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Surge-varying LOS based path following of under actuated surface vehicles

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Subject to harsh ocean environment, a novel path following control scheme with accurate guidance and high anti-disturbance ability for under actuated surface vehicles is proposed. The innovative work is as follow: (1) Based on the traditional line-of-sight (LOS), a surge-varying LOS (SVLOS) guidance law is designed to achieve double guidance of speed and heading, which enhances the flexibility and precision of the previous LOS; (2) Unknown disturbances are exactly estimated by an exact disturbance observer (EDO), wherein the limitations of bounded and asymptotic observations can be avoided; (3) The EDO-based robust tracking controllers enable accurate disturbance compensation and guided signal tracking in harsh ocean environment. Rigorous theoretical analysis and significant simulation comparison have been done to demonstrate superiority of the EDO-SVLOS scheme.

[**Keywords:** Under actuated surface vehicle; Path following; Exact disturbance observer; Surge-varying LOS guidance]

Introduction

Technological innovation is an important measure to achieve a powerful ocean country. To improve the strength of marine innovation, it is imperative to carry out research on system design of under actuated surface vehicle (USV) and its accurate motion control technology. The USVs have extensive civil and military applications[1,2,3], such as garbage disposal, drawing charts, mine clearance, anti-submarine, investigation, anti-terrorism, search and rescue, etc. The development of unmanned ship hardware systems has matured to some extent, but the precise control technology in complex environments has not been solved, which is extremely challenging. The control algorithm research of USVs includes stabilization[4], trajectory tracking[5,6,7,8,9,10] and path following[11] in literature. Many high-performance control frameworks[12,13,14,15,16,17] have been proposed to achieve USV motion control for different maritime missions. Accurate path following control (PFC) scheme can ensure that high-risk unmanned maritime missions are effectively executed in complex marine environments. This paper focuses on accurate PFC scheme design of USVs subject to harsh ocean environment.

The PFC scheme consists of guidance and control modules.[18] The guidance module is equivalent to the brain of a USV, and the guided signals are specified in combination with the sensor information. The control module is an execution system that keeps the USV's actual attitudes and guided signals consistent.

The LOS guidance method with its advantages of high precision and small calculation was first applied to ship motion control by Fossen in the Norwegian University of Science and Technology (NUST). Though continuous application and research include proportional line-of-sight (PLOS) guidance[19], integral line-of-sight (ILOS) guidance[20], adaptive line-of-sight (ALOS) guidance[21], its form is constantly changing, and its guidance performance is also constantly improving. In aforementioned guidance laws, small angle approximation and constantization assumptions need to be performed on the sideslip angle. A guidance law[22] is designed to follow a curved path. An FSO is designed to estimate sideslip angle[23]. Nevertheless, the proposed guidance laws[18,19,20,21,22] require USVs to sail at a constant surge velocity. Although the path following can be achieved by merely controlling the heading angle, it greatly affects the flexibility of the guidance system.

Within the entire PFC scheme, the control module renders USV's actual attitudes track the surge-varying LOS (SVLOS) signals accurately. A global finite-time controller[24,25] is proposed to achieve accurate tracking control, but ignores the loss of precision caused by external disturbances. The adaptive method[26] is used to approximate the upper bounds of the external disturbance, which ignores the time-varying characteristics. Fuzzy logic system[27] and neural networks[28] are finally used to approximate multiple unknowns. Observer-based control schemes[29,30] are applied to achieve accurate tracking control under complex the previous LOS where a USV is required to sail disturbances, only to achieve bounded or asymptotic disturbance observations. Nussbaum approach[31] is applied to the trajectory tracking of a USV. However, based on the above works, it can be seen that the accurate tracking control of USVs has still not been effectively solved in harsh ocean environments.

