Adaptive sliding-mode path following control system of the underactuated USV under the influence of ocean currents

CHEN Xiao, LIU Zhong*, ZHANG Jianqiang, ZHOU Dechao, and DONG Jiao

School of Weaponry Engineering, Naval University of Engineering, Wuhan 430000, China

Abstract: The path-following control of the asymmetry underactuated unmanned surface vehicle (USV) under external disturbances such as unknown constant and irrational ocean currents is discussed, and an adaptive sliding-mode path-following control system is proposed, which comprises a path-variable updated law, a modified integral line-of-sight (ILOS) guidance law based on a time-varying lookahead distance and adaptive feedback linearizing controllers combined with sliding-mode technique. A more accurate USV model without the assumption of having diagonal inertia and damping matrices is first presented, aiming at improving the performance of the path-following control. Next, the coordinate transformation is adopted to decouple the sway dynamic from the rudder angle, and the path-following errors dynamics without non-singular problem are presented in the moving Frenet-Serret frame. Then, based on the cascaded theorem and the adaptive sliding-mode method, the adaptive control law of position errors and course error are designed, among which the lookahead distance and integral gain are all computed as different functions of cross-track error to estimate and compensate the sideslip angle caused by external disturbances adaptively. Finally, according to the Lyapunov and cascaded theorem, the control system proposed is proved to be uniform globally asymptotic stability (UGAS) and uniform semiglobal exponential stability (USGES) when the control objectives are all achieved. Simulation results illustrate the precision and high-quality performance of this new controller.

Keywords: sliding-mode control, unmanned surface vehicle (USV), integral line-of-sight (ILOS), path following, proof of stability.

DOI: 10.21629/JSEE.2018.06.14

1. Introduction

The unmanned surface vehicle (USV) has a lot of advantages, such as small volume, low cost, and no casualties, which possesses extensive application prospects [1–5]. Guidance and control of USVs is a priority area within the marine control research community [6–8]. This paper

addresses a fundamental and highly applicable scenario for the USV, called path following. It is a motion control scenario where the USV has to follow a predefined path without any time constraints [7–9], which is rapidly increasing within seafloor mapping, inspection of oil and gas pipelines, and so on.

The line-of-sight (LOS) guidance law based on a lookahead distance is commonly used for path-following control [10–17]. This strategy exploits the geometry of the problem and generates a reference path for the heading angle or desired course, which is used by the autopilot. Compared to the strategy designed using the backstepping technique, the aforementioned strategies are much simpler.

Using the LOS guidance law and feedback linearization in combination with coordinate transformation of the vessel model, a new controller was developed in [18], which is proved to be uniform global k -exponential stability in the case of a straight-line path following. Regardless of the impact of environmental interference, a path-following controller based on the LOS guidance law and cascaded theorem was developed in [12], which rendered the cross-track error uniform semiglobal exponential stability (USGES). However, the LOS guidance law is susceptible to environmental disturbances such as wind, waves and ocean currents. If USVs are affected by environmental disturbances, convergence problems and path deviation will occur [13]. To compensate disturbances, a modified LOS guidance law with integral action was proposed in [14], which is called the integral line-of-sight (ILOS) guidance law. And then by using sliding-mode and adaptive feedback linearizing techniques, a straight-line path-following control system is designed, which is proved to be UGAS despite the activities of ocean currents when the control objectives are all achieved. However, the vessel model in [14] was established based on its absolute and relative ve-

Manuscript received July 18, 2017.

*Corresponding author.

This work was supported by the Pre-research Fund of Equipment (9140A01010415JB11002).

locities, which increased the complexity of the control system design and stability proof. In order to avoid the inconvenience caused by using absolute and relative velocities simultaneously, a vessel model that relies only on the relative velocity was established in [18,19]. Based on the ILOS guidance law and feedback linearization method, a straight-line pathfollowing control system is designed, which is proved to be uniform global k -exponential stability under constant current disturbance. Wiig [20] generalized the results of Caharija by recalling the method in [12] and obtained result of USGES and uniform globally asymptotic stability (UGAS). For the more general curved-line path-following scenarios, an adaptive LOS (ALOS) guidance law was proposed in [21], based on the measurement of the absolute motion velocity and a simplified vessel model, the proportion-integral-derivative (PID) controller was used to track the Dubins path under the external environment interference, and the equilibrium point of the cross-track error was proved to be USGES. Fossen and Lekkas proposed two control strategies called direct and indirect ALOS guidance laws for curvedline path following under current disturbance in [22]. Using the two control laws combined with a sliding-mode heading autopilot, two control systems were developed, whose equilibrium points of the cross-track error were proved to be UGAS and uniform globally stability (UGS), respectively. More studies of path following for USVs can be seen in [23–28].

In the above literatures and most of the USV path-following control researches currently, in order to facilitate the controller design and stability analysis, the front and rear asymmetry of the USV model is usually ignored, regarding that the inertial and damping matrices are strictly diagonal, which is not consistent with the actual USV structure. And when considering environmental disturbances, most scholars ignore the perturbation of the USV's kinematic model, and consider it as a disturbance to the USV's dynamics model along with wind, waves and unmodeled dynamics. In addition, most of the controllers cannot meet the needs of straight- and curved-line path-following, simultaneously. Motivated by the results of the aforementioned studies, a more accurate USV model without the assumption of having diagonal inertia and damping matrices is first presented, aiming at improving the performance of path-following control. Secondly, coordinate transformation is adopted to decouple the sway dynamic from the rudder angle, which facilitates the controller de-

sign and stability analysis. Then, the path-following error dynamics is established in the Serret-Frenet coordinate system. Next, in view of the disturbance such as ocean current and so on, the adaptive sliding mode technique is used to design the heading and speed tracking control law, respectively, which realizes the stabilization of heading error and longitudinal velocity tracking error. Finally, based on Lyapunov and cascade theory, the uniformly global asymptotic and semiglobal exponential stability of the tracking control system are proved. Finally, according to the Lyapunov and cascaded theorem, the control system proposed is proved to be UGAS and USGES. The theoretical analysis and simulations show effectiveness and advancement of the proposed controller.

2. Vessel model

2.1 Model of the underactuated USV

The 3 degree of freedom (3-DOF) model of the USV is considered as follows:

$$\begin{cases} \dot{\eta} = R(\psi)v \\ M_{RB}\dot{v} + C_{RB}(v) + M_A v_r + C_A(v)_r + \\ D(v_r)v_r = Bf. \end{cases} \quad (1)$$

The expression of each variable in the formula can be found in [23].

