A decoupling controller by hierarchical backstepping method for straight-line tracking of unmanned surface vehicle

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ABSTRACT
For the straight-line tracking of unmanned surface vehicle (USV), most researchers pay much attention to the course control. In the present work, a strategy of decoupling and control of the speed and yaw of the USV is proposed to maintain a constant speed and a desired course, which ensures the high efficiency of ship-borne sonar during a seabed exploration. Since USV is 3-DOF underactuated system, the Lyapunov direct method is combined with the hierarchical back stepping control method to achieve the desired speed and yaw angle of USV under the external disturbances, such as wind, waves and currents. A disturbance observer is then constructed to compensate the oscillation by predicting changes in external disturbances. The control system is further proved to be asymptotically stable by the Lyapunov theory. The validity and robustness of this decoupling controller is verified by applying to a practical USV in the straight-line tracking.

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Introduction
As a kind of motion platform, unmanned surface vehicles (USVs) can independently navigate in the marine environment and complete various tasks (Li, 2012). Because of this, they will play an increasingly important role in future maritime national security and maritime development (Xu, Su, & Pang, 2006). The premise of ensuring that USVs navigate safely and successfully in a complex marine environment is their ability to realize path tracking control independently (Guo, Wang, Sun, & Shen, 2009), of which straight-line tracking is one of the important research contents.

Dong et al. (2015) solved the problem of linear track tracking control for an underactuated USV through adaptive T–S fuzzy neural network control. Tian, Wang, Peng, and Liu (2015) obtained the desired yaw of the USV based on the line-of-sight (LOS) guidance principle and used the anti-saturation proportional–integral–derivative (PID) controller to complete straight track tracking with a track error less than 0.05 m. Fan, Guo, Zhao, Wang, and Shi (2016) considered the linear path tracking of USVs under the time-varying drift angle and combined the LOS guidance algorithm with a fuzzy adaptive PID yaw tracking controller to reduce the influence of the time-varying drift angle on the track tracking control accuracy. The controller was based on guidance and nonlinear models, and it realized the path following of an underactuated vessel by introducing sideslip compensation. Dynamic controllers were also designed (Breivik & Fossen, 2004). Børhaug, Pavlov, Panteley, and Pettersen (2011) and Burger, Pavlov, Børhaug, and Pettersen (2009) studied the linear path following and formation control of a three-degree-of-freedom (DOF) underactuated vessel based on a controller composed of an LOS guidance cross-tracking control law and a nonlinear synchronization control law. Meanwhile, Katayama and Aoki (2014) studied and analyzed the linear trajectory tracking control of underactuated sampled data ships with both state and output feedback controllers by resorting to nonlinear sampled data control theory. Liu, Bu, and Xu (2015) designed a linear tracking controller using the backstepping and Lyapunov direct methods to realize ship steering on a specified straight path. Zheng and Sun (2016) used a robust adaptive radial basis function neural network and the backstepping technology enhanced by an auxiliary design system to study the linear-path-following control problem of an unmanned marine surface vessel under the conditions of uncertainty and input saturation. Zhu, Wang, Zheng, and Wu (2016) analyzed the principle of USV’s linear path following and designed a tracking controller based on the motion mathematical model considering the influence of flow. Fossen and Lekkas (2017) proposed a direct and indirect nonlinear adaptive path following controller for marine craft based on the LOS guidance principle.
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Liu, Wang, and Peng (2017) proposed an LOS guidance law based on an extended state observer for the path following problem of underactuated marine surface vehicles with time-varying sideslip angles. Zhang and Zhang (2017) studied the path following control of underactuated ships under actuator uncertainty and unknown environmental disturbance using the new dynamic virtual ship guidance principle, feedforward approximation, dynamic surface control and robust neural damping techniques. Wang, Sun, Zheng, and Zhao (2018) proposed an adaptive fuzzy path following a control strategy based on a finite-time sideslip observer to deal with an underactuated marine vehicle with time-varying sideslip and unknown dynamics. In addition, path and trajectory tracking control were also studied in the UAV field (Tavakol & Binazadeh, 2017; Gai, Liu, Qu, & Zhang, 2018). The Takagi–Sugeno fuzzy method was also applied to control issues (Wang, Karimi, Lam, & Yan, 2019; Wang, Yang, & Yan, 2019; Wang, Xia, Shen, & Zhou, 2018). Furthermore, the controller and various optimization methods were applied to other aspects (Wu, Karimi, & Dang, 2019; Xie, Shakoor, Shen, Mills, & Sun, 2019; Wu, Jiang, & Kao, 2019).