Motivated by the above analyses, a novel exact disturbance observe (EDO)-SVLOS algorithm is proposed to complete exact PFC of a USV subject to harsh ocean environment. The SVLOS guidance law is designed to achieve double guidance of speed and heading, which enhances the flexibility and precision of at constant surge. The EDO is used to zero-error approximate disturbances in a finite time, which overcomes the limitations of bounded and asymptotic observations. The EDO-based robust tracking controllers enable accurate disturbance compensation and guided signal tracking in harsh ocean environment, and the PFC system is proven globally asymptotically stable.

The paper starts with some preliminaries, followed by the design of the SVLOS and the EDO presents the EDO-based control design and provides simulation studies to illustrate the proposed EDO-SVLOS method. The cascade analysis method is used to analyze the stability of the PFC system.

Problem Formulation and Preliminaries

Lemma 1[32]

$$\begin{aligned} \dot{\varepsilon}_0 &= -\kappa_0 P^{1/(n+1)} \left|\varepsilon_0\right|^{n/n+1} \operatorname{sgn}(\varepsilon_0) + \varepsilon_1 \\ \dot{\varepsilon}_1 &= -\kappa_1 P^{1/n} \left|\varepsilon_1 - \dot{\varepsilon}_0\right|^{n-1/n} \operatorname{sgn}(\varepsilon_1 - \dot{\varepsilon}_0) + \varepsilon_2 \\ &\vdots \\ \dot{\varepsilon}_{n-1} &= -\kappa_{n-1} P^{1/2} \left|\varepsilon_{n-1} - \dot{\varepsilon}_{n-2}\right|^{1/2} \operatorname{sgn}(\varepsilon_{n-1} - \dot{\varepsilon}_{n-2}) + \varepsilon_n \\ \dot{\varepsilon}_n &\in -\kappa_n P \left|\varepsilon_n - \dot{\varepsilon}_{n-1}\right| \operatorname{sgn}(\varepsilon_n - \dot{\varepsilon}_{n-1}) + \left[-M, M\right] \end{aligned} \quad ...(1)$$

where $P > 0, \kappa_i > 0,\ i = 1, 2, \cdots, n$ are parameters of appropriate size, the systems that can be organized into such a form are finite-time stable.

Lemma 2[33]

A cascade system is organized into the following form:

$$\begin{aligned} \dot{\boldsymbol{\chi}}_c &= f_1(\boldsymbol{\chi}_c, \boldsymbol{J}_c) \\ \dot{\boldsymbol{J}}_c &= f_2(\boldsymbol{J}_c) \qquad \boldsymbol{\chi}_c \in R^n, \boldsymbol{J}_c \in R^m \end{aligned} \quad ...(2)$$

where $(\|\boldsymbol{\chi}_c\|, \|\boldsymbol{J}_c\|) = (0,0)$ is the equilibrium of the system (2).

$\|\boldsymbol{\chi}_c\| = 0$ is a globally asymptotically stable (GAS) equilibrium of the subsystem

$$\dot{\boldsymbol{\chi}}_c = f_1(\boldsymbol{\chi}_c, 0) \quad ...(3)$$

$\|\boldsymbol{J}_c\| = 0$ is a GAS equilibrium of (4).

$$\dot{\boldsymbol{J}}_c = f_2(\boldsymbol{J}_c) \quad ...(4)$$

All $(\boldsymbol{\chi}_c(t), \boldsymbol{J}_c(t))$ of (2) are bounded for $t > 0$. Then $(\boldsymbol{\chi}_c, \boldsymbol{J}_c) = (0,0)$ is GAS equilibrium of (2).