2.2 Coordinate transformation

To eliminate the effects of the rudder moment on sway dynamics, it is necessary to move the origin to the pivot point $(\bar{x}, \bar{y})$. The transformed models are given by

$$\dot{\bar{x}} = u \cos \psi - \bar{v} \sin \psi \quad (2)$$

$$\dot{\bar{y}} = u \sin \psi + \bar{v} \cos \psi \quad (3)$$

$$\dot{\psi} = r \quad (4)$$

$$\dot{u} = F_u(u, v, r) + \Phi_u^T(\psi, r)\theta_u + \tau_u \quad (5)$$

$$\dot{\bar{v}} = X(u_r, u_c)r + Y(u_r)v_r \quad (6)$$

$$\dot{r} = F_r(u_r, v_r, r) + \Phi_r^T(u, v, r, \psi)\theta_r + \tau_r. \quad (7)$$

The expression of $F_u(u, v, r)$, $\Phi_u(\psi, r)$, θ_u , θ_r , $X(u_r, u_c)$, $F_r(u, v, r)$ can be found in [24].

The vectors τ_u and τ_r are defined as the new control inputs and the relationship with the original control inputs T and δ is demonstrated as

$$\begin{bmatrix} \tau_u \\ \tau_r \end{bmatrix} = \begin{bmatrix} \frac{b_{11}}{m_{11}} & 0 \\ 0 & \frac{m_{22}b_{32} - m_{23}b_{22}}{m_{22}m_{33} - m_{23}^2} \end{bmatrix} \begin{bmatrix} T \\ \delta \end{bmatrix} \quad (8)$$

where $m_{ij} = m_{ij}^{RB} + m_{ij}^A$ for $i, j = 1, 2, 3$.

3. Control objectives

This section formalizes the control problem solved in this paper: the controller should impel the USV to converge and follow a desired path in the presence of unknown constant irrotational ocean currents, with an expected surge velocity u_d , starting from any location. Let $w \geq 0$ denote the path variable, hence, the desired path $P(w)$ is parameterized by $(x_d(w), y_d(w))$, which acts as an arbitrary virtual target moving along the desired path. The path-following errors are described in the Serret-Frenet (SF) coordinate system. As shown in Fig. 1, the origin of the SF coordinate system is the free point on $P(w)$, the horizontal axis Y_p is the normal direction to the right, and the vertical axis X_p is along the tangent line direction of the desired path $P(w)$. The angle between the X axis of the inertial coordinate system and the axis X_p is the azimuth angle of $P(w)$, defined as

$$\psi_p(w) = \arctan(y'_d(w), x'_d(w)) \in (-\pi, \pi). \quad (9)$$

By (2) and (3) we can get

$$\dot{\mathbf{p}} \triangleq [\dot{\bar{x}}, \dot{\bar{y}}] = \mathbf{Q}(\psi) \begin{bmatrix} u \\ \bar{v} \end{bmatrix} = \begin{bmatrix} \cos \psi & -\sin \psi \\ \sin \psi & \cos \psi \end{bmatrix} \begin{bmatrix} u \\ \bar{v} \end{bmatrix}. \quad (10)$$

Fig. 1 Schematic diagram of LOS guidance algorithm for the USV

As illustrated in Fig. 1, the along- and cross-track error $x_e(t)$ and $y_e(t)$ are computed as the horizontal and orthogonal distance to the moving SF frame, respectively. Hence,

$$x_e(t) = (\bar{x} - x_d(w)) \cos(\psi_p(w)) + (\bar{y} - y_d(w)) \sin(\psi_p(w)) \quad (11)$$

$$y_e(t) = -(\bar{x} - x_d(w)) \sin(\psi_p(w)) + (\bar{y} - y_d(w)) \cos(\psi_p(w)). \quad (12)$$

The error of surge velocity can be defined as $u_e(t) \triangleq u - u_d$. Therefore, the control objectives are defined as

$$\begin{cases} \lim_{t \rightarrow \infty} x_e(t) = 0 \\ \lim_{t \rightarrow \infty} y_e(t) = 0 \\ \lim_{t \rightarrow \infty} \psi_e(t) = 0 \\ \lim_{t \rightarrow \infty} u_e(t) = 0 \end{cases} \quad (13)$$

4. Dynamics system of path-following errors

Differentiating (11) and (12), we can get the position errors dynamics:

$$\dot{x}_e(t) = -u_{pd} + r_p(w)y_e(t) + u \cos(\psi - \psi_p(w)) - \bar{v} \sin(\psi - \psi_p(w)) \quad (14)$$

$$\dot{y}_e(t) = -r_{pd}(w)x_e(t) + u \sin(\psi - \psi_p(w)) + \bar{v} \cos(\psi - \psi_p(w)). \quad (15)$$

And the rate of $\psi_p(w)$ is defined as $r_p(w) \triangleq \frac{d\psi_p(w)}{dw} \dot{w}$, which satisfies the following conditions, respectively:

$$u_{pd} = \dot{w} \sqrt{x_d'^2(w) + y_d'^2(w)} \quad (16)$$

$$r_{pd}(w) = \frac{d\psi_p(w)}{dw} \dot{w}. \quad (17)$$

The tracking error of the heading angle is defined as $\psi_e(t) \triangleq \psi - \psi_d$, in which the expected heading angle ψ_d is provided by the LOS guidance law. And in order to avoid the singularity of the side-slipping angle β_d when $u = 0$, β_d can be redefined as follows:

$$\beta_d = \arctan(\bar{v}/u_d). \quad (18)$$

The equations (14) and (15) can be rewritten as

$$\begin{aligned} \dot{x}_e(t) &= u_e(t) \cos(\psi - \psi_p(w)) + U_d \gamma_x \psi_e(t) - \\ &u_{pd} + r_{pd}(w)y_e(t) + U_d \cos(\psi_d - \psi_p(w) + \beta_d) \\ \dot{y}_e(t) &= -r_{pd}(w)x_e(t) + U_d \gamma_y \psi_e(t) U_d + \\ &\sin(\psi_d - \psi_p(w) + \beta_d) + u_e(t) \sin(\psi - \psi_p(w)) \end{aligned} \quad (19)$$

where $U_d = \sqrt{u_d^2 + \bar{v}^2} \geq u_d > 0$ and the expressions of γ_x and γ_y are defined as

$$\gamma_x = \frac{\sin \psi_e(t)}{\psi_e(t)} \sin(\psi_d - \psi_P(\omega) + \beta_d) + \frac{\cos \psi_e(t) - 1}{\psi_e(t)} \cos(\psi_d - \psi_P(\omega) + \beta_d) \quad (21)$$

$$\gamma_y = \frac{\sin \psi_e(t)}{\psi_e(t)} \cos(\psi_d - \psi_P(\omega) + \beta_d) + \frac{\cos \psi_e(t) - 1}{\psi_e(t)} \sin(\psi_d - \psi_P(\omega) + \beta_d). \quad (22)$$

Obviously, $|(\cos(\psi_e) - 1)/\psi_e| < 0.73$ and $|\sin \psi_e/\psi_e| \leq 1$, hence,

$$|\gamma_x| \leq \left| \frac{\cos \psi_e(t) - 1}{\psi_e(t)} \right| |\cos(\psi_d - \psi_P(\omega) + \beta_d)| +$$

$$\left| \frac{\sin \psi_e(t)}{\psi_e(t)} \right| |\sin(\psi_d - \psi_P(\omega) + \beta_d)| \leq 1.73 \quad (23)$$

$$|\gamma_y| \leq \left| \frac{\cos \psi_e(t) - 1}{\psi_e(t)} \right| |\sin(\psi_d - \psi_P(\omega) + \beta_d)| +$$

$$\left| \frac{\sin \psi_e(t)}{\psi_e(t)} \right| |\cos(\psi_d - \psi_P(\omega) + \beta_d)| \leq 1.73. \quad (24)$$

Moreover, $c = 1.73$ will be an upper bound for $|\gamma_x|$ and $|\gamma_y|$.

