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Brief paper

Neural network-based output feedback control for reference tracking of underactuated surface vessels ☆

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ABSTRACT

This paper proposes an adaptive output feedback control for trajectory tracking of underactuated surface vessels (USVs). For the realistic dynamical model of USVs, we consider the USV model, where the mass and damping matrices are not diagonal. Moreover, except the mass matrix, the system parameters and nonlinearities of the USV are all assumed to be unknown. Despite this uncertain circumstance, we develop an adaptive observer based on the neural networks to estimate the velocity data of USVs. Then, an output feedback control law is designed by simultaneously considering the input saturation and underactuated problems.

1. Introduction

Autonomous underwater vehicles (AUVs) and underactuated surface vessels (USVs) have received increasing attention from control engineers for developing marine resources. However, the design of controllers for USVs is complicated because the sway direction cannot be directly controlled. In addition, a USV cannot be transformed into a driftless chained system (Reyhanoglu, 1997). Because of these problems, some of the control techniques such as for mobile robots cannot be applied to the control of USVs (Chwa, 2011). Therefore, extensive research has concentrated on attempting to overcome these limitations.

A tracking controller combined with adaptive technique and backstepping technique was proposed in Godhavn, Fossen, and Berge (1998). Two constructive tracking solutions based on the Lyapunov direct method were developed in Jiang (2002) to achieve global asymptotic tracking. However, these studies designed controllers under persistent excitation condition, yielding that the yaw velocity should not be zero and thus, a straight line cannot be tracked. A solution to this problem was firstly proposed in Do, Jiang, and Pan (2002a). After this relaxed result, the controllers for stabilization and tracking of USVs were designed in Do, Jiang, and Pan (2002b) and Ghommam, Mnif, and Derbel (2010), the full-state stabilization scheme was presented in Xie and Ma (2015), and the sliding mode controllers were proposed in Perera and Soares (2012) and Yu, Zhu, Xia, and Liu (2012) to show the robustness against the uncertainties such as unknown hydrodynamic damping coefficients and external disturbances. These papers assumed that the mass and damping matrices of USVs are diagonal because in the absence of this assumption, the cascade structure is broken which leads to many problems in the design of the controller. However, since the mass and damping matrices in real USVs are not diagonal, this assumption is not tenable. A solution to this problem was proposed in Do and Pan (2005) considering non-diagonal matrices. All these papers designed the controllers based on full-state feedback.

In contrast to the state feedback results, output feedback controllers using only position information were proposed in Antonelli, Caccavale, Cjiaverini, and Villani (2000), Wondergem, Lefeber, Pettersen, and Nijmeijer (2011) and Zhang, Jia, and Qi (2011). Unfortunately, these controllers are for fully actuated ships. Therefore, an output feedback controller for underactuated ships was developed in Do, Jiang, Pan, and Nijmeijer (2004), but the mass matrices of USVs should be diagonal. For USVs having

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non-diagonal mass matrices, Do et al. proposed a solution in Do and Pan (2006). However, they assumed that the nonlinear damping matrix is diagonal and hydrodynamic derivatives are constants, and did not consider the input saturation problem. Ignoring the input saturation problem in the design of the controller can degrade the performance of the real physical system (Chen, Ge, How, & Choo, 2013).

Motivated by these observations and in order to reflect more realistic situation, we consider the USV model that neither the mass matrix nor the damping matrix is diagonal. The nonlinear damping terms in the model are further assumed to be unknown. To this setup, a neural network-based adaptive observer is first developed to estimate the velocity data of the USV despite the uncertainties and external disturbances. In combination with the observer, an output feedback controller is then proposed for the reference tracking of the USV. In particular, we develop the additional controllers that are able to deal with the input saturation and underactuated problems simultaneously. Finally, the reference trajectory can be any one, including a straight line, due to the proposed approach angle that uses only position information, and the proposed controller guarantees the ultimate boundedness of the tracking errors.

