POLISH MARITIME RESEARCH 2 (102) 2019 Vol. 26; pp. 68-75
10.2478/pomr-2019-0026

PRE-FILTERED BACKSTEPPING CONTROL FOR UNDERACTUATED SHIP PATH FOLLOWING

Zhiquan Liu
Shanghai Maritime University, China

ABSTRACT

Robust path following control for underactuated surface ships is an important issue in marine control practice. This paper aims to improve the robustness of the close-loop system with model uncertainties and time-varying disturbances. A practical adaptive backstepping control scheme with a pre-filter is proposed to force a surface vessel to track the predefined path generated by the virtual ship. Based on the Lyapunov stability theorem, this algorithm can guarantee all error signals in the overall system to be uniformly ultimately bounded, and it can be implemented without exact knowledge of the nonlinear damping structure and environmental disturbances. The proposed pre-filter can smooth the commanded heading order and obtain a better performance of the waypoint-based navigation control system. Two simulation cases are drawn to illustrate the validity of the proposed control strategy.

Keywords: Underactuated ships; path following; backstepping; pre-filter

INTRODUCTION

During the past decades, the path following and tracking control for marine vehicles have caused much attention in marine control areas, especially in the area concerning the motion control of an underactuated marine vehicle (i.e. underactuated surface ship or underwater autonomous vehicle) [1, 2]. This paper focuses on the control of an underactuated surface ship. The term "underactuated ship" means that the vessel is equipped with rudder and thrusters for the heading angle and forward speed control, whereas the sway axis cannot be actuated directly, which is the main challenge.

Linear model-based control strategies may be easy to implement. Several authors have contributed ideas for surface vessel path following control with linear ship model, including model predictive control taking into account the roll motion constraint [3, 4], PID control [5], and disturbance observer based composite control [6, 7]. When a marine surface vessel is moving in the open sea, it cannot move exactly along the desired path due to the action of rough environmental disturbances, which make the ship dynamics nonlinear and burdened with uncertainties. Robust and adaptive schemes are always selected to sustain the system robustness. Alfi et al. [8] have designed a robust H-infinity controller for tracking control of a container ship. Sliding mode controllers are also selected to solve the robust tracking control problem for underactuated ships [9, 10]. Shin et al. [11] have proposed an adaptive path following control algorithm with the surface vessel dynamic model identified from several trials. In some studies, parameter identification and neural network can also be selected to cope with tracking model uncertainties [12, 13]. These robust and adaptive algorithms are always combined with the backstepping method when solving a tracking control problem of underactuated ship. Do and Pan [14] have designed an adaptive backstepping controller for the path following control of underactuated ship under deterministic disturbances. This control considered the known linear damping coefficients and unknown nonlinear damping coefficients. Moreover, the modified practical control method based on coordinate transformation has been developed [15]. Li et al. [16] have developed the robust nonlinear backstepping path following control with feedback dominance, but it was designed with a reduced order model. Li et al. [17] have proposed a point to point navigation controller to make tracking errors converge to an invariant set. Furthermore, Sun et al. [18] have introduced a PI sliding mode backstepping path following controller with unknown plant parameters. However, the above two methods require that the nonlinear damping parameters are unknown constant vectors with known dimensions, which is a too restrictive condition. For the system nonlinear damping problem, Xu et al. [19] have designed a dynamical sliding mode adaptive tracking controller to handle uncertainties and unknown external disturbances, but it is unreasonable in practice that the two uncertain nonlinear parts are combined together to estimate.

In this paper, a pre-filtered adaptive controller is designed to deal with the path following problem of underactuated surface vessel by combining the backstepping technique. Unlike the controller developed by Li et al. [17], the here proposed control law does not require exact information on the structure and parameter vector dimensions of the uncertainty term, as the whole nonlinear hydrodynamic function and the upper bound of external disturbances are estimated individually. The pre-filtered technique can avoid larger outputs of actuators, and limits the control input of the actuation system in the vessel control system [20]. In this paper, a third order filter is used to relax the smooth trajectory assumption and thus enhance the robustness of the proposed controller, especially in point to point navigation control.

The organization of the paper is as follows. Section 2 gives the problem formulation and the system models. Section 3 formulates the systematic procedure of the proposed algorithm. The numerical simulation results are presented in Section 4 to expound the effectiveness of the tracking controller, and the conclusions are formulated in Section 5.

PROBLEM FORMULATION

Following the description by Zhang et al. [21], we consider the general kinematic and kinetic mathematical model of 3-DOF motion (surge, sway and yaw) of the underactuated ship as:

$$\begin{aligned}
\dot{x} &= u\cos(\psi) - v\sin(\psi) \\
\dot{y} &= u\sin(\psi) + v\cos(\psi) \\
\dot{\psi} &= r \\
\dot{u} &= f_u(\theta) + \frac{1}{m_{11}}\tau_u + \frac{1}{m_{11}}\tau_{wu} \\
\dot{v} &= f_v(\theta) + \frac{1}{m_{22}}\tau_{wv} \\
\dot{r} &= f_r(\theta) + \frac{1}{m_{33}}\tau_r + \frac{1}{m_{33}}\tau_{wr}
\end{aligned} \tag{1}$$

with

$$f_u(\theta) = \frac{m_{22}}{m_{11}}vr - \frac{d_{u1}}{m_{11}}u - \frac{d_{u2}}{m_{11}}|u|u - \frac{d_{u3}}{m_{11}}u^3$$