The kinematics and dynamics of a USV can be represented by

$$\begin{aligned} \dot{\boldsymbol{\eta}} &= \boldsymbol{R}(\psi)\boldsymbol{\nu} \\ \boldsymbol{M}\dot{\boldsymbol{\nu}} &= \boldsymbol{G}(\boldsymbol{\nu}) + \boldsymbol{\tau} + \boldsymbol{\tau}_\delta \end{aligned} \quad ...(5)$$

where $\boldsymbol{\eta} = [x, y, \psi]^T$ represents the position and the heading angle of the USV in earth-fixed frame, $\boldsymbol{\nu} = [u, v, r]^T$ expresses surge velocity, sway velocity and yaw velocity are expressed in the body-fixed frame. $\boldsymbol{R}(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$ is a rotation matrix. $\boldsymbol{\tau} = [\tau_u, 0, \tau_r]^T$ are control inputs, $\boldsymbol{\tau}_\delta = [\tau_{\delta_u}, \tau_{\delta_v}, \tau_{\delta_r}]^T$ are unknown external disturbances, $\boldsymbol{G}(\boldsymbol{\nu}) = [g_u, g_v, g_r]^T$ are internal dynamics, the specific form is as follows

$$\begin{aligned} g_u &= m_{22} v r - d_{11} u \\ g_v &= -m_{11} u r - d_{22} v \\ g_r &= -(m_{22} - m_{11}) u v - d_{33} r \end{aligned} \quad ...(6)$$

where m_{11}, m_{22}, m_{33} is the USV inertia including added mass, and d_{11}, d_{22}, d_{33} represent the USV hydrodynamic damping.

In Fig. 1, a predefined path is continuously parameterized by ω. A path-tangent frame is defined at $(x_t(\omega), y_t(\omega))$, and path-tangent angle φ_p is given as follows:

$$\varphi_p = \text{atan2}(y_t', x_t') \quad \ldots(7)$$

The cross- and along-track errors are as follows:

$$\begin{bmatrix} x_e \\ y_e \end{bmatrix} = \begin{bmatrix} \cos\varphi_p & -\sin\varphi_p \\ \sin\varphi_p & \cos\varphi_p \end{bmatrix}^T \begin{bmatrix} x - x_t \\ y - y_t \end{bmatrix} \quad \ldots(8)$$

The derivatives of y_e and x_e can be expressed by

$$\begin{aligned} \dot{x}_e &= u\cos(\psi-\varphi_p) - u\sin(\psi-\varphi_p)\tan\beta + \dot{\varphi}_p y_e - u_{\text{tar}} \\ \dot{y}_e &= u\sin(\psi-\varphi_p) - u\cos(\psi-\varphi_p)\tan\beta - \dot{\varphi}_p x_e \end{aligned} \quad \ldots(9)$$

where β=atan2(v,u) is the sideslip caused by external disturbance, and u_{tar} is the speed of the "virtual target", and can be expressed as follows:

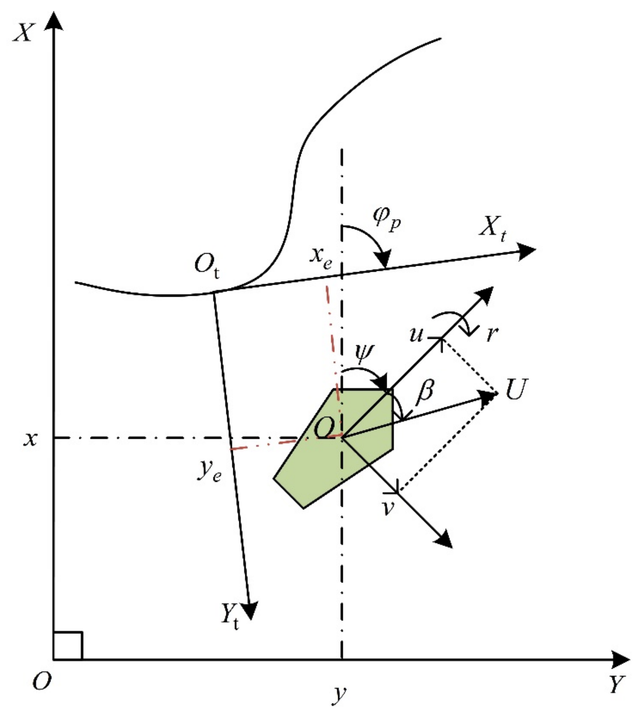

Fig. 1 — A geometrical illustration of PFC

$$u_{\text{tar}} = \dot{\omega}\sqrt{x_t'^2(\omega) + y_t'^2(\omega)} \quad \ldots(10)$$

