Research Article

Event-Triggered Controller Design for Autopilot with Input Saturation

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This paper considers the problem of autopilot design for surface ship with environmental disturbances and input saturation. Extended state observer (ESO) is used to reconstruct yaw rate and estimate unknown environmental disturbances. An auxiliary dynamic system is employed to handle the input saturation. By combining with the auxiliary dynamic system and ESO, an event-triggered controller (ETC) is designed, and energy is saved by reduction in the rudder rate. Simulation results illustrate the effectiveness and feasibility of the event-triggered proposed controller.

1. Introduction

Autopilot design of marine surface vehicles has witnessed a surge of interest. Autopilot design with sophisticated controllers has a wide application prospect in reduced manpower, adequate economy, sufficient reliability, and optimum performance [1].

A significant amount of research efforts has been focused on autopilot. In the beginning, because of simple structure and preferable antinoise ability, proportional integral differential (PID) algorithm is applied to design autopilot. However, the parameters for the PID control terms are not easy to tune. To solve these problems [2], consider a class of optimal PID control problems, each of these optimal parameter selection problems is solved as a nonlinear optimization problem [3], and present an adaptive PID control algorithm which improves the grey predictive control for temperature control. In [4], a nonlinear function is employed to describe manoeuvring characteristics that reflect the steady-state relation between the rudder deflection and the rate of turn of the hull, and two configurations of nonlinear controllers are applied to ship course.

In practice, the actual yaw angle is measured from the sensors or observer [5]. Das [6] makes an assumption that the yaw and yaw rate are all measurable, which is difficult to implement. Peng et al. [7] present a robust adaptive steering

law based on dynamic surface control technique and neural network, and a state observer is employed to reconstruct the yaw rate.

Environmental disturbances and model uncertainties are important challenges. Rigatos and Tzafestas [8] propose an adaptive fuzzy H_∞ controller for the autopilot system, and unknown part of the system dynamics can be approximated with the indirect adaptive control. Liu et al. [9] propose an output feedback adaptive steering law for an unmanned surface vehicle, and a neural network using iterative updating law is employed to handle the unknown dynamic and environmental disturbances. A sliding mode control strategy for the autopilot system is proposed in [10], where a fuzzy logic is used to handle gain and avoid the chattering effect. Xia et al. [11] address the problem of adaptive neural network controller for the surface vessel, and adaptive technique and neural network system are used to approximate uncertainties. Disturbance observer is employed to estimate the unmodeled external forces in [12, 13].

All of the above articles do not consider the limitation of rudder angle, which is widespread in practice. Input saturation degrades the quality of the control and can even destabilize the system. Hence, it is necessary to consider the limitation of the rudder angle. Tzeng and Lin [14] propose an adaptive ship steering approach which is characterized by a model-based design approach that provides clear

connections between the structure of the controller and ship model. Babaei et al. [15] present an efficient strategy to design the altitude hold mode autopilot for unmanned aerial vehicle, and a multiobjective genetic algorithm is used to mechanize the optimal determination of fuzzy logic controller parameters.

In many applications, rudder limits includes magnitude limits and rate limits. The digital computer with sampler and zero-order holder is employed to emulate the continuous-time control scheme, and the control command will be updated periodically [16]. Katayama and Aoki [17] propose the use of a performance-based supervisory switching control system for trajectory tracking unmanned surface vessels without considering the actuator magnitude limits and rate limits. The performance-based simulator includes the effects of actuator rate limits and saturation, and the results show that the orientation cannot stabilize to the tangent velocity. Furthermore, high-frequency action will lead to the mechanical abrasion and increase fuel consumption. Shipping is no different than other industries and is highly affected by fuel prices [18]. Thus, it is practical to lower the acting frequencies of actuators. An event-triggered robust fuzzy control scheme is developed for underactuated ships in [19], where fuzzy logic systems are employed to approximate the uncertainties, and the ideology of ETC is employed to avoid the frequent acting of actuators.

This paper reports an autopilot design for surface vehicle, subject to environmental disturbances and input saturation. Extended state observer (ESO) is employed to estimate the unknown environmental disturbances. An auxiliary dynamic system is designed to handle the input saturation. The control architecture is developed by ESO, auxiliary dynamic system, and event-triggered strategy. By using the event-triggered strategy, the proposed approach is able to reduce the rudder rate, which has great significance to the reduction of mechanical wear and fuel consumption. The stability analysis using Lyapunov function shows that all error signals in the closed-loop system are uniformly ultimately bounded. Simulation result shows the effectiveness of the proposed method.