$$f_v(\theta) = -\frac{m_{11}}{m_{22}}ur - \frac{d_{v1}}{m_{22}}v - \frac{d_{v2}}{m_{22}}|v|v - \frac{d_{v3}}{m_{22}}v^3$$

$$f_r(\theta) = \frac{m_{11} - m_{22}}{m_{33}}uv - \frac{d_{r1}}{m_{33}}r - \frac{d_{r2}}{m_{33}}|r|r - \frac{d_{r3}}{m_{33}}r^3$$

where (x, y, ψ) are the ship's position coordinates and yaw angle expressed in the earth-fixed frame, and $\theta = (u, v, r)$ denotes the velocity vector with surge, sway and yaw components. $f_u(\theta)$, $f_v(\theta)$ and $f_r(\theta)$ are the unknown nonlinear hydrodynamic functions, τ_u and τ_r denote the control force and moment, and $(\tau_{wu}, \tau_{wv}, \tau_{wr})$ are the external disturbances. The positive constants m_{11}, m_{22} and m_{33} are the ship inertia parameters which are assumed known. The unknown parameters $d_{ij}(i = u, v, r;\ j = 1, 2, 3)$ are considered as hydrodynamic damping terms.

Assumption 1.
The ocean environmental disturbances are bounded, i.e. $|\tau_{wu}| \le \tau_{wu\max}$, $|\tau_{wv}| \le \tau_{wv\max}$ and $|\tau_{wr}| \le \tau_{wr\max}$, where $\tau_{wu\max}$, $\tau_{wv\max}$ and $\tau_{wr\max}$ are unknown positive constants. We define new symbols $\tau_{mwu\max} = \tau_{wu\max}/m_{11}$, $\tau_{mwv\max} = \tau_{wv\max}/m_{22}$ and $\tau_{mwr\max} = \tau_{wr\max}/m_{33}$ which satisfy equations $|\tau_{wu}/m_{11}| \le \tau_{mwu\max}$, $|\tau_{wv}/m_{22}| \le \tau_{mwv\max}$ and $|\tau_{wr}/m_{33}| \le \tau_{mwr\max}$.

Assumption 2.
The states of the desired trajectory x_d, $\dot{x}_d$, $\ddot{x}_d$, y_d, $\dot{y}_d$, $\ddot{y}_d$, ψ_d, $\dot{\psi}_d$ and $\ddot{\psi}_d$ are all bounded, and the reference path is smooth.

Assumption 3.
The sway velocity v is passive bounded in the sense that $|v| \le v_{\max}$, following Li et al. [17].

Assumption 4.
The unknown environmental disturbances and uncertain hydrodynamic functions are slowly varying, i.e. $\dot{f}_i(\theta) = 0$ and $\dot{\tau}_{wi} = 0$, $i = u, v, r$.

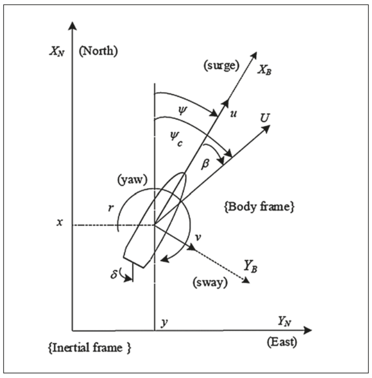

Fig. 1. General frame of path following control

In the overviewed literature, the dynamics of underactuated ship tracking control is addressed by two methods, i.e. as error dynamics in the inertial coordinate frame or the Serret-Frenet frame. Here, the first framework is selected, see Fig. 1. For the tracking control, the following tracking error variables are defined:

$$\begin{aligned} x_e &= x_d - x \qquad y_e = y_d - y \\ \psi_e &= \psi_r - \psi \qquad z_e = \sqrt{x_e^2 + y_e^2} \end{aligned} \tag{2}$$

where (x_d, y_d) is the desired point generated by the virtual ship, ψ_e is the heading error and $|\psi_e| < \pi/2$ is required in the following control law design, z_e is the position tracking error, and $\psi_r \in (-\pi, \pi)$ is the azimuth angle related to the desired virtual ship, defined as follows:

$$\psi_r = 0.5[1 - \mathrm{sgn}(x_e)]\mathrm{sgn}(y_e) \cdot \pi + \arctan(\frac{y_e}{x_e}) \tag{3}$$

where sgn(·) is the sign function. Considering $\psi_r = \psi_d$ when the position tracking error satisfies $z_e = 0$, $\psi_d = \mathrm{artctan}(\dot{y}_d/\dot{x}_d)$ is the desired yaw angle of the virtual ship.

CONTROL DESIGN

The control objective of this paper is to design a backstepping scheme for tracking control of an underactuated ship with Assumptions 1–3. In this section, the control design procedure is achieved in following steps.