Most of the abovementioned studies only considered the course-keeping control of unmanned ships and gave no further consideration to the speed stability control problem in the course of straight-line tracking. For unmanned survey boats, devices such as a side-scan sonar can be guaranteed of an effective operation only under the condition of a USV directional constant speed; therefore, this study investigates the problem of USV straight-line tracking from the following aspects: (1) The problem of track control for USVs is transformed into the problem of keeping the yaw angle and the speed according to the characteristics of straight-line tracking; (2) two controllers are designed using the Lyapunov direct method and the backstepping control method to control the speed and the yaw because the speed and the yaw of USVs must be stable in straight-line tracking; (3) considering the uncertainty of the nonlinear model of USVs and the external disturbance, a disturbance observer is taken into the controller to eliminate the chattering and improve the stability and the robustness of the vehicle speed and yaw; and (4) based on the small USV, called ‘JingHai-VIII’ of Shanghai University, the desired speed and trajectory through a linear tracking task are given, and the established control system is used for straight-line tracking.

**The ship model**

The main parameters of the USV and its hull mathematical model were introduced based on JingHai-VIII, Shanghai University’s underactuated unmanned vehicle. The vehicle adopts a double propeller propulsion mode; thus, the surge movement depends on the same speed of the double propellers, and the yaw movement is realized through the differential speed of the double propellers with no driving force in the sway direction, thereby allowing it to meet the sway movement requirements. However, the USV is often disturbed by wind, waves, currents and other external environments in the sway direction during the straight-line tracking, which results to sway errors. Therefore, errors must be eliminated using the cooperation of surge and yaw movements to realize the straight-line tracking. Table 1 lists the main parameters of the USV.

The USV was designed to be operated on the water surface in low/medium sea conditions; thus, the USV movement on the water surface can be assumed to be planar with a linear motion only in the X and Y axis directions; hence, the USV move- ment on the water surface can be assumed to be planar with no driving force in the sway direction, thereby allowing it to meet the sway movement requirements. However, the USV is often disturbed by wind, waves, currents and other external environments in the sway direction during the straight-line tracking, which results to sway errors. Therefore, errors must be eliminated using the cooperation of surge and yaw movements to realize the straight-line tracking. Table 1 lists the main parameters of the USV.

**Table 1. Hull parameters of the USV.**

| Parameters                  | Value | Parameters                  | Value |
|-----------------------------|-------|-----------------------------|-------|
| Length (m)                  | 2.70  | Propeller draft (m)         | 0.37  |
| Width (m)                   | 1.30  | Total mass of a fully loaded hull (kg) | 130  |
| Waterline length (m)        | 2.14  | Distance between the propeller centre and the hull centre of gravity (m) | 0.65  |
| Waterline breadth (m)       | 0.88  | Double thruster maximum power (W) | 1600  |
| Hull draft (m)              | 0.18  | Thruster centre distance (m) | 0.48  |

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\[
C(v) = \begin{bmatrix}
0 & 0 & -(m - Y)v \\
0 & 0 & -(m - X)u \\
(m - Y)v & (m - X)u & -mxg - Yrv - (m - X)u
\end{bmatrix}
\]

\[
D(v) = \begin{bmatrix}
-Xu - X |u|u & 0 & 0 \\
0 & -Yv - Y |v|v & -Yr - Y |r|r| \\
0 & -Nr - N |r|r| & -Nv - N |v|v
\end{bmatrix}
\]

In these equations, \(m\) is the mass of a ship; \(Xu\) is the linear drag coefficient in the surge direction; \(Yv\) is the linear drag coefficient in the sway direction; and \(Nr\) is the linear drag moment coefficient from the yaw rate. More details about the hydrodynamic coefficients can be found in a study by Fossen (2011).