Surge-Varying LOS Guidance

In the proposed SVLOS scheme, the surge guidance law self-adjusts with cross-track error, and is given as follows:

$$u_d = k_1\sqrt{y_e^2 + \Delta^2} \quad \ldots(11)$$

where $k_1 > 0,\ \Delta > 0$.

The guided heading angle is given as follows:

$$\psi_d = \varphi_p - \beta_d - \arctan\left(\frac{y_e}{\Delta}\right) \quad \ldots(12)$$

where $\beta_d = \arctan(v/u_d)$.

In addition, the speed of "virtual target" is designed as follows:

$$u_{\text{tar}} = k_2 x_e + U_d\cos(\psi - \varphi_p + \beta_d) \quad \ldots(13)$$

where $k_2 > 0$, and $U_d = \sqrt{u_d^2 + v^2}$ is the desired course speed of the USV.

Remark 1. An SVLOS guidance scheme developed in (11)-(13), and achieves double guidance of speed and heading, and thereby enhancing the decision-making ability of guidance subsystem—a "virtual target" moving on the predefined path is tracked rather than a singular projection point as in previous work (Fig. 2)[18,19,20,21,22].

Theorem 1. The SVLOS scheme (11)-(13) renders the origin $(x_e, y_e) = (0,0)$ of the system (9) globally asymptotically stable.

Proof. Construct the following Lyapunov function

$$V_1 = \frac{1}{2}(x_e^2 + y_e^2) \quad \ldots(14)$$

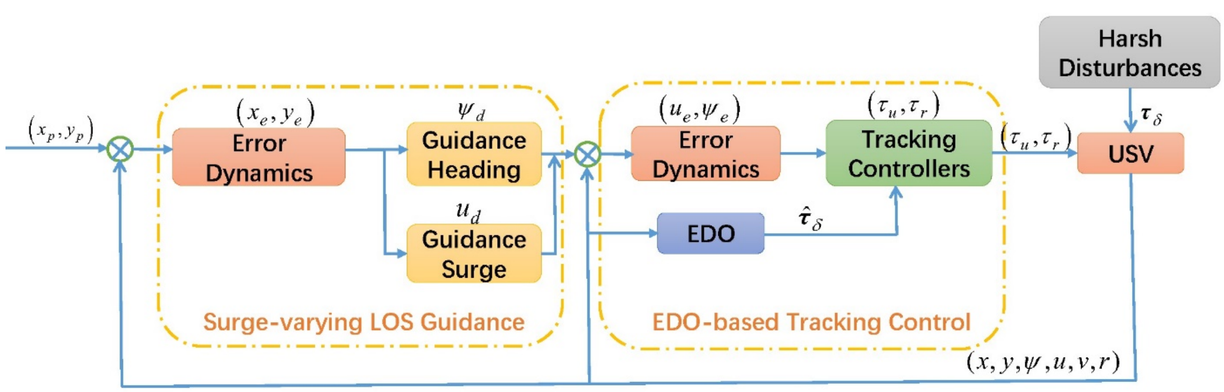

Fig. 2 — The algorithm architecture of the EDO-SVLOS .