SURGE CONTROL

In order to stabilize the position error, we define the Lyapunov function candidate (LFC):

$$V_1 = \frac{1}{2} z_e^2 \tag{4}$$

Its first derivative along the solutions of the system (1) is given as:

$$\begin{aligned} \dot{V}_1 &= z_e \dot{z}_e = z_e(\dot{x}_d \cos \psi_r + \dot{y}_d \sin \psi_r) \\ &- z_e(v \sin \psi_e + u \cos \psi_e) \end{aligned} \tag{5}$$

Remark 1. In order to derive (6), we should show the way of deriving $\dot{z}_e$. Obviously, we know that $z_e^2 = x_e^2 + y_e^2$ and $z_e \dot{z}_e = x_e \dot{x}_e + y_e \dot{y}_e$ according to the position error equation in (2). Based on (1) and (2), we derive the expression of $\dot{z}_e$ as follows:

$$\begin{aligned} \dot{z}_e &= \frac{x_e}{z_e} \dot{x}_e + \frac{y_e}{z_e} \dot{y}_e \\ &= \cos \psi_r (\dot{x}_d - \dot{x}) + \sin \psi_r (\dot{y}_d - \dot{y}) \\ &= \cos \psi_r \dot{x}_d - \cos \psi_r (u \cos \psi - v \sin \psi) \\ &+ \sin \psi_r \dot{y}_d - \sin \psi_r (u \sin \psi + v \cos \psi) \\ &= \dot{x}_d \cos \psi_r - u(\cos \psi_r \cos \psi + \sin \psi_r \sin \psi) \\ &+ \dot{y}_d \sin \psi_r - v(\sin \psi_r \cos \psi - \cos \psi_r \sin \psi) \\ &= \dot{x}_d \cos \psi_r + \dot{y}_d \sin \psi_r - u \cos \psi_e - v \sin \psi_e \end{aligned}$$

We define a virtual control signal α_u that makes $u_e = \alpha_u - u$. The virtual control is selected as

$$\alpha_u = \frac{\dot{x}_d \cos \psi_r + \dot{y}_d \sin \psi_r - v \sin \psi_e + k_{ze} z_e}{\cos \psi_e} \tag{6}$$

where $k_{ze} > 0$ is a designed parameter.

Substituting $u = \alpha_u - u_e$ and the virtual control equation (6) into (5), we get

$$\dot{V}_1 = -k_{ze} z_e^2 + z_e u_e \cos \psi_e \tag{7}$$

Rewriting the surge dynamics using the new variable yields

$$\dot{u}_e = \dot{\alpha}_u - \dot{u} = \dot{\alpha}_u - f_u(\theta) - \frac{1}{m_{11}}\tau_u - \frac{1}{m_{11}}\tau_{wu} \tag{8}$$

Then, we define a new Lyapunov function:

$$V_2 = V_1 + \frac{1}{2} u_e^2 \tag{9}$$

and its first derivative:

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + u_e \dot{u}_e = -k_{ze} z_e^2 + z_e u_e \cos \psi_e \\ &+ u_e[\dot{\alpha}_u - f_u(\theta) - \frac{1}{m_{11}}\tau_u - \frac{1}{m_{11}}\tau_{wu}] \end{aligned} \tag{10}$$

In order to make (10) negative, we design the actual control law as follows:

$$\begin{aligned} \tau_u &= m_{11} k_{ue} u_e + m_{11}[z_e \cos \psi_e + \\ &\dot{\alpha}_u - \hat{f}_u(\theta) + \delta_u \hat{\tau}_{mwu\max} u_e] \end{aligned} \tag{11}$$

where k_{ue} and δ_u are the designed positive constants, $\hat{f}_u(\theta)$ is the estimate of the nonlinear hydrodynamic function, and $\hat{\tau}_{wu\max}$ is the estimate of the upper bound of the external surge force. The corresponding update laws are chosen as follows:

$$\begin{aligned} \dot{\hat{f}}_u(\theta) &= \Gamma_u[-u_e - a_u(\hat{f}_u(\theta) - \hat{f}_{u0}(\theta))] \\ \dot{\hat{\tau}}_{mwu\max} &= \gamma_u [\delta_u u_e^2 - a_{tu}(\hat{\tau}_{mwu\max} - \hat{\tau}_{mwu\max}(0))] \end{aligned} \tag{12}$$

where Γ_u, γ_u, a_u and a_{tu} are the positive designed parameters, while $\hat{f}_{u0}(\theta)$ and $\hat{\tau}_{mwu\max}(0)$ are the initial values of the corresponding update state.

To stabilize the estimation errors, we consider the following LFC

$$V_3 = V_2 + \frac{1}{2\Gamma_u} \tilde{f}_u^2(\theta) + \frac{1}{2\gamma_u} \tilde{\tau}_{mwu\max}^2 \tag{13}$$

where $\hat{f}_u(\theta) = \hat{f}_u(\theta) - f_u(\theta)$ is the estimation error of the surge nonlinear damping function, and $\hat{\tau}_{mwu\max} = \hat{\tau}_{mwu\max} - \tau_{mwu\max}$ is the estimation error of the bound of the surge disturbance.

Differentiating both sides of (13) gives:

$$
\begin{aligned}
\dot{V}_3 &= V_2 + \frac{1}{\Gamma_u}\tilde{f}_u(\theta)\dot{\hat{f}}_u(\theta) + \frac{1}{\gamma_u}\tilde{\tau}_{mwu\max}\dot{\hat{\tau}}_{mwu\max} \\
&= k_{ze}z_e^2 - k_{ue}u_e^2 + u_e\tilde{f}_u(\theta) + \frac{1}{\Gamma_u}\tilde{f}_u(\theta)\dot{\hat{f}}_u(\theta) \\
&\quad - \delta_u\hat{\tau}_{mwu\max}u_e^2 - \frac{u_e}{m_{11}}\tau_{wu} + \frac{1}{\gamma_u}\tilde{\tau}_{mwu\max}\dot{\hat{\tau}}_{mwu\max} \\
&\le -k_{ze}z_e^2 - a_u\tilde{f}_u(\theta)[\tilde{f}_u(\theta) + f_u(\theta) - \hat{f}_{u0}(\theta)] \\
&\quad - k_{ue}u_e^2 - \delta_u\hat{\tau}_{mwu\max}u_e^2 + |u_e|\tau_{mwu\max} + \tilde{\tau}_{mwu\max}\delta_u u_e^2 \\
&\quad - \tilde{\tau}_{mwu\max}[a_{tu}(\tilde{\tau}_{mwu\max} + \tau_{mwu\max} - \hat{\tau}_{mwu\max}(0))] \\
&\le -k_{ze}z_e^2 - k_{ue}u_e^2 - a_u\tilde{f}_u^2(\theta) \\
&\quad - a_u\tilde{f}_u(\theta)[f_u(\theta) - \hat{f}_{u0}(\theta)] - \delta_u\hat{\tau}_{mwu\max}u_e^2 \\
&\quad + \delta_u\tau_{mwu\max}u_e^2 + \frac{1}{4\delta_u}\tau_{mwu\max} + \delta_u\tilde{\tau}_{mwu\max}u_e^2 \\
&\quad - a_{tu}\tilde{\tau}_{mwu\max}^2 - a_{tu}[\tau_{mwu\max} - \hat{\tau}_{mwu\max}(0)] \\
&\le -k_{ze}z_e^2 - k_{ue}u_e^2 - a_u\tilde{f}_u^2(\theta) - a_{tu}\tilde{\tau}_{mwu\max}^2 + \rho_u
\end{aligned} \tag{14}
$$

where

$$
\begin{aligned}
\rho_u &= \frac{1}{4\delta_u}\tau_{mwu\max} + \frac{1}{2}\left[\left|\tilde{f}_u(\theta)\right|^2 + \left|f_u(\theta) + \hat{f}_{u0}(\theta)\right|^2\right] \\
&\quad + \frac{1}{2}\left[\left|\tilde{\tau}_{mwu\max}\right|^2 + \left|\tau_{mwu\max} - \hat{\tau}_{mwu\max}(0)\right|^2\right]
\end{aligned}
$$

is a positive constant.

Let $\lambda_u = \min\{2k_{ue}, 2k_{ze}, a_u\Gamma_u, a_{tu}\gamma_u\}$, then (14) can be rewritten as

$$\dot{V}_3 \le -\lambda_u V_3 + \rho_u \tag{15}$$

Therefore, all tracking errors listed in (13) are uniformly ultimately bounded (UUB).

YAW CONTROL

According to the error dynamics of yaw motion in (1) and (2), we define the following LFC:

$$V_4 = \frac{1}{2}\psi_e^2 \tag{16}$$

and its time derivative yields:

$$\dot{V}_4 = \psi_e\dot{\psi}_e = \psi_e(\dot{\psi}_r - r) \tag{17}$$

Similarly, in order to let $\dot{V}_4$ negative, we introduce a virtual control of yaw rate that satisfies $r_e = \alpha_r - r$. This control can be expressed as follows:

$$\alpha_r = k_{\psi e}\psi_e + \dot{\psi}_r \tag{18}$$

where $k_{\psi e}$ is the designed positive constant.

In order to stabilize the new error signal, we define LFC:

$$V_5 = V_4 + \frac{1}{2}r_e^2 \tag{19}$$

Differentiating both sides of (19) gives the derivative of that LFC:

$$
\begin{aligned}
\dot{V}_5 &= \dot{V}_4 + r_e\dot{r}_e = -k_{\psi e}\psi_e^2 + r_e\psi_e \\
&\quad + r_e[\dot{\alpha}_r - f_r(\theta) - \frac{1}{m_{33}}\tau_r - \frac{1}{m_{33}}\tau_{wr}]
\end{aligned} \tag{20}
$$

In order to stabilize the heading error and yaw velocity error, we choose the control law τ_r as follows:

$$\tau_r = m_{33}[k_{re}r_e + \dot{\alpha}_r + \psi_e - \hat{f}_r(\theta) + \delta_r\hat{\tau}_{mwr\max}r_e] \tag{21}$$

where k_{re} and δ_r are the designed positive constants, $\hat{f}_r(\theta)$ is the estimate of the nonlinear hydrodynamic term, and $\hat{\tau}_{wr\max}$ is the estimate of the upper bound of the yaw moment caused by waves. The corresponding update laws are chosen as follows:

$$
\begin{aligned}
\dot{\hat{f}}_r(\theta) &= \Gamma_r[-r_e - a_r(\hat{f}_r(\theta) - \hat{f}_{r0}(\theta))] \\
\dot{\hat{\tau}}_{mwr\max} &= \gamma_r[\delta_r r_e^2 - a_{tr}(\hat{\tau}_{mwr\max} - \hat{\tau}_{mwr\max}(0))]
\end{aligned} \tag{22}
$$

where Γ_r, γ_r, a_r and a_{tr} are the positive designed parameters, while $\hat{f}_{r0}(\theta)$ and $\hat{\tau}_{wr\max}(0)$ are the initial values of the corresponding update state.