By differentiating the variables $u_e(t)$ and $\psi_e(t)$ and recalling the transformed dynamics from (5) and (7), the overall dynamics of path-following errors can be arranged into the cascaded structure which comprises two subsystems $\sum 1$ and $\sum 2$.

$\sum 1$:

$$\begin{bmatrix} \dot{x}_e \\ \dot{y}_e \end{bmatrix} = \begin{bmatrix} -u_{pd} + r_P(\omega)y_e + U_d \cos(\psi_d - \psi_P(\omega) + \beta_d) \\ -r_P(\omega)x_e + U_d \sin(\psi_d - \psi_P(\omega) + \beta_d) \end{bmatrix} +$$

$$\begin{bmatrix} \cos(\psi - \psi_P(\omega)) & U_d \gamma_x & 0 \\ \sin(\psi - \psi_P(\omega)) & U_d \gamma_y & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u_e \\ \psi_e \\ \dot{\psi}_e \end{bmatrix} =$$

$$\sum 1_n + \mathbf{g}(t, e, \xi) \cdot [u_e, \psi_e, \dot{\psi}_e]^T \quad (25)$$

$\sum 2$:

$$\begin{bmatrix} \dot{u}_e \\ \dot{\psi}_e \\ \ddot{\psi}_e \end{bmatrix} = \begin{bmatrix} F_u(u, v, r) + \Phi_u^T(\psi, r)\theta_u + \tau_u - \dot{u}_d \\ r - \dot{\psi}_d \\ F_r(u_r, v_r, r) + \Phi_r^T(u, v, r, \psi)\theta_r + \tau_r - \ddot{\psi}_d \end{bmatrix}. \quad (26)$$

Therefore, the system $\sum 1$ can be recognized as the nominal system $\sum 1_n$ that is perturbed by subsystem $\sum 2$ through an interconnection matrix.

5. Control system and stability analysis

5.1 Modified ILOS guidance law and path-variable updated law

The traditional ILOS guidance law is defined as follows [14]:

$$\psi_d = \psi_P(\omega) - \arctan(y_e(t)/\Delta) - \beta_d \quad (27)$$

$$\Delta = nlpp, \quad n = 2 - 5. \quad (28)$$

In the equation above, Δ is the lookahead distance and lpp is the length of the USV.

Considering the time-varying lookahead distance makes the USV control more flexible, a modified ILOS guidance law is proposed and illustrated in Fig. 1.

$$\psi_d = \psi_P(\omega) - \arctan(y_e(t)/\Delta(t)) - \beta_d \quad (29)$$

$$\Delta(t) = (\Delta_{\max} - \Delta_{\min})e^{-\sigma y_e^2(t)} + \Delta_{\min} \quad (30)$$

In the equation above, $\Delta(t)$ represents the time-varying lookahead distance, $\Delta_{\min}$ and $\Delta_{\max} > 0$ represent the minimum and maximum allowed values, the gain $\sigma > 0$ is defined as the convergence rate.

Remark 1 The intuitive fact is that the basis of the expression $\Delta(t)$ in (30) is necessary because when the USV is far from the given path, a small value of $\Delta(t)$ is a more appropriate choice to obtain more aggressive behaviour, which tends to eliminate the crosstrack error more rapidly. Conversely, when the USV is close to the given path, a large value of $\Delta(t)$ is better to avoid overshooting.

The path-variable updated law is chosen as

$$\dot{\omega} = \frac{U_d + k_x x_e(t)}{\sqrt{x_d^2(\omega) + y_d^2(\omega)}} \quad (31)$$

where the parameter k_x satisfies

$$k_x > \frac{U_d}{\Delta(t)}. \quad (32)$$

5.2 Surge and heading controllers

By analysing the composition of the system $\sum 2$, the sliding-mode technique with the advantages of faster convergence and stronger robustness is used to design the controllers for heading angle and surge velocity. In addition, the adaptive technique is used to compensate both for the curvature of the path and the disturbance of ocean current without knowing the exact components of these measurements. Firstly, a sliding surface is defined as

$$S_1 = k_\psi \psi_e(t) + \dot{\psi}_e(t) \quad (33)$$

where $k_\psi > 0$ is a design parameter.

By differentiating along the trajectories of S_1 and recalling to (7), we get

$$\begin{aligned} \dot{S}_1 &= k_\psi(r - \dot{\psi}_d) + F_r(u_r, v_r, r) + \\ &\quad \Phi_r^T(u, v, r, \psi)\theta_r + \tau_r - \ddot{\psi}_d. \end{aligned} \quad (34)$$

Defining the vector $\hat{\theta}_r$ as an estimation of the ocean current θ_r and $\tilde{\theta}_r \triangleq \theta_r - \hat{\theta}_r$. Choosing the positive, definite and radially unbounded Lyapunov function candidate (LFC):

$$V_1(t, S_1, \tilde{\theta}_r) = \frac{S_1^2 + \tilde{\theta}_r^T \tilde{\theta}_r}{2}, \quad S_1 \neq 0; \tilde{\theta}_r \neq 0. \quad (35)$$

Then differentiating V_1 with respect to time along the trajectories of the cross-track error and recalling to (34), we get

$$\begin{aligned} \dot{V}_1(t, S_1, \tilde{\theta}_r) &= \\ S_1 \left(k_\psi(r - \dot{\psi}_d) + F_r(u_r, v_r, r) + \right. &\quad \left. \Phi_r^T(u, v, r, \psi)\theta_r + \tau_r - \ddot{\psi}_d \right) - \tilde{\theta}_r^T \dot{\hat{\theta}}_r. \end{aligned} \quad (36)$$

In order to make the system reach the sliding surface within a finite time from any initial state, the control law is designed as

$$\begin{aligned} \tau_r &= -k_\psi(r - \dot{\psi}_d) - \Phi_r^T(u, v, r, \psi)\hat{\theta}_r - \\ &\quad F_r(u_r, v_r, r) + \ddot{\psi}_d - k_{s1}S_1 - k_{sg1}\text{sgn}(S_1) \end{aligned} \quad (37)$$

where $k_{s1} > 0$ and $k_{sg1} > 0$ are design parameters. Substituting (37) into (36) yields

$$\begin{aligned} \dot{V}_1(t, S_1, \tilde{\theta}_r) &= -k_{s1}S_1^2 - k_{sg1}|S_1| + \\ &\quad \Phi_r^T(u, v, r, \psi)\tilde{\theta}_r S_1 - \tilde{\theta}_r^T \dot{\hat{\theta}}_r. \end{aligned} \quad (38)$$

Select the adaptive control law as

$$\dot{\hat{\theta}}_r = \Phi_r(u, v, r, \psi)S_1. \quad (39)$$

Then substituting (39) into (38) yields

$$\dot{V}_1(t, S_1, \tilde{\theta}_r) = -k_{s1}S_1^2 - k_{sg1}|S_1| \leq 0. \quad (40)$$

Similarly, the adaptive sliding-mode controller is designed to track the surge velocity and compensate both for the curvature of the path and the ocean current.