Differentiating V_1 along the dynamics (9) yields

$$\dot{V}_1 = x_e\left[\frac{u}{\cos\beta}\cos(\psi-\varphi_p+\beta)-u_{\text{tar}}\right] + y_e\frac{u}{\cos\beta}\sin(\psi-\varphi_p+\beta) \quad \ldots(15)$$

Substitute (11)–(13) into (15), we get

$$\begin{aligned}\dot{V}_1 &= -k_2x_e^2 - y_e\frac{k_1\sqrt{y_e^2+\Delta^2}}{\cos\beta_d}\frac{y_e}{\sqrt{y_e^2+\Delta^2}}\\ &\le -k_1y_e^2-k_2x_e^2\\ &\le -kV_1\end{aligned} \quad \ldots(16)$$

The system (9) is GAS that has been proven.

Exact Disturbance Observer

Among that, $\boldsymbol{\tau}_\delta$ can be exactly estimated by the EDO:

$$\begin{aligned}&\boldsymbol{M}\dot{\hat{\boldsymbol{v}}} = \boldsymbol{\rho}+\boldsymbol{G}(\boldsymbol{v})+\boldsymbol{\tau}\\ &\boldsymbol{\rho} = -\sigma_1\boldsymbol{H}^{1/2}sig^{1/2}(\boldsymbol{M}\hat{\boldsymbol{v}}-\boldsymbol{M}\boldsymbol{v})+\hat{\boldsymbol{\tau}}_\delta\\ &\dot{\hat{\boldsymbol{\tau}}}_\delta = -\sigma_2\boldsymbol{H}\,\text{sgn}(\hat{\boldsymbol{\tau}}_\delta-\boldsymbol{\rho})\end{aligned} \quad \ldots(17)$$

where $\boldsymbol{\rho}=[\rho_u,\rho_v,\rho_r]^T$, $\boldsymbol{H}=diag(H_u,H_v,H_r)$, $H_{u,v,r}>0$, $\sigma_1,\sigma_2>0$, $\hat{\boldsymbol{\tau}}_\delta$ is the estimate of $\boldsymbol{\tau}_\delta$.

Remark 2. The EDO can approximate the unknown term with zero error, which overcomes the speed and accuracy limitations of bounded and asymptotic observations.

Theorem 2. The $\boldsymbol{\tau}_\delta$ can be exactly observed by the EDO (17).

Proof. The observation errors are defined as:

$$\begin{aligned}&\boldsymbol{O}_1 = \boldsymbol{M}\hat{\boldsymbol{v}}-\boldsymbol{M}\boldsymbol{v}\\ &\boldsymbol{O}_2 = \hat{\boldsymbol{\tau}}_\delta-\boldsymbol{\tau}_\delta\end{aligned} \quad \ldots(18)$$

Differentiating $\boldsymbol{O}_1$ and $\boldsymbol{O}_2$ yields:

$$\begin{aligned}\dot{\boldsymbol{O}}_1 &= \boldsymbol{M}\dot{\hat{\boldsymbol{v}}}-\boldsymbol{M}\dot{\boldsymbol{v}}\\ &= -\sigma_1\boldsymbol{H}^{1/2}sig^{1/2}(\boldsymbol{O}_1)+\boldsymbol{O}_2\\ \dot{\boldsymbol{O}}_2 &= \dot{\hat{\boldsymbol{\tau}}}_\delta-\dot{\boldsymbol{\tau}}_\delta\\ &\in -\sigma_2\boldsymbol{H}\,\text{sgn}(\boldsymbol{O}_2-\dot{\boldsymbol{O}}_1)+[-M_\delta,M_\delta]\end{aligned} \quad \ldots(19)$$

Using **Lemma 1**, the finite-time convergence of $\boldsymbol{O}_1$ and $\boldsymbol{O}_2$ can be proven, i.e., in a short time $0<T_{\text{obs}}<\infty$, we get

$$\hat{\boldsymbol{\tau}}_\delta(t)\equiv\boldsymbol{\tau}_\delta(t),\ \forall t\ge T_{\text{obs}} \quad \ldots(20)$$

The zero-error disturbance approximation has been proven.