This paper is organized as follows. Section 2 formulates the surface ship model with input saturation and the problem formulation. Section 3 depicts the design of the extended state observer. Section 4 presents the design of the controller by using the event-trigger strategy and auxiliary dynamic system, gives the stability analysis, and demonstrates the effectiveness of the proposed control scheme. Section 5 provides a simulation to illustrate the theoretical result. Section 6 concludes this paper.

2. Mathematical Model

2.1. Notation. The following notations will be used throughout this paper. $|\cdot|$ denotes the absolute value unless specified. $\|\cdot\|$ represents the Euclidean norm. $\mathbb{R}^{m \times n}$ represents the $m \times n$ -dimensional Euclidean Space. $\lambda_{\min}$ represents minimum eigenvalue of a square matrix. $(\cdot)^T$ denotes the transpose of a matrix.

2.2. Model of the Ship. As shown in Figure 1, assume that the ship has an xz -plane of symmetry, and heave, pitch, and roll motions are neglected. The body-fixed frame coordinate origin is set in the center-line of the ship. The mathematical model of the ship moving in a horizontal plane is described as [20]

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

where $\eta = [x, y, \psi]^T$ is the vector denoting the ship position (x, y) and yaw angle ψ with coordinates in the earth-fixed frame, $\nu = [u, v, r]^T$ is the vector denoting surge, sway, and yaw velocities of the ship in the body-fixed frame, $d = [d_1, d_2, d_3]^T$ is the vector representing environmental disturbances, and $\tau = [\tau_u, \tau_v, \tau_r]^T$ is the control vector of the ship which consists of the surge force τ_u , sway force τ_v , and yaw moment τ_r . The matrices $J(\psi)$ is given by

$$\begin{aligned}J(\psi) &= \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}, \\ M &= \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - X_{\dot{v}} & mx_g - Y_{\dot{r}} \\ 0 & mx_g - N_{\dot{v}} & I_z - N_{\dot{r}} \end{bmatrix},\end{aligned}\quad (2)$$

where m is the mass of the ship, I_z is the moment of inertia about z -axis in the b-frame, x_g is the center of gravity in the body-fixed frame, and $X_{\dot{v}}$, $Y_{\dot{r}}$, $N_{\dot{v}}$, and $N_{\dot{r}}$ are the hydrodynamic parameters:

$$C = \begin{bmatrix} 0 & 0 & c_{13} \\ 0 & 0 & c_{23} \\ c_{31} & c_{32} & 0 \end{bmatrix}, \quad (3)$$

where $c_{13} = -(m - X_{\dot{v}})v - (mx_g - Y_{\dot{r}})r$, $c_{23} = (m - X_{\dot{u}})u$, $c_{31} = (m - X_{\dot{v}})v + (mx_g - Y_{\dot{r}})r$, and $c_{32} = -(m - X_{\dot{u}})u$. $C(\nu) = -C^T(\nu) \in \mathbb{R}^{3 \times 3}$ represents a skew-symmetric matrix of Coriolis and centripetal term:

$$D = \begin{bmatrix} d_{11} & 0 & 0 \\ 0 & d_{22} & d_{23} \\ 0 & d_{32} & d_{33} \end{bmatrix}, \quad (4)$$

where $d_{11} = -(X_u + X_{|u|}|u|)$, $d_{22} = -(Y_v + Y_{|v|}|v| + Y_{|r|}|r|)$, $d_{23} = -(Y_r + Y_{|v|r}|v| + Y_{|r|r}|r|)$, $d_{32} = -(N_v + N_{|v|}|v| + N_{|r|}|r|)$, $d_{33} = -(N_r + N_{|v|r}|v| + N_{|r|r}|r|)$, and X_u , $X_{|u|}$, Y_v , $Y_{|v|}$, $Y_{|r|}$, $Y_{|v|r|}$, $Y_{|r|r|}$, N_v , $N_{|v|}$, $N_{|r|}$, $N_{|v|r|}$, and $N_{|r|r|}$ are linear and quadratic drag coefficients.