A sliding surface is then defined as

$$S_2 = k_u \int_0^t u_e(\tau) d\tau + u_e(t) \quad (41)$$

where $k_u > 0$ is a design parameter.

By differentiating along the trajectories of S_2 and recalling to (5), we get

$$\dot{S}_2 = k_u u_e(t) + F_u(u, v, r) +$$

$$\Phi_u^T(\psi, r)\theta_u + \tau_u - \dot{u}_d. \quad (42)$$

Therefore, the error is defined as $\tilde{\theta}_u = \theta_u - \hat{\theta}_u$, in which the vector $\hat{\theta}_u$ is an estimation of θ_u . We choose the positive, definite and radially unbounded LFC:

$$V_2(t, S_2, \tilde{\theta}_u) = \frac{1}{2}S_2^2 + \tilde{\theta}_u^T \tilde{\theta}_u > 0,$$

$$S_2 \neq 0; \tilde{\theta}_u \neq 0. \quad (43)$$

Then differentiating V_2 with respect to time along the trajectories of the cross-track error and recalling to (42), we get

$$\begin{aligned} \dot{V}_2(t, S_2, \tilde{\theta}_u) &= \\ S_2 \left(k_u u_e(t) + F_u(u, v, r) + \Phi_u^T(\psi, r)\theta_u + \tau_u - \dot{u}_d \right) - &\quad \tilde{\theta}_u^T \dot{\hat{\theta}}_u. \end{aligned} \quad (44)$$

Select the sliding-mode control law and adaptive control law as

$$\tau_u = -k_u u_e(t) - F_u(u, v, r) +$$

$$\Phi_u^T(\psi, r)\hat{\theta}_u + \dot{u}_d - k_{s2}S_2 - k_{sg2}\text{sgn}(S_2) \quad (45)$$

$$\dot{\hat{\theta}}_u = \Phi_u(\psi, r)S_2 \quad (46)$$

where $k_{s2} > 0$ and $k_{sg2} > 0$ are design parameters. Then substituting (45) and (46) into (44) yields

$$\dot{V}_2(t, S_2, \tilde{\theta}_u) = -k_{s2}S_2^2 - k_{sg2}|S_2| \leq 0. \quad (47)$$

5.3 Stability analysis

5.3.1 Stability property of the system $\sum 2$

Proposition 1 The equilibrium point $(\psi_e(t), \dot{\psi}_e(t), u_e(t)) = (0, 0, 0)$ of the subsystem $\sum 2$ is uniform globally exponential stability (UGES), when the sliding surfaces are chosen as defined in (33) and (41), the adaptive feedback linearizing controller (37), (39), (45) and (46), along with the parameter restrictions in (51) and (56).

Proof By resorting the control law (56) and (53), we get the error dynamics of the heading control system:

$$\dot{S}_1 = \Phi_r^T(u, v, r, \psi)\tilde{\theta}_r - k_{s1}S_1 - k_{sg1}\text{sgn}(S_1) \quad (48)$$

$$\dot{\hat{\theta}}_r = \Phi_r(u, v, r, \psi)S_1. \quad (49)$$

As shown in (40), $\dot{V}_1$ is negative semi-definite. It thus follows, from standard Lyapunov arguments, that the equilibrium point $(S_1, \tilde{\theta}_r) = (0, 0)$ is UGS. It is important to note that UGAS cannot be obtained for the origin $(S_1, \tilde{\theta}_r) = (0, 0)$. This is because the persistency of the excitation condition is not satisfied; in other words, the regressor $\Phi_r(u, v, r, \psi)$ is not persistently exciting (PE),

and a persistently exciting regressor is needed to obtain the UGAS for adaptive systems as the system defined by (48) and (49), according to [28–32].

Since $V_1(t, S_1, \tilde{\theta}_r) > 0$ and $\dot{V}_1(t, S_1, \tilde{\theta}_r) \leq 0$, then $V_1(t, S_1, \tilde{\theta}_r) \leq V_1(0, 0, \mathbf{0})$, thus, the time-varying variable $\tilde{\theta}_r$ is bounded and there exists a bound $\alpha_{\theta_r} > 0$ such that $\|\tilde{\theta}_r\| \leq \alpha_{\theta_r}$. It is thus straightforward to show that

$$\begin{aligned} & \left| \Phi_r^T(u, v, r, \psi) \tilde{\theta}_r \right| = \\ & \left| \phi_1 \tilde{V}_x + \phi_2 \tilde{V}_y + \phi_3 \tilde{V}_x^2 + \phi_4 \tilde{V}_y^2 + \phi_5 \tilde{V}_x \tilde{V}_y \right| \leq \\ & |\phi_1| |\tilde{V}_x| + |\phi_2| |\tilde{V}_y| + |\phi_3| |\tilde{V}_x^2| + |\phi_4| |\tilde{V}_y^2| + |\phi_5| |\tilde{V}_x \tilde{V}_y| \leq \\ & \alpha_{\theta_r} (|\phi_1| + |\phi_2| + |\phi_3| + |\phi_4| + |\phi_5|) = \\ & \alpha_{\theta_r} \|\Phi_r(u, v, r, \psi)\|. \end{aligned} \quad (50)$$

When the design parameter k_{sg1} satisfies

$$k_{sg1} > 2\alpha_{\theta_r} \|\Phi_r(u, v, r, \psi)\| \quad (51)$$

then (40) can be rewritten as

$$\begin{aligned} \dot{V}_1(t, S_1, \tilde{\theta}_r) & \leq -\alpha_{\theta_r} \|\Phi_r(u, v, r, \psi)\| |S_1| \leq \\ & -k_{s1} S_1^2 < 0. \end{aligned} \quad (52)$$

As shown in (52), $\dot{V}_1(t, S_1, \tilde{\theta}_r)$ is negative definite. Hence, the origin $(S_1, \tilde{\theta}_r) = (0, \mathbf{0})$ is a UGAS equilibrium point of the interconnected system defined by (48) and (49). Furthermore, Theorem 4.10 in [33] is satisfied with $k_1 = k_2 = 1/2$, $k_3 = k_{s1}$ and $a = 2$, which implies the origin $(S_1, \tilde{\theta}_r) = (0, \mathbf{0})$ is a UGES equilibrium point of the system defined by (48) and (49), thus,

$$\begin{cases} \lim_{t \rightarrow \infty} \psi_e(t) = \lim_{t \rightarrow \infty} (\psi - \psi_d) = 0 \\ \lim_{t \rightarrow \infty} \dot{\psi}_e(t) = \lim_{t \rightarrow \infty} (\dot{\psi} - \dot{\psi}_d) = 0 \\ \lim_{t \rightarrow \infty} \ddot{\psi}_e(t) = \lim_{t \rightarrow \infty} (\ddot{\psi} - \ddot{\psi}_d) = 0 \end{cases} \quad (53)$$

where k_1, k_2, k_3 and a are design parameters.