2. Underactuated surface vessel model

The kinematics and dynamics of USVs in the horizontal plane are described as follows Skjetne, Fossen, and Kokotovic (2005):

$$\begin{aligned} M\dot{\nu} &= -C(\nu)\nu - D(\nu)\nu + \tau_d + \sigma(\tau), \\ \dot{\eta} &= J(\psi)\nu, \end{aligned} \tag{1}$$

where $\eta = [x, y, \psi]^T$ denotes position (x, y) and yaw angle ψ of USV in the earth-fixed frame; $\nu = [u, v, r]^T$ denotes surge, sway, and yaw velocities of USV in the body-fixed frame, respectively; $\tau_d = [\tau_{d,u}, \tau_{d,v}, \tau_{d,r}]^T$ is the bounded disturbances induced by waves, wind, and ocean currents; and $\tau = [\tau_u, 0, \tau_r]^T$ is the control vector of the surge force τ_u and the yaw moment τ_r. The saturated control $\sigma(\tau) = [\sigma_u(\tau_u), 0, \sigma_r(\tau_r)]^T$ is defined as follows: $\sigma_i = \tau_{i,\min}$ if $\tau_i \le \tau_{i,\min}$, $\sigma_i = \tau_i$ if $\tau_{i,\min} < \tau_i < \tau_{i,\max}$, $\sigma_i = \tau_{i,\max}$ if $\tau_i \ge \tau_{i,\max}$, where $i = u, r$, and the bounds $\tau_{i,\min}$ and $\tau_{i,\max}$ are known. We define the mismatch between the controls with saturation and without saturation as the dead-zone function $\varpi = [\varpi_u, 0, \varpi_r]^T = \tau - \sigma(\tau)$. Then, the saturated control in (1) is given by $\sigma(\tau) = \tau - \varpi$.

The matrices $J(\psi)$, $D(\nu)$, $C(\nu)$, and M are given as

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

$$M = \begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & m_{23} \\ 0 & m_{23} & m_{33} \end{bmatrix},$$

$$C(\nu) = \begin{bmatrix} 0 & 0 & -m_{22}v - m_{23}r \\ 0 & 0 & m_{11}u \\ m_{22}v + m_{23}r & -m_{11}u & 0 \end{bmatrix},$$

$$D(\nu) = \begin{bmatrix} d_{11}(u) & 0 & 0 \\ 0 & d_{22}(v,r) & d_{23}(v,r) \\ 0 & d_{32}(v,r) & d_{33}(v,r) \end{bmatrix},$$

where $m_{11} = m - X_{\dot{u}}$, $m_{22} = m - Y_{\dot{v}}$, $m_{23} = mx_g - Y_{\dot{r}}$, $m_{33} = I_z - N_{\dot{r}}$, $d_{11}(u) = -(X_u + X_{u|u|}|u|)$, $d_{22}(v, r) = -(Y_v + Y_{|v|v}|v| + Y_{|r|v}|r|)$, $d_{23}(v, r) = -(Y_r + Y_{|v|r}|v| + Y_{|r|r}|r|)$, $d_{32}(v, r) = -(N_v + N_{|v|v}|v| + N_{|r|v}|r|)$, and $d_{33}(v, r) = -(N_r + N_{|v|r}|v| + N_{|r|r}|r|)$. Here, m is the mass of USV; $X_{\dot{u}}$, $Y_{\dot{v}}$, $Y_{\dot{r}}$, and $N_{\dot{r}}$ are the added masses; x_g is the X_b-coordinate of USV center of gravity in the body-fixed frame; I_z is the inertia with respect to the vertical axis; X_u, $X_{u|u|}$, Y_v, $Y_{|v|v}$, $Y_{|r|v}$, Y_r, $Y_{|v|r}$, $Y_{|r|r}$, N_v, $N_{|v|v}$, $N_{|r|v}$, N_r, $N_{|v|r}$, and $N_{|r|r}$ are linear and quadratic drag coefficients. In this paper, we assume that η is measurable, while ν is not. Moreover, M is only known.[1]

Remark 1. We emphasize that the off-diagonal term m_{23} of the mass matrix M is not zero in general because the shape of the bow is different from that of the stern. This means that the sway dynamics is also influenced by the yaw moment τ_r and thus, reflects a complicated but realistic structure of the USVs.