2.3. Model Decoupling. The mathematical model represented by equation (1) can be simplified by supposing a constant surge speed $u = u_0$. The sway-yaw dynamics can be separated from model and is described as

$$M_{vr}\dot{\nu}_{vr} + N(u_0)\nu_{vr} = \tau_{vr}, \quad (5)$$

FIGURE 1: Body-fixed frame $X_B O_B Y_B$ and earth-fixed frame $X_E O_E Y_E$.

where $v_{vr} = [v, r]^T$ is the state vector, τ_{vr} is a vector which represents the force and moment in sway and yaw directions, respectively, and

$$M_{vr} = \begin{bmatrix} m - X_{\dot{v}} & mx_g - Y_{\dot{r}} \\ mx_g - N_{\dot{v}} & I_z - N_{\dot{r}} \end{bmatrix},$$

$$N(u_0) = \begin{bmatrix} -Y_v & -Y_r + (m - X_{\dot{u}})u_0 \\ -N_v + (X_{\dot{u}} - Y_{\dot{v}})u_0 & -N_r + (mx_g - Y_{\dot{r}})u_0 \end{bmatrix}. \quad (6)$$

One notes that $N(u_0)$ can be attained by

$$N(u_0) = C_{vr} + D_L, \quad (7)$$

where

$$C_{vr} = \begin{bmatrix} 0 & (m - X_{\dot{u}})u_0 \\ (X_{\dot{u}} - Y_{\dot{v}})u_0 & (mx_g - Y_{\dot{r}})u_0 \end{bmatrix}, \quad (8)$$

$$D_L = \begin{bmatrix} -Y_v & -Y_r \\ -N_v & -N_r \end{bmatrix}.$$

Assume that the ship has a single rudder, and the following is obtained:

$$\tau_{vr} = b\delta, \quad (9)$$

where $b = [-Y_{\delta}, -N_{\delta}]^T$, Y_{δ} and N_{δ} are the coefficients of force in sway and moment in yaw, respectively.

In this model, equation (5) can be transformed into Nomoto's model by eliminating the sway velocity written as

$$\frac{r(s)}{\delta(s)} = \frac{K(1 + T_3 s)}{(1 + T_1 s)(1 + T_2 s)}, \quad (10)$$

where T_i ($i = 1, 2, 3$) is the parameter related to the characteristics of the ship, r is the yaw rate, δ is the rudder angle, and K is the gain constant related to the hydrodynamic coefficients. Experimentally, the constants T_2 and T_3 are nearly equal. Hence, equation (10) can be written as

$$\frac{r(s)}{\delta(s)} = \frac{K}{1 + Ts}, \quad (11)$$

where $T = T_1 + T_2 - T_3$.

Consider input saturation, and it can be attained that $-U_m \leq \delta \leq U_m$, where U_m is the maximum rudder deflection. Define the mismatch function between input without saturation and with saturation as $\sigma = \delta_c - \delta$, where δ_c is the rudder angle calculated by the controller.

2.4. Control Objective. The desired angle ψ_d provided by the guidance system, in here, it is given directly. The desired yaw rate r_d is the signals derived from the following second-order filter:

$$\begin{aligned} \dot{\psi}_a &= r_d, \\ \dot{r}_d &= \iota_1^2 (\psi_a - \psi_d) - 2\iota_1 r_d, \end{aligned} \quad (12)$$

where $\iota_1 \in \mathbb{R}$ is a positive constant.

The control objective is to force the surface vehicle to track a reference heading signal ψ_d and lower the acting frequencies of actuators, such that

$$\lim_{t \rightarrow +\infty} |\psi - \psi_d| \leq \varepsilon, \quad (13)$$

where ε is a positive constant which can be made small enough.

3. Extended State Observer

The proposed autopilot controller is designed based on ESO which is designed to reconstruct the unmeasurable yaw rate, environmental disturbances, and model uncertainties.

Reshape dynamic (11) with the mismatch function to facilitate the controller design:

$$\dot{r} = \frac{K}{T} (\delta_c - \sigma + \delta_w) - \frac{1}{T} r, \quad (14)$$

where δ_w is unknown and bounded environmental disturbances.

In order to facilitate the ESO design, equation (14) is rewritten in the state space form as

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= x_3 + a + b_0 u_t, \\ \dot{x}_3 &= h, \end{aligned} \quad (15)$$

where $x_1 = \psi$, $x_2 = r$, $x_3 = (K/T)\delta_w$, $a = -(1/T)r$, $b_0 = (K/T)$, and $u_t = \delta_c - \sigma$.

Assumption 1. There exists a positive constant h^* satisfying $\|h\| \leq h^*$.

Remark 1. Assumption 1 is reasonable because of the environmental disturbances assumed to be bounded. a represents the plant dynamics, x_3 represents the environmental disturbances, h represents the differential of environmental disturbances, and u_t is input signal.