By resorting the control law (45) and (42), we get the error dynamics of the surge control system:

$$\dot{S}_2 = \Phi_u^T(\psi, r) \tilde{\theta}_u - k_{s2} S_2 - k_{sg2} \text{sgn}(S_2) \quad (54)$$

$$\dot{\tilde{\theta}}_u = \Phi_u(\psi, r) S_2. \quad (55)$$

As shown in (47), $\dot{V}_2(t, S_2, \tilde{\theta}_u)$ is negative semi-definite. Hence, the origin $(S_2, \tilde{\theta}_u) = (0, \mathbf{0})$ is a UGS equilibrium of the interconnected system defined by (54) and (55).

When the parameter k_{sg2} satisfies

$$k_{sg2} > 2\alpha_{\theta_u} \|\Phi_u(\psi, r)\| \quad (56)$$

for a bound $\alpha_{\theta_u} > 0$ such that $\|\tilde{\theta}_u\| \leq \alpha_{\theta_u}$.

The equation (47) can be rewritten as

$$\dot{V}_2(t, S_2, \tilde{\theta}_u) = -k_{s2} S_2^2 < 0. \quad (57)$$

As shown in (57), $\dot{V}_2(t, S_2, \tilde{\theta}_u)$ is negative definite. Theorem 4.10 in [33] is satisfied with $k_1 = k_2 = 1/2$, $k_3 = k_{s2}$ and $a = 2$, which implies that the origin $(S_2, \tilde{\theta}_u) = (0, \mathbf{0})$ is a UGES equilibrium point of the system defined by (54) and (55), then

$$\lim_{t \rightarrow \infty} u_e(t) = \lim_{t \rightarrow \infty} (u - u_d) = 0. \quad (58)$$

Therefore, the equilibrium point $(\psi_e(t), \dot{\psi}_e(t), u_e(t)) = (0, 0, 0)$ of the subsystem $\sum 2$ is UGES. $\square$

5.3.2 Stability property of the system $\sum 1_n$

Proposition 2 If the desired heading angle can be obtained by using the time-varying LOS guidance law defined in (29) and (30), the path-variable updated law is expressed as in (31), and the design parameter satisfies as in (32), then the equilibrium point $(x_e, y_e) = (0, 0)$ of the system $\sum 1_n$ is USGES.

Proof The proof is similar to the analysis performed in [12], [20] and [21], while making additional use of the comparison Lemma 3.4, as defined in [33].

Notice that $\sum 1_n$ is a non-autonomous system, and then we choose the positive, definite and radially unbounded LFC

$$V_3(t, e(t)) = \frac{1}{2}(x_e^2(t) + y_e^2(t)). \quad (59)$$

Differentiating $V_3(t, e(t))$ with respect to time and recalling to (42), we get

$$\begin{aligned} \dot{V}_3(t, e(t)) & = -x_e(t)(u_p - U_d) + \\ & y_e(t)U_d \sin(\psi_d - \psi_p(\omega) + \beta_d) + \\ & x_e(t)U_d (\cos(\psi_d - \psi_p(\omega) + \beta_d) - 1). \end{aligned} \quad (60)$$

From (16) and (31), we can obtain

$$u_p = U_d + k_x x_e(t). \quad (61)$$

Substituting (29) and (30) into (60),

$$\begin{aligned} \dot{V}_3(t, e(t)) & = x_e(t)U_d (\cos(\psi_d - \psi_P(\omega) + \beta_d) - 1) + \\ & [-k_x x_e^2(t)] - \frac{U_d}{\sqrt{y_e^2(t) + \Delta^2(t)}} y_e^2(t). \end{aligned} \quad (62)$$

According to mathematical knowledge, $|\cos(\psi_d - \psi_P(\omega) + \beta_d) - 1| \leq |\sin(\psi_d - \psi_P(\omega) + \beta_d)|$, the expression $\dot{V}_3(t, e(t))$ thus becomes

$$\dot{V}_3(t, e(t)) \leq -k_x x_e^2(t) + \frac{U_d |x_e(t)| |y_e(t)|}{\sqrt{y_e^2(t) + \Delta^2(t)}} - \frac{U_d y_e^2(t)}{\sqrt{y_e^2(t) + \Delta^2(t)}}. \quad (63)$$

According to (32), the following bound can be found:

$$\begin{aligned} & -\frac{1}{2} \left(k_x x_e^2(t) - 2 \frac{U_d/\Delta(t)}{\sqrt{(y_e(t)/\Delta(t))^2 + 1}} |x_e(t)| |y_e(t)| \right. \\ & \quad \left. + \frac{U_d/\Delta(t)}{\sqrt{(y_e(t)/\Delta(t))^2 + 1}} y_e^2(t) \right) \leq \\ & -\frac{1}{2} \left(\sqrt{k_x} |x_e(t)| - \frac{\sqrt{U_d/\Delta(t)}}{\sqrt{(y_e(t)/\Delta(t))^2 + 1}} |y_e(t)| \right)^2 \leq 0. \end{aligned} \quad (64)$$

Hence, it follows from (63) and (64) that

$$\dot{V}_3(t, e(t)) \leq -\frac{1}{2} \left[k_x x_e^2(t) - \frac{U_d y_e^2(t)}{\sqrt{y_e^2(t) + \Delta^2(t)}} \right]. \quad (65)$$

Therefore, $k_x > 0$ and $\Delta_{\min} < \Delta(t) < \Delta_{\max}$ exist along with $U_d = \sqrt{u_d^2 + \dot{v}^2} \geq u_d > 0$, guaranteeing that $\dot{V}_3(t, e(t)) \leq 0$.

