damping forces in (2) are dominant in the sway direction and, as a result, the sway velocity is damped out by these forces, Assumption 1 is reasonable. The interested reader is referred to [4] for a detailed discussion about this assumption.

Remark 2. In practice, the response of actuators and thrusters is much faster than the surface vehicle response. Therefore, their dynamics is reasonably neglected in this paper and their trivial effects are considered as unmodeled dynamics.

Assumption 2. The disturbance signals $\tau_{wu}(t)$, $\tau_{wv}(t)$ and $\tau_{wr}(t)$ are bounded such that $|\tau_{wu}(t)| \leq \lambda_{wu}$, $|\tau_{wv}(t)| \leq \lambda_{wv}$, and $|\tau_{wr}(t)| \leq \lambda_{wr}$ where λ_{wu}, λ_{wv} and λ_{wr} and are unknown positive constants.

Considering Assumptions 1 and 2, the following tracking problem is addressed in this paper:

Definition 2. Given a smooth bounded reference trajectory (i.e. $x_d(t)$, $y_d(t)$ and $\psi_d(t)$) which is generated by an open-loop motion planner whose motion equations are given by (1) and (2), the *control objective* discussed in this paper is to design the surge force and yaw moment, i.e. $\tau_a(t) = [\tau_u(t),\ \tau_r(t)]^T$, for an underactuated surface vehicle system under the requirements that (i) tracking errors $\eta_e = \eta_d - \eta = [x_e,\ y_e,\ \psi_e]^T$ (where $x_e = x_d - x$, $y_e = y_d - y$ and