Expression (15) can be rewritten in terms of the matrix as follows:

$$\dot{x} = Ax + Bu + Eh, \quad (16)$$

where $x = [x_1, x_2, x_3]^T$ is the extended state vector,

$$\begin{aligned}
A &= \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{1}{T} & 1 \\ 0 & 0 & 0 \end{bmatrix}, \\
B &= \begin{bmatrix} 0 \\ b_0 \\ 0 \end{bmatrix}, \\
E &= \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}.
\end{aligned} \tag{17}$$

Consider an ESO as follows:

$$\dot{\hat{x}} = A\hat{x} + Bu + Le, \tag{18}$$

where $e = x_1 - \hat{x}_1$, $\hat{x} = [\hat{x}_1, \hat{x}_2, \hat{x}_3]^T$ is the estimation of x , and $L = [k_1, k_2, k_3]^T$ is observer gain matrix with k_i , $i = 1, 2, 3$ is positive constant.

Subtracting equation (18) from equation (16), the following can be attained:

$$\dot{\tilde{x}} = A\tilde{x} + Eh - Le, \tag{19}$$

where $\tilde{x} = x - \hat{x}$.

Define that $Le = LC\tilde{x}$ with $C = [1, 0, 0]$. Hence, equation (19) can be rewritten as follows:

$$\dot{\tilde{x}} = (A - LC)\tilde{x} + Eh. \tag{20}$$

Select the appropriate matrix L to stabilize the matrix $A - LC$. Under Assumption 1, dynamic (20) shows observer (18) ensures that the estimation of the environmental disturbances converges to its real value in a finite time.

4. Controller Design

Auxiliary dynamic system is constructed to handle the input constraint in [21], in here, the auxiliary dynamic system is designed as

$$\dot{\beta}_1 = -L_1\beta_1 + \beta_2, \tag{21}$$

$$\dot{\beta}_2 = -L_2\beta_2 - b_0\sigma, \tag{22}$$

where L_1 and L_2 are positive constants.

The controller design process is presented.

Step 1. Define the surface error vector as

$$z_1 = \hat{\psi} - \psi_d - \beta_1, \tag{23}$$

and choose the Lyapunov candidate function as

$$V_1 = \frac{1}{2}z_1^2. \tag{24}$$

Along (23) and (21), the time derivative of V_1 is represented by

$$\dot{V}_1 = z_1\dot{z}_1 = z_1(\hat{r} - r_d + L_1\beta_1 - \beta_2), \tag{25}$$

where $\hat{r}$ is the estimate of r .

Define the second surface error as

$$z_2 = \hat{r} - \bar{\alpha} - \beta_2, \tag{26}$$

where $\bar{\alpha}$ is the signals derived from the following first-order low-pass filters $\iota_2\ddot{\alpha} + \dot{\bar{\alpha}} = \dot{\alpha}$ with ι_2 is a positive constant and α is a virtual control defined as

$$\alpha = -c_1z_1 + r_d - L_1\beta_1, \tag{27}$$

where $c_1 > 0$ is a constant.

Synthesizing with equations (25) and (27),

$$\dot{V}_1 = -c_1z_1^2 + z_1(z_2 + \tilde{\alpha}), \tag{28}$$

where $\tilde{\alpha} = \bar{\alpha} - \alpha$.

Step 2. Choose a Lyapunov function as follows:

$$V_2 = V_1 + \frac{1}{2}z_2^2. \tag{29}$$

From (18), (22), and (26), the following can be attained:

$$\dot{z}_2 = -\frac{1}{T}\hat{x}_2 + \hat{x}_3 + b_0(\delta_c - \sigma) - k_2e - \dot{\bar{\alpha}} + L_2\beta_2 + b_0\sigma. \tag{30}$$

Substituting (30) into the time derivative of V_2 and synthesizing with equation (28),

$$\dot{V}_2 = -c_1z_1^2 + z_1(z_2 + \tilde{\alpha}) + z_2\left(-\frac{1}{T}\hat{x}_2 + \hat{x}_3 + b_0\delta_c - k_2e - \dot{\bar{\alpha}} + L_2\beta_2\right). \tag{31}$$

To stabilize z_2 , a controller is designed as

$$\delta_c = \frac{1}{b_0}\left(-z_1 + \frac{1}{T}\hat{x}_2 - \hat{x}_3 + \dot{\bar{\alpha}} - c_2z_2 - L_2\beta_2\right), \tag{32}$$

where c_2 is a positive constant.