EDO-based Tracking Control

Theorem 3. The ESO-based controllers are as follows:

$$\begin{aligned}\tau_u &= -g_u-\hat{\tau}_{\delta_u}-m_{11}(k_u(u-u_d)-\dot{u}_d)\\ \tau_r &= -g_r-\hat{\tau}_{\delta_r}-m_{33}(k_r(r-r_d)+\psi_e-\dot{r}_d)\end{aligned} \quad \ldots(21)$$

where $k_u,k_r>0$, and $\hat{\tau}_{\delta_u}$, $\hat{\tau}_{\delta_r}$ are obtained in (17).

$$r_d = -k_\psi(\psi-\psi_d)+\dot{\psi}_d \quad \ldots(22)$$

where $k_\psi>0$, the SVLOS guidance signals (u_d, ψ_d) can be exactly tracked.

Proof. Construct the Lyapunov function

$$V_2 = \frac{1}{2}\left(u_e^2+\psi_e^2+r_e^2\right) \quad \ldots(23)$$

where

$$\begin{cases}u_e = u-u_d\\ \psi_e = \psi-\psi_d\\ r_e = r-r_d\end{cases} \quad \ldots(24)$$

are the surge, heading and yaw tracking errors.
Differentiating V_2, we get

$$\begin{aligned}\dot{V}_2 &= u_e\left[\frac{1}{m_{11}}(g_u+\tau_u+\tau_{\delta_u})-\dot{u}_d\right]+\psi_e(r_d+r_e-\dot{\psi}_d)\\ &\quad + r_e\left[\frac{1}{m_{33}}(g_r+\tau_r+\tau_{\delta_r})-\dot{r}_d\right]\\ &= -k_uu_e^2-k_\psi\psi_e^2-k_rr_e^2\\ &\le -k_{V_2}V_2\end{aligned} \quad \ldots(25)$$

where $k_{V_2}=2\min\{k_u,k_\psi,k_r\}$, $\hat{\tau}_{\delta_u}\equiv\tau_{\delta_u}$, $\hat{\tau}_{\delta_r}\equiv\tau_{\delta_r}, \forall t\ge T_{\text{obs}}$ in (17), and the SVLOS guidance signals can be accurately tracked.

The control subsystem is GAS that has been proven.

Cascade System Stability Analysis

The position errors and guided signal tracking errors in integrated guidance-control system can be organized into cascaded forms

$$\Sigma_1:\begin{cases}\dot{x}_e=-u_d\sin(\psi_d-\varphi_p)\tan\beta_d\\ \quad +u_d\cos(\psi_d-\varphi_p)+\dot{\varphi}_p y_e-u_{\text{tar}}+C_{x_e}\\ \dot{y}_e=-u_d\cos(\psi_d-\varphi_p)\tan\beta_d\\ \quad +u_d\sin(\psi_d-\varphi_p)-\dot{\varphi}_p x_e+C_{y_e}\end{cases} \quad ...(26)$$

where

$$\begin{aligned}C_{x_e}(u_e,\psi_e,\tilde{\beta})&=\left[u_e+(\cos\psi_e-1)u_d\right]\frac{\cos(\psi-\varphi_p+\beta)}{\cos\beta}-\sin\psi_e u_d\frac{\sin(\psi-\varphi_p+\beta)}{\cos\beta}\\&\quad -u_d\sin(\psi_d-\varphi_p)\frac{\sin\tilde{\beta}}{\cos\beta\cos\beta_d}\\ C_{y_e}(u_e,\psi_e,\tilde{\beta})&=\left[u_e+(\cos\psi_e-1)u_d\right]\frac{\sin(\psi-\varphi_p+\beta)}{\cos\beta}-\sin\psi_e u_d\frac{\cos(\psi-\varphi_p+\beta)}{\cos\beta}\\&\quad -u_d\cos(\psi_d-\varphi_p)\frac{\sin\tilde{\beta}}{\cos\beta\cos\beta_d}\end{aligned} \quad ...(27)$$

which implies that

$$C_{x_e}(0)=C_{y_e}(0)=0 \quad ...(28)$$

where $\tilde{\beta}=\beta-\beta_d$.