**Design of the disturbance observer and controller**

The USV controller must be robust to the uncertainty of the nonlinear dynamic model and the external disturbance. The disadvantage of the traditional control algorithm in dealing with a nonlinear uncertain system is observed to become gradually obvious. Based on the parameter of JingHai-VIII, the desired yaw angle was obtained according to the desired straight track. In the controller design aspect, the controls of speed and yaw were separated, and two controllers were designed. The speed controller was designed based on the Lyapunov direct method, whereas the yaw controller was designed based on the backstepping method. In dealing with the external disturbances, the speed and yaw observers were constructed to provide an estimation of the surge and yaw disturbances. The estimations were introduced into the controller design to constitute the overall control system of the USV (Figure 1).

**Disturbance observer**

Considering that the USV is disturbed by the time-varying uncertainties of wind, waves and currents when sailing on the sea surface, a disturbance observer was constructed herein to effectively estimate the disturbance. The disturbance estimation was taken as one of the inputs of the speed and yaw controller system to realize the closed-loop control of the whole control system. Assuming that the disturbance and its derivative were bounded, the disturbance observer could be designed as follows based on the nonlinear exponential convergence observer proposed by Do (2010) and Yang, Du, Liu, Guo, and Abraham (2014) and according to Equation (1):

\[
\dot{\hat{d}} = \delta + K_0 M v
\]

and

\[
\dot{\delta} = -K_0 \delta - K_0 \left[ -C(v) v - D(v) v + \tau + K_0 M v \right]
\]

where \(\hat{d} = [\hat{d}_x, \hat{d}_y, \hat{d}_z]^T\) is the observer’s estimation of the disturbance, \(K_0\) is a three-dimensional (3D) positive definite gain symmetric square matrix, and \(\delta\) is a 3D intermediate auxiliary vector. The validity of the disturbance observer is proven next.

The disturbance observer error is defined as \(d_e = d - \hat{d}\). The Lyapunov function was constructed to analyze the disturbance observer stability:

\[
V_d = \frac{1}{2} d_e^T d_e
\]
We can obtain the following by combining Equations (1), (5), and (6):
\[ \dot{d}_e = \dot{d} - \ddot{d} = \ddot{d} - (\dot{d} + K_0 \dot{M} \dot{v}) = \ddot{d} - K_0 d_e \] (8)

The first derivative of the Lyapunov function of the disturbance observer was obtained and combined with Equations (7) and (8) to obtain
\[ \dot{V}_d = d_e^T \dot{d}_e = -K_0 d_e^T d_e + \frac{1}{4\mu} \dot{d}_e^T \dot{d} \] (9)

The following results can be obtained by transforming \( \dot{V}_d \) based on the complete square inequality:
\[ \dot{V}_d \leq -K_0 d_e^T d_e + \mu d_e^T d_e + \frac{1}{4\mu} \dot{d}_e^T \dot{d} \leq -2(\chi_{\min}(K_0) - \mu) V_d + \frac{1}{4\mu} \dot{d}_e^T \dot{d} \] (10)

where \( \chi_{\min}(K_0) - \mu > 0 \), and the solution of the above differential equation can be
\[ 0 \leq V_d(t) \leq \frac{1}{2(\chi_{\min}(K_0) - \mu)} [V_d(0) - \frac{1}{2(\chi_{\min}(K_0) - \mu)}] e^{-2(\chi_{\min}(K_0) - \mu)t} \] (11)

According to Equation (11), \( V_d \) was ultimately bounded, and the disturbance estimation error can be improved by appropriately adjusting parameter \( \mu \) and gain matrix \( K_0 \). In the case of \( d = 0 \), when \( t \rightarrow \infty \), \( d_e \rightarrow 0 \), and \( \dot{d} \rightarrow \ddot{d} \), the disturbance error eventually converged to zero, and the actual disturbance approached the estimated value, proving that the designed disturbance observer was asymptotically stable.