In order to deal with the situation that τ_r acts directly on the sway dynamics by the non-diagonal nature of M, we use the following state transformations (Do & Pan, 2005): $\bar{x} = x + \varepsilon\cos\psi$, $\bar{y} = y + \varepsilon\sin\psi$, and $\bar{v} = v + \varepsilon r$, where $\varepsilon = m_{23}/m_{22}$. Then, the USV (1) can be rewritten as

$$\begin{aligned} \dot{\bar{x}} &= u\cos\psi - \bar{v}\sin\psi, & \dot{u} &= \varphi_u + d_1 + ((\tau_u - \varpi_u)/m_{11}), \\ \dot{\bar{y}} &= u\sin\psi + \bar{v}\cos\psi, & \dot{\bar{v}} &= \varphi_v + d_2, \\ \dot{\psi} &= r, & \dot{r} &= \varphi_r + d_3 + (m_{22}(\tau_r - \varpi_r)/\Delta), \end{aligned} \tag{2}$$

where $\varphi_u = \frac{m_{22}}{m_{11}}vr + \frac{m_{23}}{m_{11}}r^2 - \frac{d_{11}(u)}{m_{11}}u$, $\varphi_v = -\frac{m_{11}}{m_{22}}ur - \frac{d_{22}(v,r)}{m_{22}}v - \frac{d_{23}(v,r)}{m_{22}}r$, $\varphi_r = \frac{1}{\Delta}\{(m_{11}m_{22} - m_{22}^2)uv + (m_{11}m_{23} - m_{23}m_{22})ur - (d_{33}(v,r)r + d_{32}(v,r)v)m_{22} + (d_{23}(v,r)r + d_{22}(v,r)v)m_{23}\}$, $d_1 = \tau_{d,u}/m_{11}$, $d_2 = \tau_{d,v}/m_{22}$, $d_3 = (-m_{23}\tau_{d,v} + m_{22}\tau_{d,r})/\Delta$, and $\Delta = m_{22}m_{33} - m_{23}^2$. In addition, $\varpi_u = \tau_u - \sigma_u$ and $\varpi_r = \tau_r - \sigma_r$. Note that, since M is only known, φ_i and the bounded d_i are uncertain.

The *control objective* is to design a dynamic output feedback controller so that, under the controller, the USV (1) with the output η tracks the trajectory given below.

Assumption 1. The reference trajectory is the one generated by $\dot{\eta}_d = J(\psi_d)\nu_d$, i.e., $\dot{\psi}_d = r_d$ and

$$\dot{x}_d = u_d\cos\psi_d - v_d\sin\psi_d, \qquad \dot{y}_d = u_d\sin\psi_d + v_d\cos\psi_d,$$

where $\eta_d = [x_d, y_d, \psi_d]^T$ and $\nu_d = [u_d, v_d, r_d]^T$ are the vectors to be tracked. Moreover, ψ_d and ν_d are continuous and bounded with their first derivatives again bounded.

With the assumption, we define the tracking errors as

$$x_e = \bar{x} - \bar{x}_d, \qquad y_e = \bar{y} - \bar{y}_d, \qquad \psi_e = \psi - \psi_a, \tag{3}$$

where $\bar{x}_d = x_d + \varepsilon\cos\psi_d$, $\bar{y}_d = y_d + \varepsilon\sin\psi_d$, and ψ_a is an approach angle to be defined later.

3. Main results

In this section, we design the controller using an adaptive observer, which is capable of estimating the velocity data of USV even in the presence of uncertainties.

3.1. Neural network

Neural networks (NNs) can be used to approximate the unknown nonlinearities according to the universal approximation property (Oussar, Rivals, & Dreyfus, 1998). NN can approximate any continuous function $F(\chi_j)$ over the compact set $\Omega_{\chi_j} \in \mathbb{R}^{N_i}$ to arbitrary any accuracy as Chen and Ge (2013) $F(\chi_j) = W_j^{*T}\Theta(\chi_j) + \kappa_j^*$ where $j = 1, 2, 3$, $W_j^* \in \mathbb{R}^{N_h}$ is the constant optimal weights, κ_j^* is the bounded reconstruction error, and $\Theta(\chi_j) = [\Theta_{j,1}, \ldots, \Theta_{j,N_h}]^T$ is composed of the Gaussian activation functions

[1] In fact, M can be calculated using semi-empirical methods or hydrodynamic computation programs as in Skjetne et al. (2005).