If we intend to stabilize the estimation errors, the following Lyapunov function is selected:

$$V_6 = V_5 + \frac{1}{2\Gamma_r}\tilde{f}_r^2(\theta) + \frac{1}{2\gamma_r}\tilde{\tau}_{mwr\max}^2 \tag{23}$$

Its derivative yields:

$$
\begin{aligned}
\dot{V}_6 &= \dot{V}_5 + \frac{1}{\Gamma_r}\tilde{f}_r(\theta)\dot{\hat{f}}_r(\theta) + \frac{1}{\gamma_r}\tilde{\tau}_{mwr\max}\dot{\hat{\tau}}_{mwr\max} \\
&= -k_{\psi e}\psi_e^2 - k_{re}r_e^2 + r_e\tilde{f}_r(\theta) + \frac{1}{\Gamma_r}\tilde{f}_r(\theta)\dot{\hat{f}}_r(\theta) \\
&\quad - \delta_r\hat{\tau}_{mwr\max}r_e^2 - \frac{r_e}{m_{33}}\tau_{wr} + \frac{1}{\gamma_r}\tilde{\tau}_{mwr\max}\dot{\hat{\tau}}_{mwr\max} \\
&\le -k_{\psi e}\psi_e^2 - k_{re}r_e^2 - a_r\tilde{f}_r(\theta)[\tilde{f}_r(\theta) + f_r(\theta) - \hat{f}_{r0}(\theta)] \\
&\quad - \delta_r\hat{\tau}_{mwr\max}r_e^2 + |r_e|\tau_{mwr\max} + \tilde{\tau}_{mwr\max}\delta_r r_e^2 \\
&\quad - \tilde{\tau}_{mwr\max}[a_{tr}(\tilde{\tau}_{mwr\max} + \tau_{mwr\max} - \hat{\tau}_{mwr\max}(0))] \\
&\le -k_{\psi e}\psi_e^2 - k_{re}r_e^2 - a_r\tilde{f}_r^2(\theta) \\
&\quad - a_r\tilde{f}_r(\theta)[f_r(\theta) - \hat{f}_{r0}(\theta)] - \delta_r\hat{\tau}_{mwr\max}r_e^2 \\
&\quad + \delta_r\tau_{mwr\max}r_e^2 + \frac{1}{4\delta_r}\tau_{mwr\max} + \delta_r\tilde{\tau}_{mwr\max}r_e^2 \\
&\quad - a_{tr}\tilde{\tau}_{mwr\max}^2 - a_{tr}[\tau_{mwr\max} - \hat{\tau}_{mwr\max}(0)] \\
&\le -\lambda_r V_6 + \rho_r
\end{aligned} \tag{24}
$$

where: $\lambda_r = \min\{2k_{re}, 2k_{\psi e}, a_r, \Gamma_r, a_{tr}\gamma_r\}$, and

$$\rho_r = \frac{1}{4\delta_r}\tau_{mwr\max} + \frac{1}{2}[|\tilde{f}_r(\theta)|^2 + |f_r(\theta) - \hat{f}_{r0}(\theta)|^2] + \frac{1}{2}[|\tilde{\tau}_{mwr\max}|^2 + |\tau_{mwr\max} - \hat{\tau}_{mwr\max}(0)|^2]$$

is the positive constant. Then, all error signals listed in (23) are UUB.

PRE-FILTER

According to the formulas (18) and (21), the yaw control law needs the smooth first and second derivatives of the reference heading angle ψ_r. To avoid algebraic loop problems caused by the derivative modulus, and to obtain the derivative of the reference heading angle and heading rate easily, Zhang et al. [21] selected the discrete transformation method instead of the direct analytical method to get differential signals. Alternatively, a pre-filter is proposed in this paper to obtain smooth signals of ψ_r, $\dot{\psi}_r$ and $\ddot{\psi}_r$. Based on the commanded heading angle ψ_r^c calculated by the trajectory generator (3), the third order pre-filter [22] is modified as follows:

$$\dddot{\psi}_r + (2\xi + 1)\omega\ddot{\psi}_r + (2\xi + 1)\omega^2\dot{\psi}_r + \omega^3\psi_r = \omega^3\psi_r^c \quad (25)$$

where ξ is the damping, and ω is the frequency of this filter. The reference model also satisfies $\lim\psi_r(t) = \psi_r^c$ if ψ_r^c is constant. The values of filter parameters are chosen as $\xi = 1$ and $\omega = 10$.

SIMULATIONS

In this section, two simulation cases are analyzed to demonstrate the effectiveness of the proposed algorithm. The results of these simulations are compared with those obtained by Li et al. [17]. The vessel model in this paper is taken from Do et al. [22], while the external disturbance models are taken directly from Zhang et al. [21]. The initial values of the plant and controller are similar to those applied in Ref. [17], and are as follows:

$$[x(0), y(0), \psi(0), u(0), v(0), r(0)] = [-80, 20, 0, 0, 0, 0]$$

$$\hat{\tau}_{mwu\max}(0) = 0{,}7\,\tau_{mwu\max} \qquad \hat{\tau}_{mwr\max}(0) = 0{,}7\,\tau_{mwr\max}$$

$$\tau_{mwu\max} = 1 \qquad \tau_{mwr\max} = 1.5$$

$$\hat{f}_{u0}(\theta) = 0{,}7\,f_u(\theta) \qquad \hat{f}_{r0}(\theta) = 0{,}7\,f_r(\theta)$$

$$f_u(\theta) = -20 \qquad f_r(\theta) = 1$$

The parameters of the controller are defined as

$$k_{ze} = 0.1 \qquad k_{ue} = 0.5 \qquad k_{\psi e} = 0.5 \qquad k_{re} = 10$$

$$a_u = 0.002 \qquad a_r = 0.2 \qquad a_{tu} = 0.005 \qquad a_{tu} = 0.1$$

$$\Gamma_u = 0.003 \qquad \Gamma_r = 0.05$$

$$\gamma_u = \gamma_r = 1 \qquad \delta_u = \delta_r = 0.1$$

Case 1 is the curve path following. The sinusoidal reference trajectory has been taken from Do and Pan [14]. The obtained simulation results are displaced in Figs. 2–6. As shown in Fig. 2, the ship can track the reference path accurately and smoothly under the condition of time-varying disturbances and unknown dynamics. Fig. 3 compares the attitude errors and the position errors. It is observed that both methods make the tracking error quickly converge to an invariant set. However, the heading error performance is visibly improved by the proposed control law.