**Speed controller**

The USV speed controller was designed based on the Lyapunov direct method considering the separate designs of the USV speed and yaw controllers. We obtained the following by dividing Equation (1) to obtain Equation (12) in the surge degree of freedom:
\[ \dot{u} = \frac{1}{m_1} (-m_{22} u v + m_{23} u r + X_{uv} u + X_{uu} u^2 + \tau_x + d_x) \] (12)

Only the surge degrees of freedom were considered; thus, the sway and yaw motions were neglected, then \( v = 0 \) and \( r = 0 \). Equation (12) can be written as Equation (13) to facilitate the algorithm processing by assuming that \( a = X_u + X_{uv} |u| + X_{uuv} u^2 \):
\[ \dot{u} = \frac{1}{m_1} (au + \tau_x + d_x) \] (13)

The speed error was defined as \( u_e = u - u_d \), and the first derivative was taken to obtain Equation (14):
\[ \dot{u}_e = \dot{u} - \dot{u}_d = \frac{1}{m_1} (au + \tau_x + d_x) - \dot{u}_d \] (14)

\[ V_0 = u_e \dot{u}_e + u_e (\dot{u}_e - ku_e + \mu u_e) = -ku_e^2 + u_e (\dot{u}_e + ku_e) \]
\[ = -ku_e^2 + u_e (x + \tau_x + d_x - \dot{u}_d + k(u - u_d)) \]
\[ = -ku_e^2 + u_e \left[ \frac{1}{m_1} (au + \tau_x + d_x) - \dot{u}_d + k(u - u_d) \right] \] (15)

A virtual Lyapunov energy function \( V_0 = 1/2u_e^2 \) was constructed for the speed control system according to the Lyapunov direct method. The first derivative of the constructed Lyapunov function was obtained as Equation (15) to meet the requirements of the stability theorem.

For the speed control system, the energy function constructed by the speed error \( u_e \) was positive definite, and its first derivative was negative. The speed control system was asymptotically stable when \( V_0 \leq 0 \) and Lyapunov function \( V_0 \geq 0 \). The control law of the speed controller can be obtained as follows:
\[ \tau_x = m_11 (\dot{u}_d - k(u - u_d)) - au - \dot{d}_x \]
\[ = m_11 \dot{u}_d - k(u - u_d) \]
\[ - (X_u + X_{uv} |u| + X_{uuv} u^2) u - \dot{d}_x \] (16)

where \( k \) is a controller parameter that can be adjusted, and \( k > 0 \).

**Yaw controller**

The yaw controller was designed by using the backstepping method considering the separate designs of the USV yaw and speed controllers. We obtained Equation (17) by dividing Equation (1) in the yaw degree of freedom:
\[ \dot{r} = \frac{1}{m_23 + m_33} \left( \frac{m_{22} v r + m_{23} r^2 - m_{11} u r + Y_{fr}}{Y_{fr} + N_{fr} |r| (r^2 + d_2)} \right) \] (17)

Only the degree of freedom in the yaw direction was considered; therefore, the surge and sway motions were ignored, that is, \( u = 0 \) and \( v = 0 \). Let \( b = 1/(m_{23} + m_{33}) \)
to facilitate the algorithm processing. Therefore, Equation (17) can be written as Equation (18):
\[
\dot{r} = b(m_{23}r^2 + Y_r r + Y_{r|r} |r| r + N_r r + N_{r|r} |r| r) + b(r_2 + d_2) 
\]  
(18)

Let \( \sigma_1 = \psi, \sigma_2 = \dot{\psi} = r, f(\sigma_2) = b(m_{23}r^2 + Y_r r + Y_{r|r} |r| r + N_r r + N_{r|r} |r| r) \), where \( \psi \) is the yaw angle of the USV; the desired yaw angle for the straight-line tracking is \( \psi_d \); the yaw error of the system \( \psi_e = \psi - \psi_d \); the yaw controller output is \( g \in \mathbb{R} \) and \( g = \sigma_1 \); and the control input is \( \xi = \tau_2 + \dot{d}_2 \). The nonlinear mathematical model of the USV can then be modelled as Equation (19):
\[
\begin{align*}
\dot{\sigma}_1 &= \sigma_2 \\
\dot{\sigma}_2 &= f(\sigma_2) + b\xi \\
g &= \sigma_1
\end{align*}
\]  
(19)