Substituting (32) into (31), then

$$\dot{V}_2 = -c_1z_1^2 - c_2z_2^2 + z_1\tilde{\alpha} - k_2z_2e. \tag{33}$$

As shown in [22], it can prove that $\tilde{\alpha}$ is bounded. Let $\tilde{\alpha}_u$ be the upper bound of $\tilde{\alpha}$. Using Young's inequality,

$$\begin{aligned}
z_1\tilde{\alpha} &\leq z_1\tilde{\alpha}_u \\
&\leq \frac{1}{2}z_1^2 + \frac{1}{2}\tilde{\alpha}_u^2,
\end{aligned} \tag{34}$$

$$\begin{aligned}
z_2e &\leq \frac{1}{2}z_2^2 + \frac{1}{2}e^2 \\
&\leq \frac{1}{2}z_2^2 + \frac{1}{2}\tilde{x}^T\tilde{x}.
\end{aligned} \tag{35}$$

Step 3. Consider the total Lyapunov function candidate as

$$V = V_2 + \frac{1}{2}\beta_1^2 + \frac{1}{2}\beta_2^2 + \frac{1}{2}\tilde{x}^T\tilde{x}. \quad (36)$$

Differentiating V along (20)–(22), (34), and (35), the following can be attained:

$$\begin{aligned} \dot{V} \leq & -\left(c_1 - \frac{1}{2}\right)z_1^2 - \left(c_2 - \frac{k_2}{2}\right)z_2^2 - \left(c_3 - \frac{k_2}{2}\right)\tilde{x}^T\tilde{x} \\ & -L_1\beta_1^2 - L_2\beta_2^2 + \beta_1\beta_2 - b_0\beta_2\sigma + h^* + \frac{1}{2}\tilde{\alpha}_u^2, \end{aligned} \quad (37)$$

where $c_3 = \lambda_{\min}(A - LC)$ and h^* is given according to $\|Eh\| \leq h^*$.

Define $\bar{\sigma}$ is upper bound of σ , and using Young's inequality,

$$\begin{aligned} \beta_2\sigma & \leq \beta_2\bar{\sigma} \\ & \leq \frac{1}{2}\beta_2^2 + \frac{1}{2}\bar{\sigma}^2, \\ \beta_1\beta_2 & \leq \frac{1}{2}\beta_1^2 + \frac{1}{2}\beta_2^2. \end{aligned} \quad (38)$$

Then, (37) can be rewritten as

$$\begin{aligned} \dot{V} \leq & -\left(c_1 - \frac{1}{2}\right)z_1^2 - \left(c_2 - \frac{k_2}{2}\right)z_2^2 - \left(c_3 - \frac{k_2}{2}\right)\tilde{x}^T\tilde{x} \\ & -\left(L_1 - \frac{1}{2}\right)\beta_1^2 - \left(L_2 - \frac{1}{2} - \frac{b_0}{2}\right)\beta_2^2 + \mu_1, \end{aligned} \quad (39)$$

where $\mu_1 = h^* + (1/2)\tilde{\alpha}_u^2 + (b_0/2)\bar{\sigma}^2$.

Step 4. In the common continuous control schemes, the design has already been complete in Step 3. Here, the ideology of event-trigger control is employed and the triggering condition will be established in this step. During the flow period between two successive triggering instants, zero-order hold is employed to keep δ_c unchanged. The key to a successful ETC design is to select an appropriate trigger condition. The current triggering instant is denoted as t_{g_i} and the next triggering instant $t_{g_{i+1}}$ is determined by satisfying the following triggering condition:

$$t_{g_{i+1}} = \inf\{t \in \mathbb{R} \mid t > t_{g_i} \wedge W_a \geq \gamma V\}, \quad (40)$$

where $W_a = (c_1 - (1/2))z_1^2 + (c_2 - (k_2/2))z_2^2$ and $0 < \gamma < \lambda_{\min}\{(c_1 - (1/2)), (c_2 - (k_2/2))\}$ is the adjustable variable. Once the triggering condition is satisfied, thus $W_a \leq \gamma V$, and it renders

$$0 > -W_a > -\gamma V, \quad (41)$$

and it implies $-W_a$ is bounded. Then,

$$\begin{aligned} \dot{V} & \leq -W_a - \left(c_3 - \frac{k_2}{2}\right)\tilde{x}^T\tilde{x} - \left(L_1 - \frac{1}{2}\right)\beta_1^2 - \left(L_2 - \frac{1}{2} - \frac{b_0}{2}\right)\beta_2^2 + \mu_1 \\ & \leq -\left(c_3 - \frac{k_2}{2}\right)\tilde{x}^T\tilde{x} - \left(L_1 - \frac{1}{2}\right)\beta_1^2 - \left(L_2 - \frac{1}{2} - \frac{b_0}{2}\right)\beta_2^2 + \mu_1, \end{aligned} \quad (42)$$