The guided signal tracking error dynamics are reformulated as follows:

$$\Sigma_2:\begin{cases}\dot{u}_e=\dfrac{1}{m_{11}}(g_u+\tau_u+\tau_{\delta_u})-\dot{u}_d\\ \dot{\psi}_e=r_d-\dot{\psi}_d+r_e\\ \dot{r}_e=\dfrac{1}{m_{33}}\left[g_r+\tau_r+\tau_{\delta_r}\right]-\dot{r}_d\end{cases} \quad ...(29)$$

Theorem 4. The EDO-SVLOS scheme consisting of SVLOS guidance law (11)–(13) with the controllers (21) render the cascade system (26) and (29) is GAS.

Proof. The globally asymptotic stability of Σ_2-subsystem (29) has been proven in Theorem 3. In addition, Σ_1-subsystem (26) is GAS by using the SVLOS (11)–(13), which has been proven in Theorem 1. Using Lemma 2, the cascade system (26) and (29) is GAS.

The cascade system stability has been proven.

Simulation

Here, the simulation results on Cybership I[34] are provided to validate the superiority of the proposed EDO-SVLOS scheme.

The Cybership I's inertia parameters are shown in Table 1.

To simulation set-ups, complex disturbances are prescribed by

$$\boldsymbol{\tau}_\delta=[\sin(t+\frac{\pi}{3}),\ \cos(t+\frac{\pi}{10}),\ \sin(t+\frac{\pi}{5})]^T \quad ...(30)$$

The states of the USV on initial conditions are as follows: $[x,y,\psi]=[10,0,0]$, $[u,v,r]=[0,0,0]$.

The predefined parameterized path is as follows:

$$\begin{cases}x_t(\omega)=10\sin(0.1\omega)+\omega\\ y_t(\omega)=\omega\end{cases} \quad ...(31)$$

where ω is the time-independent path variable and its dynamics given by

$$\dot{\omega}=\frac{u_{\text{tar}}}{\sqrt{x_t'^2(\omega)+y_t'^2(\omega)}} \quad ...(32)$$

User-defined parameters of the EDO-SVLOS: $k_1=1,\ k_2=1, \Delta=1.2,\ \mathbf{H}=diag(400,400,400)$, $\sigma_1=0.2, \sigma_2=0.01,\ k_u=1.2,\ k_\psi=1.2,\ k_r=1.$

The simulation comparisons include comparison with other guidance approaches (ILOS and ALOS) and comparison with the SVLOS scheme without the EDO. Simulation results on the entire EDO-SVLOS scheme are shown in Figures 2–11, from which we can see that the guidance-control loop errors including path-following errors, tracking errors and estimate errors, can simultaneously converge with high accuracy.

Comparison with ILOS and ALOS

The ILOS guidance is as follows:

$$\begin{aligned}\psi_{\text{ILOS}}&=\varphi_p-\tan^{-1}\left(\frac{y_e+\sigma y_{\text{int}}}{\Delta}\right)\\ \dot{y}_{\text{int}}&=\frac{\Delta y_e}{(y_e+\sigma y_{\text{int}})^2+\Delta^2}\end{aligned} \quad ...(33)$$

where Δ, σ > 0 are inherent parameters, y_{int} is an integral term.

In addition, the ALOS guidance is governed by:

$$\begin{aligned}\psi_{\text{ALOS}}&=\varphi_p-\tan^{-1}\left(\frac{y_e}{\Delta}+\hat{\beta}\right)\\ \dot{\hat{\beta}}&=\gamma\frac{U\Delta}{\sqrt{(y_e+\Delta\hat{\beta})^2+\Delta^2}}\end{aligned} \quad ...(34)$$

where Δ, γ > 0 are method inherent parameters, $\hat{\beta}$ is an adaptive term.