Step 1: Make a variable substitution; introduce state variable \( z_1 = \sigma_1 - \psi_d \); construct the Lyapunov function \( V_1 = 1/2z_1^2 \); and calculate its first derivative:
\[
\dot{V}_1 = z_1\dot{z}_1 = z_1(\dot{\sigma}_1 - \dot{\psi}_d) = z_1(\sigma_2 - \dot{\psi}_d) 
\]  
(20)

By assuming that \( z_2 \) is a new state variable, we can obtain:
\[
\sigma_2 = z_2 + \alpha(z_1) 
\]  
(21)

Substituting Equation (21) into Equation (20) yields
\[
\begin{align*}
\dot{z}_1 &= z_2 + \alpha(z_1) - \dot{\psi}_d \\
\dot{V}_1 &= z_1(\dot{z}_2 + \alpha(z_1) - \dot{\psi}_d)
\end{align*}
\]  
(22)

At this time, the intermediate virtual control law \( \alpha(z_1) \) is constructed as
\[
\alpha(z_1) = \dot{\psi}_d - k_1z_1 
\]  
(23)

Equation (23) is substituted into Equation (22) if the virtual control law \( \alpha(z_1) \) is substituted into state variable \( z_1 \) and the first derivative \( \dot{V}_1 \) of the Lyapunov function:
\[
\begin{align*}
\dot{z}_1 &= -k_1z_1 + z_2 \\
\dot{V}_1 &= z_1\dot{z}_1 = -k_1z_1^2 + z_1z_2
\end{align*}
\]  
(24)

where \( k_1 \) is the design parameter of the yaw controller, and \( k_1 > 0 \). A control law to stabilize the new state variable \( z_2 \) subsystem must be designed, and the yaw controller must be continuously designed using the backstepping method to stabilize the constructed state variable subsystem \( z_1 \).

Step 2: The new state variable \( z_2 = \sigma_2 - \alpha(z_1) \) of subsystem \( z_2 \) can be obtained from Equation (21), and the first derivative of state variable \( z_2 \) can be obtained from Equation (19):
\[
\dot{z}_2 = \dot{\sigma}_2 - \dot{\alpha}(z_1) = f(\sigma_2) + b\xi - \dot{\alpha}(z_1) 
\]  
(25)

The Lyapunov function \( V_2 = V_1 + 1/2z_2^2 \) is further constructed, and the first derivative is obtained:
\[
\dot{V}_2 = \dot{V}_1 + z_2\dot{z}_2 = -k_1z_1^2 + z_2[f(\sigma_2) + b\xi - \dot{\alpha}(z_1) + z_1] 
\]  
(26)

The yaw control system is a second-order nonlinear system; thus, only when subsystem \( z_2 \) reaches stability can subsystem \( z_1 \) reach asymptotic stability, ensuring that the whole yaw control system would achieve global asymptotic stability. The Lyapunov function \( V_2 \) constructed by the \( z_2 \) subsystem was positive definite, and its first derivative \( V_2 \) was negative definite. The yaw control system was asymptotically stable. Hence, the control law of the yaw controller when \( V_2 \leq 0 \) can be obtained as follows:
\[
\xi = \frac{1}{b}[(\dot{\psi}_d) - (f(\sigma_2) - z_1 - k_2z_2)] 
\]  
(27)

where \( k_2 \) is the design parameter of the controller, and \( k_2 > 0 \). The control law can be designed as follows based on Equations (19)–(27):
\[
\xi = \frac{1}{b}[(\dot{\psi}_d - (k_1k_2 + 1)(\sigma_1 - \psi_d) - (k_1 + k_2)(\sigma_2 - \dot{\psi}_d) - f(\sigma_2)) - (k_1 + k_2)(\sigma_1 - \psi_d) - f(\sigma_2)] 
\]  
(28)

The control law of the yaw controller can finally be obtained as follows considering the disturbance of the sea waves:
\[
\tau_2 = \xi - \dot{d}_2 = (m_{23} + m_{33})[\dot{\psi}_d - (k_1k_2 + 1)(\psi - \psi_d) - (k_1 + k_2)(\dot{r} - \dot{\psi}_d)] - m_{23}r^2 + Y_n r + Y_{n|r} |r| r + N_n r + N_{n|r} |r| r - \dot{d}_2 
\]  
(29)

