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Neural network formation control of underactuated autonomous underwater vehicles with saturating actuators

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A B S T R A C T

This paper addresses a neural network-based formation control of underactuated AUVs with limited torque input under environmental disturbances in three-dimensional space. For this purpose, a second-order dynamic model is developed based on a coordinate transformation for underactuated AUVs. Then, a saturated formation controller is proposed by employing saturation functions in order to bound closed-loop error variables. This technique effectively reduces the risk of actuators saturation by decreasing the amplitude of generated control signals. Multi-layer neural networks are combined with an adaptive robust control strategy to deal with the actuator saturation and model uncertainties including unknown vehicle parameters, approximation errors, and constant or time-varying environmental disturbances induced by waves and ocean currents. A Lyapunov synthesis is used to guarantee semi-global uniform ultimate boundedness of tracking errors for all AUVs. Finally, simulation results demonstrate the performance of the proposed formation controller.

1. Introduction

Autonomous underwater vehicles (AUVs) are widely utilized in robotic and ocean engineering for different purposes such as search, exploration, surveillance, reconnaissance, rescue operations, oceanographic mapping, ocean floor survey, oil and gas extraction, geological sampling, mine-sweeping, and deep sea archeology. Accordingly, the motion control and navigation of such systems are of great importance to operate autonomously in the ocean environment. The formation control of multiple vehicles is related to designing a stabilizing or tracking controller to make a group of vehicles to maintain desired positions and orientations relative to one or more reference points [1–8]. This cooperative motion control provides more efficiency, robustness and redundancy than a single vehicle. There exist some popular approaches including behavioral-based [1] virtual structure [2], or leader-following strategies [3,4]. However, AUVs are often underactuated in practice which means that the number of their actuators is fewer than their degrees-of-freedom (DOF). This characteristic increases the degree of complexity in the design of formation controllers for such vehicles. Yang and Gu [8] have proposed a nonlinear formation-keeping and mooring controller for multiple AUVs. In [9], the leader-following formation control of AUVs has been addressed for a planar motion. In [10], the coordination control of underactuated omni-directional intelligent navigators has been addressed in three-dimensional space. Millan et al. [11] proposed a virtual leader-based formation controller for multiple AUVs in presence of communication delays. The formation control problem of underwater vehicles with time delays has also been addressed in [12] by using a decoupled controller. Park [13] proposed an adaptive formation controller for underactuated AUVs. Adaptive coordinated tracking control of multiple autonomous underwater vehicles has been addressed in [14] as well. However, most of these works are not applicable to the three-dimensional formation control of multiple AUVs. Ma and Zeng [15] have proposed a distributed formation controller for 6-DOF AUVs. However, their proposed controller is not applicable to underactuated underwater vehicles.

Another shortcoming of previous works [8–15] is that they assume that AUV actuators are capable of tolerating any level of input signals and generate the necessary level of torque signals. However, large amplitudes of generated control signals may force the actuators to go beyond their natural capabilities which may lead to their saturation in practical situations. The actuator saturation is not desirable in practice and it may deteriorate the tracking performance of the proposed controller especially in the transient response. In addition, long-term saturation may lead to thermal, electrical or mechanical failures of the actuators. One solution to improve this situation is bounding of the closed-loop error variables by applying a saturation function in the design of the tracking controller. This paper addresses the above mentioned problems for autonomous underwater vehicles.

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To the best of author's knowledge, three-dimensional formation control of underactuated AUVs with actuators saturation has not been addressed sufficiently in the literature. Toward this end, this paper proposes a saturated formation tracking controller to solve this problem in three-dimensional space for the first time. For this purpose, a coordinate transformation is introduced based on a 5-DOF AUV model which contains all posture variables to incorporate the AUV dynamics in all directions and to involve all control inputs. This transformation helps us derive a new second-order formulation for the AUV model. The main contributions of this paper are listed as follows. (i) Compared with the previous works [8–15], the risk of actuators saturation is reduced by using saturation functions and neural networks in the design of the controller, which improves the transient response of the formation control system. (ii) According to the existing literature [8–15], there are a few works which solve three-dimensional formation tracking control of multiple underactuated autonomous underwater vehicles. This problem is addressed in this paper by employing a 5-DOF AUV model and a coordinate transformation. (iii) A multi-layer neural network and adaptive robust control techniques are used to compensate the saturation nonlinearity, uncertain parameters, unmodeled dynamics and environmental disturbances due to waves, wind and ocean currents.

The rest of the paper is arranged as follows. The problem formulation is presented in the next section. A variable transformation is introduced to develop a second-order leader-following formation model which plays a key role in the design of the formation controller. In Section 3, a saturated formation controller is proposed. Then, a Lyapunov-based stability analysis is presented in Section 4. Section 5 provides simulation examples to show the effectiveness of the proposed formation controller. Section 6 discusses on the tuning of NN-based control parameters. Finally, conclusions are drawn in Section 7.