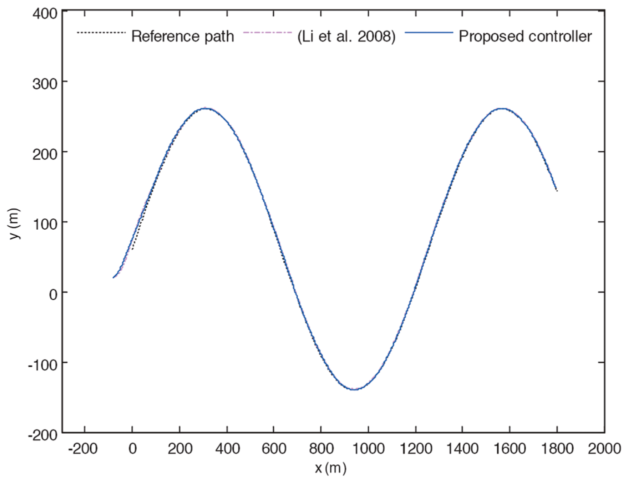

Fig. 2. Curve path tracking

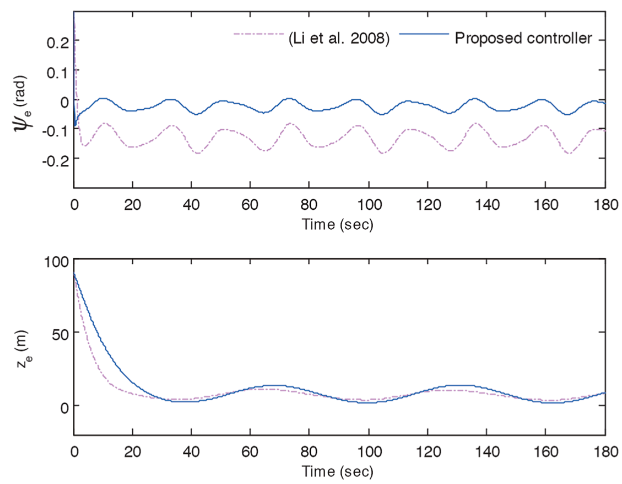

Fig. 3. Tracking errors – case 1

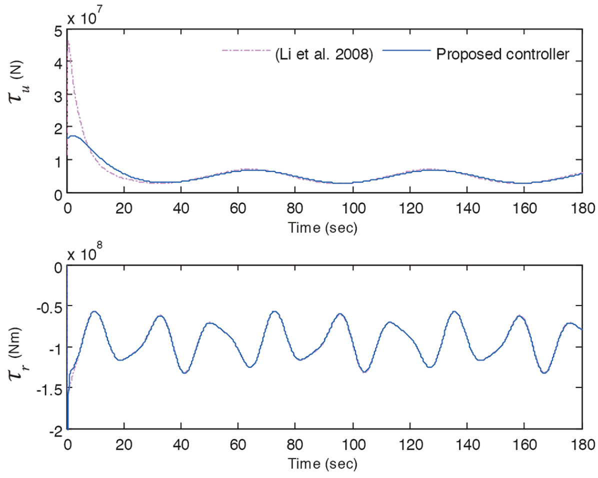

Fig. 4. Control inputs – case 1

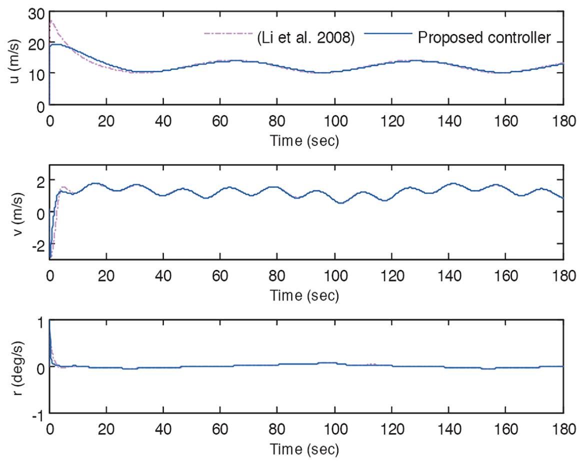

Fig. 5. Ship motion responses – case 1

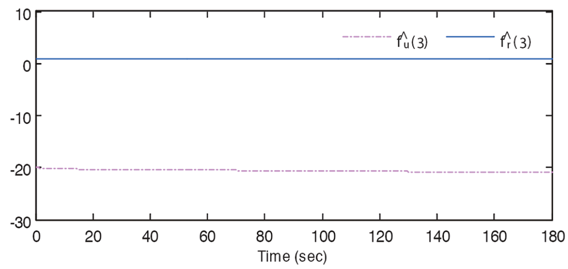

Fig. 6. Estimates of nonlinear hydrodynamic terms – case 1

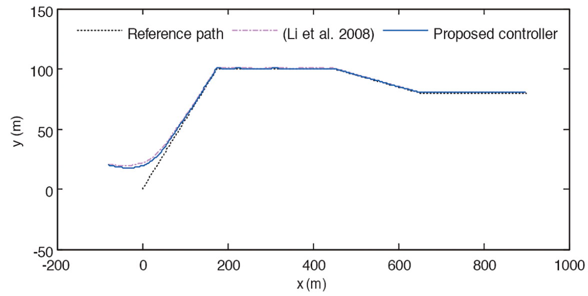

Fig. 7. Point to point navigation

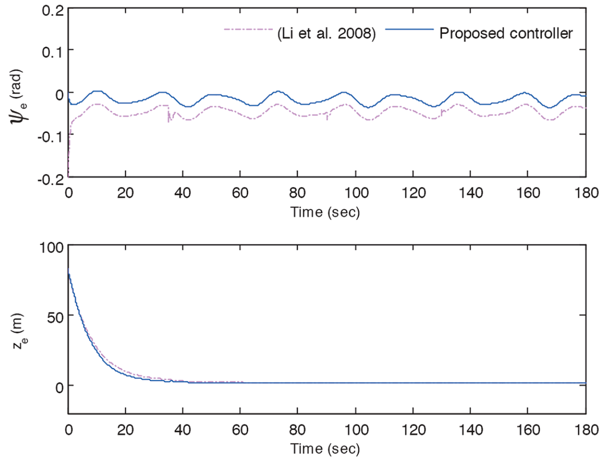

Fig. 8. Tracking errors – case 2

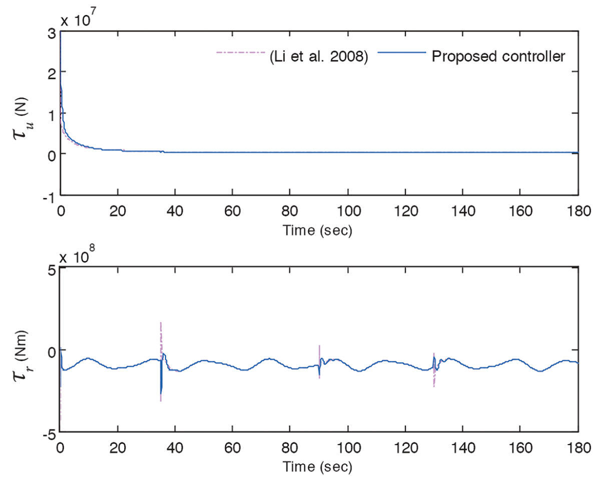

Fig. 9. Control inputs – case 2

Fig. 4 compares the control input surge forces and the yaw moments. It can be seen that the proposed algorithm can produce a much smoother surge control force, which decreases the power consumption by the propeller and the resultant energy cost. The ship motion responses are compared in Fig. 5, and the estimates of the nonlinear hydrodynamic force and moment, given in (12) and (22), are presented in Fig. 6.

Case 2 is the point-to-point navigation. Following the route analyzed by Do et al. [23], we assume that the vessel moves along the trajectory which consists of straight lines connecting the desired points: (0,0), (175,100), (450,100) and (650,80). Consequently, the reference trajectory is non-smooth. Figs. 7–11 present the