Since $V_3(t, e(t)) > 0$ and $\dot{V}_3(t, e(t)) \leq 0$, it follows that the origin $(x_e(t), y_e(t)) = (0, 0)$ is uniform bounded (UB) and

$$\begin{cases} |x_e(t)| \leq |x_e(t_0)| \\ |y_e(t)| \leq |y_e(t_0)| \\ \forall t \geq t_0. \end{cases} \quad (66)$$

According to Theorem 4.8 in [33], define

$$\Gamma(t, e(t)) = \frac{U_d}{\sqrt{y_e^2(t) + \Delta^2(t)}}. \quad (67)$$

For each condition in which $\mu > 0$ and all $\|e(t)\| \leq \mu$, we can get

$$\Gamma(t, e(t)) \geq \frac{u_d}{\sqrt{\mu^2 + \Delta_{\max}^2(t)}} = c(\mu). \quad (68)$$

The LFC can be rewritten as

$$V_3(t, e(t)) = \frac{(x_e^2(t) + y_e^2(t))}{2} = \frac{e^T(t) P e(t)}{2} \quad (69)$$

where $P = \text{diag}\{1 \ 1\}$ is a positive matrix. Then substituting (68) into (65) yields

$$\dot{V}_3(t, e(t)) \leq$$

$$\begin{aligned} & -\Gamma(t, e(t)) \left(\frac{k_x}{2\Gamma(t, e(t))} x_e^2(t) - \frac{1}{2} y_e^2(t) \right) \leq \\ & -c(\mu) e^T(t) Q(t) e(t) \end{aligned} \quad (70)$$

where $Q(t) = \text{diag}\left\{k_x \sqrt{y_e^2 + \Delta^2(t)}/2U_d, \frac{1}{2}\right\}$ is a time-varying, positive matrix. Hence,

$$\begin{aligned} & \dot{V}_3(t, e(t)) \leq \\ & -2 \frac{q_{\min}}{p_{\max}} c(\mu) V_3(t, e(t)), \forall \|e(t)\| \leq \mu \end{aligned} \quad (71)$$

where $p_{\max} = \lambda_{\max}(P) = 1$ and $q_{\min} = \lambda_{\min}(Q(t))$.

The above statement holds for all trajectories generated by the initial conditions $e(t_0)$ according to (66). Thus, it follows, based on the comparison Lemma 3.4 defined in [33], that $v_3(t) \leq e^{-2(q_{\min}/p_{\max})c(\mu)(t-t_0)} v_3(t_0)$ for $v_3(t) = V_3(t, e(t))$, since the differential equation $\dot{\theta} = -2(q_{\min}/p_{\max})c(\mu)\theta$ yields the solution $\theta(t) = e^{-2(q_{\min}/p_{\max})c(\mu)(t-t_0)} \theta(t_0)$. Therefore, defining $p_{\min} = \lambda_{\min}(P) = 1$ yields

$$\begin{aligned} \|e(t)\| & \leq \sqrt{\frac{p_{\max}}{p_{\min}}} e^{-(q_{\min}/p_{\max})c(\mu)(t-t_0)} \|e(t_0)\| = \\ & e^{-(q_{\min}/p_{\max})c(\mu)(t-t_0)} \|e(t_0)\|. \end{aligned} \quad (72)$$

For all $t \geq t_0$, $\|e(t_0)\| \leq \mu$ and any $\mu > 0$. Consequently, the equilibrium point $(x_e(t), y_e(t)) = (0, 0)$ is USGES, which can be deduced by using definition 2.7 from [17]. $\square$

5.3.3 The stability property of the closed-loop system $\Sigma 1$

Theorem 1 If Propositions 1 and 2 hold true, the nominal system $\Sigma 1_n$ is USGES and the subsystem $\Sigma 2$ is UGES, then $(x_e(t), y_e(t), \psi_e(t), \dot{\psi}_e(t), u_e(t)) = (0, 0, 0, 0, 0)$ of the cascaded system $\Sigma 1 - \Sigma 2$ is USGES and UGAS, when the control objectives are all achieved.

Proof According to (23) and (24), $c = 1.73$ is an upper bound for $|\gamma_x|$ and $|\gamma_y|$, thus, the interconnection matrix $g(t, e, \xi)$ satisfies the inequation

$$\begin{aligned} \|g(t, e, \xi)\| & \leq |\sin(\psi - \psi_P(\omega))| + |U_d \gamma_x| + \\ & |\cos(\psi - \psi_P(\omega))| + |U_d \gamma_y| \leq 2 + 3.46U_d. \end{aligned} \quad (73)$$

Therefore, the interconnection matrix $g(t, e, \xi)$ satisfies the inequation

$$\|g(t, e, \xi)\| \leq \theta_1(\|\xi\|) + \theta_2(\|\xi\|) \|e\| \quad (74)$$

for some continuous functions defined as $\theta_1 > 0, \theta_2 > 0$. Furthermore, Propagation 1 indicates that the perturbing system $\sum 2$ is UGES, and Propagation 2 indicates that the system $\sum 1_n$ is USGES. Hence, all conditions of Proposition 2.3 in [17] are satisfied, which guarantee that the origin of the cascaded system $\sum 1 - \sum 2$ is UGAS and USGES, when the control objectives are all achieved. $\square$

6. Simulation results and analysis

This section provides contrast simulation results in MATLAB to validate the effectiveness and superiority of the proposed controller. The CyberShip is chosen as the simulated USV, and the parameters of the CyberShip can be found in [34] and [35]. In general, the desired path of USV is divided into two types: straight- and curved-line paths. Hence, the two control algorithms combined with the traditional and modified ILOS guidance law proposed in this paper respectively are carried out under both straight- and curved-line path conditions. The parameters of the heading and speed controllers of two algorithms under the two conditions are all set as $k_x = 0.4, k_\phi = 0.03, k_{s1} = 2.5, k_{sg1} = 0.1, k_u = 1, k_{s2} = 0.1, k_{sg2} = 0.1$. And the lookahead distances of two algorithms are set respectively as $\Delta = 6$ m, $\Delta_{\min} = 4$ m, $\sigma = 0.03$. The unknown constant ocean current velocity is $V_c = [0.1 \text{ m/s}, 0.1 \text{ m/s}, 0 \text{ rad/s}]^T$.

Simulation 1 The initial states of the USV are set as $(x_0, y_0) = (50 \text{ m}, -100 \text{ m})$, $u(0) = 0.5 \text{ m/s}$, $\psi(0) = \pi/4$ rad. The desired straight-line path is set as $y = x$, and the desired surge velocity is set at $u_d = 3 \text{ m/s}$. Simulation results are shown in Fig. 2–Fig. 6.

Fig. 2 Straight-line path following of the USV under two strategies

Fig. 3 Along- and cross-track error of the USV under two strategies

Fig. 4 Surge velocities under two strategies

Fig. 5 Lookahead distances under two strategies

Fig. 6 Course angle varying of the USV under two strategies

Simulation 2 The initial states of the USV are set as $(x_0, y_0) = (0 \text{ m}, -10 \text{ m})$, $u(0) = 0.5 \text{ m/s}$, $\psi_0 = \pi/4 \text{ rad}$. The desired route is a continuous curved path through the points $(0, 0)$, $(100, 50)$, $(200, 100)$, $(300, 50)$, $(600, 200)$, which is generated by the cubic spline interpolation method. The desired surge velocity is set at $u_d = 3 \text{ m/s}$. Simulation results are shown in Figs. 7–12.