**Proof of stability**

By considering the Lyapunov function for the whole controller system
\[
V = \frac{1}{2}u^2 + \frac{1}{2}z_1^2 + \frac{1}{2}z_2^2 + \frac{1}{2}d_e^2 
\]  
(30)

\( V \) can then be derived from time:
\[
\dot{V} = u\dot{u} + v\dot{e} + r_e\dot{r} + d_e\dot{d}_e = u\left[-m_{22}uv - m_{23}ur + X_u u + X_{u|u}|u|u\right] 
\]
Combining Equations (16), (29), and (31) yield the following because \( v = 0 \) and \( v_d = 0 \):

\[
\dot{V} = u_e \dot{u}_e + v_e \dot{v}_e + r_e \dot{r}_e + d_e \dot{d}_e
\]

\[
= u_e [\dot{u}_d - k (u - u_d) - \dot{u}_d] + r_e [\dot{r}_d]
\]

\[
- (k_1 k_2 + 1) (\psi - \psi_d)
\]

\[
\text{(31)}
\]

\[
V \text{ was ultimately bounded through Equations (10), (11), and (32). According to the Lyapunov theorem, when}
\]

| Parameters | Value | Parameters | Value | Parameters | Value |
|------------|-------|------------|-------|------------|-------|
| \( X_u \)  | -13.75 | \( X_v \)  | -60.20 | \( X_{uuu} \) | 10.42 |
| \( Y_{uv} \) | -26.60 | \( Y_{uv} \) | -10.87 | \( Y_{vvr} \) | -95.50 |
| \( N_{uv} \) | -228.50 | \( Y_{uv} \) | 84.07  | \( N_{vr} \)  | 45.04 |
| \( Y_{vvr} \) | -118.40 | \( N_{vvr} \) | 5.42   | \( Y_{fr} \)  | -5.554 |
| \( Y_{frr} \) | -47.31  | \( Y_{frr} \) | 2.807  | \( N_{fr} \)  | -5.902 |
| \( Y_{vvr} \) | 5.459   | \( Y_{vvr} \) | -2.706 | \( N_{fvr} \) | 6.493 |

\[
- (k_1 + k_2) (r - \psi_d) - \dot{r}_d
\]

\[
+ v_e (\dot{v} - \dot{v}_d) - K_0 d_e \dot{d}_e + d_e \dot{d}_e
\]

\[
= -ku_e - [(k_1 k_2 + 1) (\psi - \psi_d)]
\]

\[
+ (k_1 + k_2) (r - \psi_d) r_e - K_0 d_e \dot{d}_e + d_e \dot{d}_e.
\]

\[
\text{(32)}
\]
$t \to \infty$, $u_e \to 0$, and $u \to u_d$ can be obtained in control law (10), the speed approaches the desired value, and the error converges to zero. Meanwhile, according to yaw control law (29) and system (19), $\psi_e \to 0$ when $r \to 0$ and $\psi \to \psi_d$ can be obtained, the yaw angle approaches the desired value, and the error converges to zero. The disturbance error finally converged to zero when $t \to \infty$, $d_e \to 0$, $d \to \hat{d}$. Therefore, the designed speed yaw classification controller and disturbance observer can make the system's surge speed and yaw angle globally asymptotically stable without generating chattering.

**Simulation**

A series of simulations were realized through MATLAB/Simulink based on JingHai-VIII. The control effect based on the Lyapunov direct method combined with the backstepping method was analyzed by the desired yaw angle and speed under the condition with the external disturbance and without the disturbance observer. In the presence of external disturbances, the effectiveness of the observer was verified by comparing the presence and the absence of the disturbance observers. The effectiveness of the proposed control system was verified for the

![Simulation Results](image)

**Figure 3.** Under the disturbance, the speed (a) and the yaw angle (b) changed with time before and after addition of the disturbance observer.
Figure 4. Under the disturbance, the speed (a) and the yaw angle (b) changed with time between the PID and backstepping controllers without or with an observer.

straight-line tracking. Table 2 presents the uncorrected hydrodynamic coefficients.