simulation results. Fig. 7 shows that both control schemes force the underactuated vessel to track the predefined path closely. The position tracking errors converge to small nonzero values at similar rates, as shown in Fig. 8. The proposed controller can effectively reduce the heading error and let it converge to a smaller set.

The corresponding control inputs are detailed in Fig. 9. As can be seen, similar control forces and moments are generated by the two control laws. Their high magnitudes mainly result from the fact that the system with large-magnitude external disturbances is simulated. Several

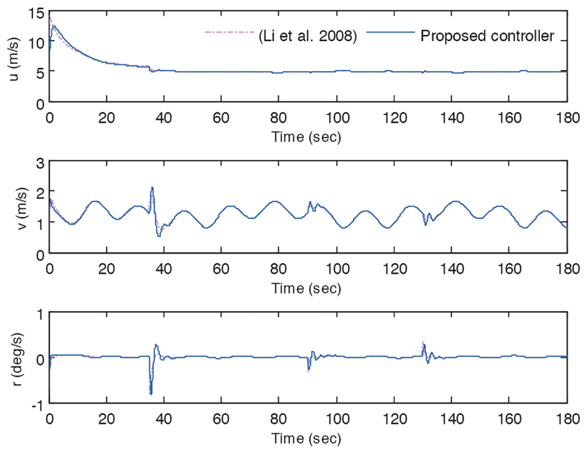

Fig. 10. Ship motion responses – case 2

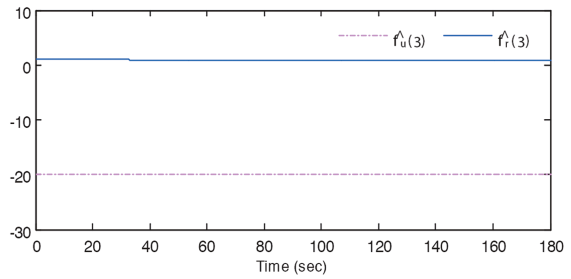

Fig. 11. Estimates of nonlinear hydrodynamic terms – case 2

picks observed in τ_r are due to the inflection points in the trajectory. Furthermore, compared to the controller in Li et al [17], the proposed controller can more effectively reject the chattering (picks) of the yaw moment when the vessel crosses the waypoint. These picks are mainly caused by the large inertia of the ship and the non-smooth reference heading. The corresponding ship motion responses in Case 2 are addressed in Fig. 10, and the corresponding estimates of the nonlinear hydrodynamic force and moment, given in (12) and (22), are presented in Fig. 11.