from the definition of V , it is sure that V , $\tilde{x}$, β_1 , and β_2 are bounded and convergent. From $W_a \leq \gamma V$, then z_1 and z_2 are bounded. Owing to the convergence of V proved, then the convergences of z_1 and z_2 are proved. Therefore, all signals in the closed-loop are bounded.

Thus, (40) can be rewritten as

$$\dot{V} \leq -cV + \mu_1, \quad (43)$$

where c is a positive constant, and if the triggering condition is satisfied, $c = \lambda_{\min}\{(c_3 - (k_2/2)), (L_1 - (1/2)), (L_2 - (1/2) - (b_0/2))\}$, otherwise $c = \lambda_{\min}\{(c_1 - (1/2)), (c_2 - (k_2/2)), (c_3 - (k_2/2))\}$.

The following can be attained:

$$V(t) \leq \left(V(0) - \frac{\mu_1}{c - \gamma}\right)e^{-(c - \gamma)t} + \frac{\mu_1}{c - \gamma}. \quad (44)$$

From the definition of V , it can conclude that z_1 , z_2 , $\tilde{x}$, β_1 , and β_2 are bounded. From (44), z_1 exponentially converges to the compact set $\Pi = \{z_1 \mid |z_1| \leq 2(\mu_1/(c - \gamma))\}$ that can be made arbitrarily small by adjusting $c - \gamma$. Then, it holds $\lim_{t \rightarrow +\infty} |\psi - \psi_d| \leq \epsilon$, and the control object is completed.

5. Simulations and Results

In this section, comparison with normal PID controller (PIDC) is given through Matlab simulation, and simulation result is provided to validate the effectiveness and feasibility of the proposed controller. The parameters for ESO are set to $k_1 = 4$, $k_2 = 5$, and $k_3 = 10$. The rudder angle is constrained as $|\delta| \leq 35^\circ$. The sampling period of trigger condition is 0.01 s, i.e., $t_{g_{i+1}} - t_{g_i} = 0.01$. $\gamma = 0.01$, the reference heading signal is set as $\psi_d = 30^\circ$ for $0 \leq t \leq 150$ s, $\psi_d = 0^\circ$ for $150 \leq t \leq 300$ s.

The output responses of the proposed controller are plotted in Figure 2, where it shows that the actual yaw of the surface ship tracks the reference yaw accurately. By comparison with normal PIDC, ETC has the problems of tiny jitter. Figure 3 shows that ETC has a shock in the yaw rate, and the yaw rate is a smooth curve varying with time under PIDC, and the estimation of the yaw rate converges nicely to the actual yaw rate. Figure 4 describes the environmental disturbances and estimation, and it shows that the ESO can accurately estimate the environmental disturbances. Figure 5 shows the rudder angle δ varying with time under ETC and PIDC, and the local enlarged diagrams of control input δ around 65 s for the rudder is shown. The rudder angle δ is updated 30,000 times under PIDC and 8,512 times under ETC. Though the simulation on the system control part carries on the contrast analysis, PID control strategy reflects the good control performance, but it is hard to implement.

FIGURE 2: Simulation of heading angle tracking under ETC and PIDC.

FIGURE 3: Yaw rate r under ETC and PIDC and estimation $\hat{r}$.

The ETC is easier to implement and energy is saved by the reduction in the rudder rate. In Figure 3, the yaw rate suffers from sudden jumps. To solve this problem, the actuator magnitude and rate limits can be considered as a part of future works.

FIGURE 4: Actual disturbances (blue solid line) and estimation (red dotted line).

FIGURE 5: Rudder action under ETC (blue line) and PIDC (red line) and local enlarged diagram around 65 s.

6. Conclusions

This paper addresses the autopilot design for a surface vehicle in the presence of environmental disturbances and input saturation. The control architecture is proposed based on ESO and the event-triggered strategy. The ESO is employed to reconstruct the yaw rate. Simulation result shows the designed controller can ensure that the actual yaw of the surface ship tracks the reference yaw accurately. A stability analysis based on Lyapunov direct method proves that all signals are bounded and tracking errors converge to a neighborhood of the origin.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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