In the state without an external disturbance, \((k = 1000, k_1 = 0.50, k_2 = 0.50)\) and \((k = 100, k_1 = 0.89, k_2 = 1.10)\) were the two sets of data applied to the speed and yaw controllers without the disturbance observer. The simulation can be obtained by taking the initial speed and yaw angle as 0, the desired speed as 2 m/s, and the desired yaw angle as 45° (Figure 2). Compared with the second group, the chattering of that first set of parameters was greater; hence, the second group of parameters has a better control effect than that of the first group. The average steady-state error of the controller cannot be completely eliminated because of the nonlinear model uncertainty. Therefore, the control system can make the speed and yaw angle quickly reach the desired value and remain stable, thus proving that the control strategy of the USV is effective and feasible.

The volume of the USV and the windward area above the waterline were very small; thus, the influence of the wind force on the sea voyage was almost negligible, and \(\tau_{\text{wind}}\) approached 0. The wave model based on the International Towing Tank Conference, ITTC frequency spectral density function introduced the disturbance of the second-order wave force to both the speed and the yaw. The simplified transfer function model is represented by Equation (33):

\[
h(s) = \frac{0.05s}{s^2 + 0.6s + 3.76} \tag{33}
\]

On the premise that the parameters of the speed and yaw controllers were unchanged, a disturbance observer was introduced to provide the estimated wave force. \((K_{u0} = 1.0, K_{r0} = 5.0)\) and \((K_{u0} = 0.50, K_{r0} = 1.30)\) were the two sets of data applied to the speed and yaw controllers with the disturbance observer. The simulation results indicated the desired and actual speeds and the desired and actual yaw angles by taking the initial speed and yaw angle as 0, the desired speed as 2 m/s, and the desired yaw angle as 60° (Figure 3). Under the condition of introducing an external disturbance, the speed and yaw controllers exhibited an obvious oscillation phenomenon after stabilization. Compared with those of the second group, the first group of parameters had a larger stability error in speed and took longer to reach stability in the angle. Therefore, the second group of parameters had a better control effect than that of the first group, and the oscillation problem caused by the external disturbance and the nonlinear model uncertainty was solved. The disturbance observer had an obvious effect of suppressing the chattering.

Selecting the parameters \((k = 100, k_1 = 0.89, k_2 = 1.10)\) and \((K_{u0} = 0.50, K_{r0} = 1.30)\), and compared with existing methods, such as PID, the controller parameters were set as \(K_p = 40.0, K_i = 30.0,\) and \(K_d = 40.0\) for the speed and \(K_p = 5.0, K_i = 0.01,\) and \(K_d = 10.0\) for the yaw. Figure 4 illustrates comparison results relevant to those under the disturbance of the second-order wave force. The backstepping method with the observer was more robust than the PID; therefore, the control method was effective.

Finally, the desired initial coordinate point \((0, 0)\) and end point \((100, 100)\) were set based on the proposed control system with a disturbance observer. The USV made a straight track tracking from the origin (Figure 5) under the condition of an external disturbance. The tracking error of
the USV with the disturbance observer was almost zero compared with that of the control system without the observer, and the effect was closer to the set track. Therefore, the proposed separated design of the speed and the yaw and the control system with the disturbance observer can control the USV to accurately track straight lines.

**Conclusion**

Based on the series of parameters of JingHai-VIII, this study proposed the strategy of separating the USV speed and the yaw for an underactuated USV using the Lyapunov direct and backstepping control methods. The disturbance observer was constructed to solve the chattering caused by the external disturbance and the uncertainty of the nonlinear hull model. All states of the designed closed-loop control system were bounded, and the steady-state error converged to zero. Combined with the simulation, the robustness of the control system was proven under the condition of an external wave and current disturbance, and the accurate tracking of the straight line by the USV was guaranteed. Under the action of the disturbance observer, this control strategy had a better anti-disturbance performance than that of the non-disturbance observer. However, it has limitation of being able to work only under medium and low sea conditions.

A new strategy of speed and yaw control was proposed in theory. On the basis of actually maintaining a stable speed, the yaw was controlled to be stable to ensure the normal operation of the survey ship. Future research will focus on the tracking of various trajectories of a USV at varying speeds.

**Disclosure statement**

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