2. Problem formulation

2.1. Notations

Throughout this paper, $\lambda_{\max}(\bullet)$ ($\lambda_{\min}(\bullet)$) represents the largest (smallest) eigenvalue of a matrix. $\|\boldsymbol{x}\| := \sqrt{\boldsymbol{x}^T\boldsymbol{x}}$ represents Euclidean norm of a vector $\boldsymbol{x} \in \Re^n$, while the norm of a matrix $\boldsymbol{A}$ is denoted by the induced norm $\|\boldsymbol{A}\| := \sqrt{\lambda_{\max}(\boldsymbol{A}^T\boldsymbol{A})}$. Frobenius norm of a matrix is given by $\|\mathbf{A}\|_F := \sqrt{\mathrm{tr}\{\mathbf{A}^T\mathbf{A}\}}$ where $\mathrm{tr}\{\bullet\}$ shows the trace operator. The matrix $\mathbf{I}_n$ denotes n-dimensional identity matrix. $\{a_i\}_{i=1}^N$ represents a set of a_i, $i=1,2,\dots,N$. To simplify the subsequent control design and its stability analysis, the following notations are used: $s(\boldsymbol{\eta}) := [s_1(\eta_1), s_2(\eta_2), \dots, s_n(\eta_n)]^T$ and $s'(\boldsymbol{\eta}) = \mathrm{diag}[s_1'(\eta_1), \dots, s_1'(\eta_n)]$, where $\boldsymbol{\eta} = [\eta_1, \eta_2, \dots, \eta_n]^T \in \Re^n$, diag $[\bullet]$ denotes a diagonal matrix, $s_k(\bullet)$, $k=1,\dots,n$ and $s_k'(\bullet)$ denote saturation functions and their derivatives, respectively. In addition, $\Re^+$ denotes positive real numbers.

2.2. Kinematic and dynamic models of AUVs

Consider a group of N underactuated autonomous underwater vehicles whose 5-DOF kinematic model is defined as follows [17,18]:

$$\dot{\boldsymbol{\eta}}_i = \begin{bmatrix} \dot{\boldsymbol{\eta}}_{1i} \\ \dot{\boldsymbol{\eta}}_{2i} \end{bmatrix} = \underbrace{\begin{bmatrix} \mathbf{T}_{1i}(\boldsymbol{\eta}_{2i}) & 0 \\ 0 & \mathbf{T}_{2i}(\boldsymbol{\eta}_{2i}) \end{bmatrix}}_{\mathbf{T}_i(\boldsymbol{\eta}_{2i})} \underbrace{\begin{bmatrix} \mathbf{v}_{1i} \\ \mathbf{v}_{2i} \end{bmatrix}}_{\mathbf{v}_i}, \ i=1,2,\dots,N, \tag{1}$$

where $\mathbf{T}_{1i}(\boldsymbol{\eta}_{2i})$ and $\mathbf{T}_{2i}(\boldsymbol{\eta}_{2i})$ are given by

$$\mathbf{T}_{1i}(\boldsymbol{\eta}_{2i}) = \begin{bmatrix} \cos(\psi_i)\cos(\theta_i) & -\sin(\psi_i) & \sin(\theta_i)\cos(\psi_i) \\ \sin(\psi_i)\cos(\theta_i) & \cos(\psi_i) & \sin(\theta_i)\sin(\psi_i) \\ -\sin(\theta_i) & 0 & \cos(\theta_i) \end{bmatrix},$$
$$\mathbf{T}_{2i}(\boldsymbol{\eta}_{2i}) = \begin{bmatrix} 1 & 0 \\ 0 & 1/\cos(\theta_i) \end{bmatrix}. \tag{2}$$

In addition, their dynamic model is described by the following equations

$$\begin{aligned}
\dot{u}_i &= \frac{m_{22i}}{m_{11i}} v_i r_i - \frac{m_{33i}}{m_{11i}} w_i q_i - \frac{d_{11i}}{m_{11i}} u_i + \frac{1}{m_{11i}} \tau_{sui} - \frac{1}{m_{11i}} \tau_{wui}(t), \\
\dot{v}_i &= -\frac{m_{11i}}{m_{22i}} u_i r_i - \frac{d_{22i}}{m_{22i}} v_i - \frac{1}{m_{22i}} \tau_{wvi}(t), \\
\dot{w}_i &= \frac{m_{11i}}{m_{33i}} u_i q_i - \frac{d_{33i}}{m_{33i}} w_i - \frac{1}{m_{33i}} \tau_{wwi}(t), \\
\dot{q}_i &= \frac{m_{33i} - m_{11i}}{m_{55i}} u_i w_i - \frac{d_{55i}}{m_{55i}} q_i - \frac{\rho_i g \nabla GM_{Li} \sin(\theta_i)}{m_{55i}} \\
&\quad + \frac{1}{m_{55i}} \tau_{sqi} - \frac{1}{m_{55i}} \tau_{wqi}(t), \\
\dot{r}_i &= \frac{m_{11i} - m_{22i}}{m_{66i}} u_i v_i - \frac{d_{66i}}{m_{66i}} r_i + \frac{1}{m_{66i}} \tau_{sri} - \frac{1}{m_{66i}} \tau_{wri}(t),
\end{aligned} \tag{3}$$