Fig. 2 and Fig. 7 show that the two path following control algorithms combined with the traditional and modified ILOS guidance law designed in this paper can ensure that the USV quickly tracks the desired straight-line and curved-line path and follows the desired paths, only with the forward thrust and steering torque. In the process of the path following, when the curvature change is large, the traditional ILOS guidance law is overshooted and the shock is larger, while the modified ILOS guidance law leads to smaller overshoot and shock. It can be seen from Fig. 3, Fig. 8 and Fig. 9 that the two control algorithms can ensure that the position error eventually converges to zero in the straight-line and curved-line path following process. Under the traditional ILOS guidance law, the shock is larger and the duration is longer, while in the modified ILOS guidance law, the shock is smaller, and the duration is shorter. From analysis of Fig. 4 and Fig. 10, we can see, in the process of the path following, the two control algorithms can ensure that the speed control is near $u_d = 3 \text{ m/s}$, and the steady-state error is small. It can be seen from Fig. 6 that the two algorithms can both track the expected heading angle, but the traditional algorithm makes the heading angle greater shocks, and the improved algorithm makes the heading angle relatively gentle.

Fig. 7 Curved-line path following of the USV under two strategies

Fig. 8 Cross-track error of the USV under two strategies

Fig. 9 Along-track error of the USV under two strategies

Fig. 10 Surge velocities under two strategies

Fig. 11 Lookahead distances under two strategies

Fig. 12 Course angle varying of the USV under two strategies

In order to verify the universality and robustness of the path-following controller designed in this paper, simula-

tion comparison experiments of the symmetry and asymmetry USV model under slow-time-varying current conditions are carried out in simulation 3.

Simulation 3 The unknown slow-time-varying current is set as $\mathbf{V}_c = [v_c^x \text{ m/s}, v_c^y \text{ m/s}, 0 \text{ rad/s}]^T$.

v_c^x and v_c^y are both random values within $[1, 2]$. The desired straight-line path is set as $y = 0$, the desired surge velocity is set as $u_d = 3 \text{ m/s}$. And the initial states of the USV are set as $(x_0, y_0) = (0 \text{ m}, 0 \text{ m})$, $u(0) = 0 \text{ m/s}$, $\psi_0 = \pi/4 \text{ rad}$. The desired curved-line path is set as $x^2 + y^2 = (45 \text{ m})^2$, the desired surge velocity is set as $u_d = 3 \text{ m/s}$. And the initial states of the USV are set as $(x_0, y_0) = (0 \text{ m}, -55 \text{ m})$, $u(0) = 0 \text{ m/s}$, $\psi_0 = \pi/4 \text{ rad}$. Simulation results are shown as in Fig. 13–Fig. 16, among which T_1 represents the tracking results of the controller based on asymmetric model, T_2 represents the tracking results of the controller based on the symmetric model.

Fig. 13 Straight-line path following of the USV

Fig. 14 Tracking errors of straight-line path following

Fig. 15 Curved-line path following of the USV

Fig. 16 Tracking errors of curved-line path following

It can be seen from Fig. 13 and Fig. 15 that the path-following controllers designed in this paper can track the desired path in the two situations of the symmetry and asymmetry USV model under slow-time-varying current, but the performance of the path-following controller using the asymmetry USV model is much better than the other. It can be seen from Fig. 14 and Fig. 16 that the tracking errors of the path-following controller using the asymmetry USV model is smaller than the other. And the neglect of the asymmetry factor in the USV model will bring intense tracking error to the proposed controller, which can be regarded as the impact of the unaccuracy model. Therefore, the controller proposed in this paper has certain universality and robustness, and the unaccuracy model has a greater impact on the performance of the path-following controller.

7. Conclusions

In this paper, a new path-following controller is proposed to drive the underactuated USV onto a predefined path under external disturbances such as irrotational and constant ocean currents, which comprises an ILOS guidance law

and adaptive feedback linearizing controllers combined with sliding-mode technique. And the proposed controller has the following advantages:

(i) By using the cascaded theorem, the control algorithm does not need to design the Lyapunov function of the entire path-following control system, which is more concise.

(ii) The control algorithm is only based on the measurement of the absolute velocity of the USV, thereby avoiding the cost of using the high relative velocity measurement equipment.

(iii) The LOS guidance law is designed based on a time-varying lookahead distance, which improves the manoeuvring flexibility of the USV and can be simultaneously applied to both curved-and straight-line path following.

(iv) The control system proposed is proved to be UGAS and USGES, when the control objectives are all achieved. Compared to uniform global k -exponential stability, the USGES has stronger robustness and faster convergence rate.

In the future work, the disturbances of wind and waves on the USV dynamics model and the path-following controller with modeling error will be studied, and the control algorithm will be optimized to improve the performance of path-following control.

References

- [1] FAULWASSER T, FINDEISEN R. Nonlinear model predictive control for constrained output path following. *IEEE Trans. on Automatic Control*, 2016, 61(4): 1026–1039.
- [2] CAHARIJA W, PETTERSEN K Y, BIBULI M, et al. Integral line-of-sight guidance and control of underactuated marine vehicles: theory, simulations and experiments. *IEEE Trans. on Control Systems Technology*, 2016, 24(5): 1623–1642.
- [3] ZHENG Z, SUN L. Path following control for marine surface vessel with uncertainties and input saturation. *Neurocomputing*, 2016, 177(3): 158–167.
- [4] LIU L, WANG D, PENG Z. Coordinated path following of multiple underactuated marine surface vehicles along one curve. *ISA Transactions*, 2016, 64: 258–268.
- [5] LIU C, ZOU Z J, HOU X R. Stabilization and tracking of underactuated surface vessels in random waves with fin based on adaptive hierarchical sliding mode technique. *Asian Journal of Control*, 2014, 16(5): 1492–1500.
- [6] LIU L, WANG D, PENG Z, et al. Predictor-based LOS guidance law for path following of underactuated marine surface vehicles with sideslip compensation. *Ocean Engineering*, 2016, 124(7): 340–348.
- [7] MASOOD G, SERGEY G N, GARRETT C. Finite-time tracking using sliding mode. *Journal of the Franklin Institute*, 2014, 351(5): 2966–2990.
- [8] HARMOUCHE M, LAGHROUCHE S, CHITOUR Y. Global tracking for underactuated ships with bounded feedback controllers. *International Journal of Control*, 2014, 87(10): 2035–2043.
- [9] FOSSEN T I. *Handbook of marine craft hydrodynamics and motion control*. Chichester: Wiley, 2011.