CONCLUSIONS

The paper presents a practical backstepping controller that is able to steer an underactuated surface vessel along a desired trajectory under the conditions of time-varying disturbances and uncertainties. Under the assumption that the sway dynamics is passive bounded, the adaptive technique is applied to estimate the nonlinear hydrodynamic term and the upper bound of the unknown external disturbances. This method does not require the knowledge about the non-modeled dynamics. In order to relax the assumption of smooth reference heading and trajectory, a pre-filter is applied to smooth the commanded heading signal and enhance the system robustness. By comparison with the scheme in Li et al. [17], the presented numerical simulations demonstrate the validity and effectiveness of the proposed controller.

REFERENCES

1. Liu T., Dong Z., Du H., Song L. Mao Y.: *Path following control of the underactuated USV on the improved line-of-sight guidance algorithm*. Polish Maritime Research, 2017, 24(1): 3–11.
2. Shojaei K., DolatshahiM.: *Line-of-sight target tracking control of underactuated autonomous underwater vehicles*. Ocean Engineering, 2017, 133: 244–252.
3. Liu C., Sun J., Zou Z.: *Integrated line of sight and model predictive control for path following and roll motion control using rudder*. Journal of Ship Research, 2015, 59(2): 99–112.
4. Zhang J., Sun T., Liu Z.: *Robust model predictive control for path following of underactuated surface vessels with roll constraints*. Ocean Engineering, 2017, 143: 125–132.
5. Moreira L., Fossen T.I., Soares C.G.: *Path following control system for a tanker ship model*. Ocean Engineering, 2007, 34(14): 2074–2085.
6. Hu C., Wang R., Yan F., Chen N.: *Robust composite nonlinear feedback path following control for underactuated surface vessels with desired heading amendment*. IEEE Transactions on Industrial Electronic, 2016, 63(10): 6386–6394.
7. Das S., Talole S.E.: *GESO based robust output tracking controller for marine vessels*. Ocean Engineering, 2016, 121: 156–165.
8. Alfi A., Shokrzadeh A., Asadi M.: *Reliability analysis of H-infinity control for a container ship in way-point tracking*. Applied Ocean Research, 2015, 52: 309–316.
9. Ashrafiuon H., Muske K.R., Mcninch L.C., Slotan R.A.: *Sliding mode tracking control of surface vessels*. IEEE Transactions on Industrial Electronics, 2008, 55(11): 4004–4012.
10. Yu R., Zhu Q., Xia G., Liu Z.: *Sliding mode tracking control of an underactuated surface vessel*. IET Control Theory and Applications, 2012, 6(3): 461–466.
11. Shin J., Kwak D., Lee Y.: *Adaptive path following control for an unmanned surface vessel using an identified dynamic model*. IEEE Transactions on Mechatronics, 2017, 22(3): 1143–1153.
12. Xu H., Soares C.G.: *Vector field path following for surface marine vessel and parameter identification based on LS-SVM*. Ocean Engineering, 2016, 113: 151–161.
13. Zhang G., Zhang X.: *Practical robust neural path following control for underactuated marine vessels with actuators uncertainties*. Asian Journal of Control, 2017, 19(1): 173–187.

14. Do K.D., Pan J.: *Global robust adaptive path following of underactuated ships*. Automatica, 2006, 42(10): 1713–1722.

15. Do K.D.: *Practical control of underactuated ships*. Ocean Engineering, 2010, 37(13): 1111–1119.

16. Li Z., Sun J., Oh S.: *Design, analysis and experimental validation of a robust nonlinear path following controller for marine surface vessels*. Automatica, 2009, 45(7): 1649–1658.

17. Li J., Lee P.M., Jun B.H., Kim Y.K.: *Point-to-point navigation of underactuated ships*. Automatica, 2008, 44(12): 3201–3205.

18. Sun Z., Zhang G., Yi B., Zhang W.: *Practical proportional integral sliding mode control for underactuated surface ship in the fields of marine practice*. Ocean Engineering, 2017, 142: 217–223.

19. Xu J., Wang M., Qiao L.: *Dynamical sliding mode control for trajectory tracking of underactuated unmanned underwater vehicles*. Ocean Engineering, 2015, 105: 54–63.

20. Peara L.P., Soares C.G.: *Pre-filtered sliding mode control for nonlinear ship steering associated with disturbances*. Ocean Engineering, 2012, 51(3): 49–62.

21. Zhang G., Zhang X., Zhang Y.: *Adaptive neural path-following control for underactuated ships in fields of marine practice*. Ocean Engineering, 2015, 104: 558–567.

22. Fossen T.I.: *Handbook of marine craft hydrodynamics and motion control*. Wiley, United Kingdom 2011.

23. Do K.D., Jiang Z.P., Pan J.: *Robust adaptive path following of underactuated ships*. Automatica, 2004, 40(6): 929–944.

CONTACT WITH THE AUTHORS

Zhiquan Liu
e-mail: liuzhiquan215@sina.com

Key Laboratory of Marine Technology
and Control Engineering
Ministry of Communications
Shanghai Maritime University
1550 Haigang AVE, 201306 Shanghai
CHINA