where x_j, y_j, z_j, θ_j and ψ_i denote the positions (i.e. surge, sway, heave displacements), and orientations (i.e. pitch and yaw angles), respectively, in the earth-fixed frame, which are denoted by the vector $\boldsymbol{\eta}_i = [\boldsymbol{\eta}_{1i}^T, \boldsymbol{\eta}_{2i}^T]^T$ where $\boldsymbol{\eta}_{1i} = [x_i, y_i, z_i]^T$ and $\boldsymbol{\eta}_{2i} = [\theta_i, \psi_i]^T$. The signals u_i, v_i, w_i, q_i and r_i represent the surge, sway, heave, pitch and yaw velocities in the body-fixed frame which are denoted by the vector $\mathbf{v}_i = [\mathbf{v}_{1i}^T, \mathbf{v}_{2i}^T]^T$ where $\mathbf{v}_{1i} = [u_i, v_i, w_i]^T$ and $\mathbf{v}_{2i} = [q_i, r_i]^T$. The signals τ_{sui}, τ_{sqi} and τ_{sri} are the torque inputs which are provided by the actuators, $\tau_{wui}(t)$, $\tau_{wvi}(t)$, $\tau_{wwi}(t)$, $\tau_{wqi}(t)$, $\tau_{wri}(t) \in \Re$ are bounded time-varying disturbances and unmodeled dynamics, m_{ii}, $i=1,\dots,5$ denote the mass and inertia parameters of AUV, d_{ii}, $i=1,\dots,5$ are damping coefficients and other symbols are referred to [17] and [18]. It should be noted that models (1) and (3) are valid when AUVs are operating at low speeds and are equipped with independent internal or external roll actuators [18].

To simplify the controller design in the next section, the kinematic model (1) is expressed in the actuated degrees of freedom as follows:

$$\dot{\boldsymbol{\eta}}_i = \mathbf{S}_i(\boldsymbol{\eta}_i)\boldsymbol{\upsilon}_i + \boldsymbol{\delta}_i(\boldsymbol{\eta}_i, \mathbf{w}_i), \tag{4}$$

where $\mathbf{S}_i(\boldsymbol{\eta}_i)$ is a new kinematic matrix, $\boldsymbol{\upsilon}_i = [u_i, q_i, r_i]^T$ and $\mathbf{w}_i = [v_i, w_i]^T$ are considered as new velocity vectors in the actuated and unactuated directions, respectively, and $\boldsymbol{\delta}_i(\boldsymbol{\eta}_i, \mathbf{w}_i) \in \Re^5$ denotes a vector of kinematic disturbances which are defined by

$$\mathbf{S}_i(\boldsymbol{\eta}_i) = \begin{bmatrix} \cos(\psi_i)\cos(\theta_i) & 0 & 0 \\ \sin(\psi_i)\cos(\theta_i) & 0 & 0 \\ -\sin(\theta_i) & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1/\cos(\theta_i) \end{bmatrix},$$
$$\boldsymbol{\delta}_i(\boldsymbol{\eta}_i, \mathbf{w}_i) = \begin{bmatrix} -v_i \sin(\psi_i) + w_i \sin(\theta_i)\cos(\psi_i) \\ v_i \cos(\psi_i) + w_i \sin(\theta_i)\sin(\psi_i) \\ w_i \cos(\theta_i) \\ 0 \\ 0 \end{bmatrix} \tag{5}$$

The actuated dynamics of the vehicle is reformulated as follows:

$$\mathbf{M}_{1i}\dot{\boldsymbol{\upsilon}}_i + \mathbf{C}_{1i}(\mathbf{w}_i)\boldsymbol{\upsilon}_i + \mathbf{D}_{1i}\boldsymbol{\upsilon}_i + \mathbf{G}_{1i}(\boldsymbol{\eta}_i) + \boldsymbol{\tau}_{w1i}(t) = \boldsymbol{\tau}_{si}, \tag{6}$$

where $\boldsymbol{\tau}_{si} = [\tau_{sui}, \tau_{sqi}, \tau_{sri}]^T$ represents the vector of the torque inputs to the saturating actuators, $\mathbf{M}_{1i} \in \Re^{3\times3}$ denotes the inertia matrix, $\mathbf{C}_{1i}(\mathbf{w}_i) \in \Re^{3\times3}$ is the Coriolis and centripetal forces, $\mathbf{D}_{1i} \in$