- [10] MOREIRA L, FOSSEN T I, SOARES C G. Path following control system for a tanker ship model. *Ocean Engineering*, 2007, 34(14): 2074–2085.
- [11] FREDRIKSEN E, PETTERSEN K Y. Global k-exponential way-point maneuvering of ships: theory and experiments. *Automatica*, 2006, 42(4): 677–687.
- [12] FOSSEN T I, PETTERSEN K Y. On uniform semiglobal exponential stability (USGES) of proportional line-of-sight guidance laws. *Automatica*, 2014, 50(11): 2912–2917.
- [13] ZHENG Z W, HUO W, WU Z. Direct-adaptive fuzzy path following control for an autonomous airship. *Control and Decision*, 2014, 29(3): 1418–1424. (in Chinese)
- [14] BORHAUG E, PAVLOV A, PETTERSEN K Y. Integral LOS control for path following of underactuated marine surface vessels in the presence of constant ocean currents. *Proc. of the 47th IEEE Conference on Decision and Control*, 2008: 4984–4991.
- [15] XIE W J, MA B L. Universal practical tracing control of a planar underactuated vehicle. *Asian Journal of Control*, 2015, 17(3): 1016–1026.
- [16] FISCHER N, HUGHES D, WALTERS P. Nonlinear RISE-based control of an autonomous underwater vehicle. *IEEE Trans. on Robotics*, 2014, 30(4): 845–852.
- [17] LORIA A, PANTELEY E. *Advanced topics in control systems theory*. New York: Springer Verlag, 2004.
- [18] CAHARIJA W. Relative velocity control and integral LOS for path following of underactuated surface vessels. *Proc. of the 9th IFAC Conference on Manoeuvring and Control of Marine Craft*, 2012: 380–385.
- [19] CAHARIJA W, PETTERSEN K Y, SORENSEN A J, et al. Relative velocity control and integral line of sight for path following of autonomous surface vessels: merging intuition with theory. *Proceedings of the Institution of Mechanical Engineers Part M. Journal of Engineering for the Maritime Environment*, 2014, 228(2): 180–191.
- [20] WIIG M S, PETTERSEN K Y, KROGSTAD T R. Uniform semiglobal exponential stability of integral line-of-sight guidance laws. *IFAC Papersonline*, 2015, 48(16): 61–68.
- [21] FOSSEN T I, PETTERSEN K Y, GALEAZZI R. Line-of-sight path following for Dubins paths with adaptive sideslip compensation of drift forces. *IEEE Trans. on Control Systems Technology*, 2015, 23(2): 820–827.
- [22] FOSSEN T I, LEKKAS A M. Direct and indirect adaptive integral line-of-sight path-following controllers for marine craft exposed to ocean currents. *International Journal of Adaptive Control and Signal Processing*, 2017, 31(4): 445–463.
- [23] MOE S, PETTERSEN K Y, FOSSEN T I, et al. Line-of-sight curved path following for underactuated USVs and AUVs in the horizontal plane under the influence of ocean currents. *Proc. of the Mediterranean Conference on Control and Automation*, 2016: 38–45.
- [24] CHEN X, LIU Z, ZHANG J Q, et al. Path following control of the underactuated USV based on the modified integral line-of-sight strategies. *Journal of Beijing University of Aeronautics and Astronautics*, 2018, 44(3): 489–499.
- [25] LIU L, WANG D, PENG Z. ESO-based line-of-sight guidance law for straight line path following with exact sideslip compensation. *Proc. of the World Congress on Intelligent Control and Automation*, 2016: 677–681.
- [26] LIONEL L, JOUVENCEL B. Robust nonlinear path-following control of an AUV. *IEEE Journal of Oceanic Engineering*, 2008, 33(2): 1734–1744.
- [27] GHOMMAN J, MNIF F, BEHAL A, et al. Nonsingular serret-frenet based path following control for an underactuated surface vessel. *Journal of Dynamic Systems Measurement and Control*, 2009, 131(2): 211–216.
- [28] PANTELEY E, LORIA A, TEEL A. Relaxed persistency of excitation for uniform asymptotic stability. *IEEE Trans. on Automatic Control*, 2002, 46(12): 1874–1886.
- [29] LIAO Y L, SU Y M, CAO J. Trajectory planning and tracking control for underactuated unmanned surface vessels. *Journal of Central South University*, 2014, 21(2): 540–549.
- [30] MIAO J, WANG S, ZHAO Z, et al. Spatial curvilinear path following control of underactuated AUV with multiple uncertainties. *ISA Transactions*, 2017, 67: 107–130.
- [31] SORDALEN O J, EGELAND O. Exponential stabilization of nonholonomic chained systems. *IEEE Trans. on Automatic Control*, 1995, 40(1): 35–49.
- [32] LORIA A, PANTELEY E, POPOVIC D, et al. A nested Matrosov theorem and persistency of excitation for uniform convergence in stable nonautonomous systems. *IEEE Trans. on Automatic Control*, 2005, 50(2): 183–198.
- [33] KHALIL H K. *Nonlinear systems*. Englewood Cliffs: Prentice-Hall, 2002.
- [34] WANG H, WANG D, PENG Z H. Adaptive neural control for cooperative path following of marine surface vehicles: state and output feedback. *International Journal of Systems Science*, 2016, 47(2): 343–359.
- [35] BREIVIK M. *Nonlinear maneuvering control of underactuated ships*. Norway: Trondheim, Norwegian University of Science and Technology, 2003.

Biographies

CHEN Xiao was born in 1990. He received his M.S. degree in communication engineering from Naval University of Engineering (NUE), Wuhan, China, in 2015. He is currently a Ph.D. candidate at Shipborne Command & Control Department, NUE. His research interests include the guidance and control of USV, and stability of nonlinear system.
E-mail: 15623115746@163.com

LIU Zhong was born in 1963. He received his M.S. and Ph.D. degrees from NUE, Wuhan, China, in 1984 and 2004 respectively. He is currently a full professor at Shipborne Command & Control Department, NUE. His research interests include nonlinear systems and robust control.
E-mail: liuzh531@163.com

ZHANG Jianqiang was born in 1980. He received his M.S. and Ph.D. degrees from National University of Defense Technology (NUDT), Changsha, China, in 2005 and NUE, Wuhan, China, in 2015. He is currently an associate professor at NUE. His research interests include nonlinear systems and robust control.
E-mail: zhangjianq@yahoo.cn

ZHOU Dechao was born in 1972. He received his M.S. and Ph.D. degrees from NUE, Wuhan, China, in 2001 and 2008 respectively. He is currently an associate professor at NUE. His research interests include nonlinear systems and robust control.
E-mail: zhoujdc@yahoo.cn

DONG Jiao was born in 1991. He received his M.S. degree in Communication Engineering from NUE, Wuhan, China, in 2016. He is currently a Ph.D. candidate at Shipborne Command & Control Department, NUE. His research interests include the guidance and control of USV, stability of nonlinear system.

E-mail: 1124668612@qq.com