Table 1 — Cybership I parameters

m_{11}	19kg	m_{22}	35.2kg	m_{33}	4.2kg
d_{11}	4kg/s	d_{22}	1kg/s	d_{33}	10kg/s

Figure 3 illustrates that the proposed SVLOS guidance compared to ILOS and ALOS approaches, can achieve faster response and more accurate path following performance. From Figure 4, x_e and y_e with the SVLOS guidance can converge to zero with high-precision; however, cannot converge to zero with ILOS and ALOS guidance.

Comparison with SVLOS scheme

From Figure 5, we can see that the USV can accurately follow the predefined reference path in harsh ocean environment with the EDO–SVLOS scheme. However, without EDO, the USV cannot achieve accurate path following control. From Figure 6, x_e and y_e with the EDO-SVLOS scheme can converge smoothly to zero while without EDO cannot converge exactly under complex unknown disturbances. Figures 7–8 show the accurate surge and heading tracking achieved with the EDO-SVLOS scheme, but there exist large tracking errors with the SVLOS scheme. Moreover, from Figures 9–10, we can see that the complex disturbances can be

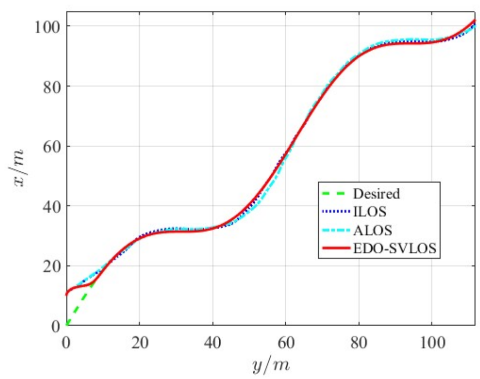

Fig. 3 — Path following performance.

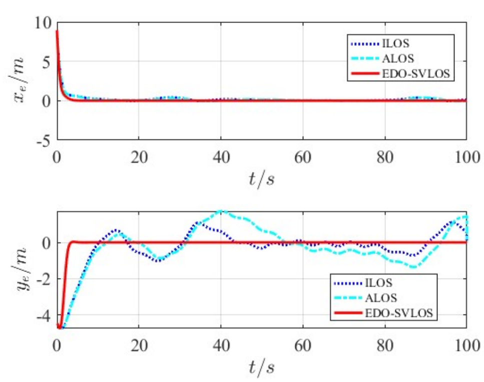

Fig 4. — Cross- and along-track errors.

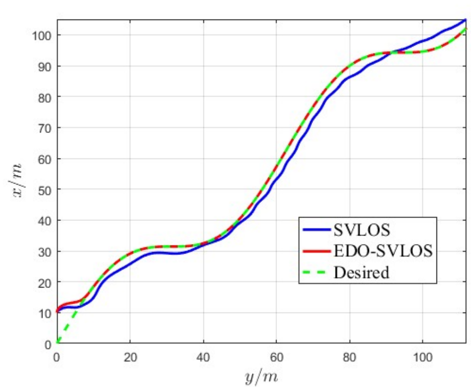

Fig 5. — Path following performance.

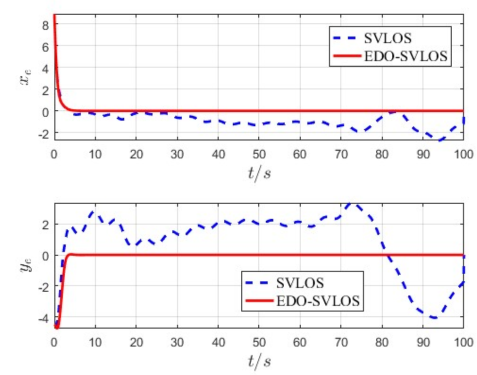

Fig. 6 — Cross- and along-track errors.

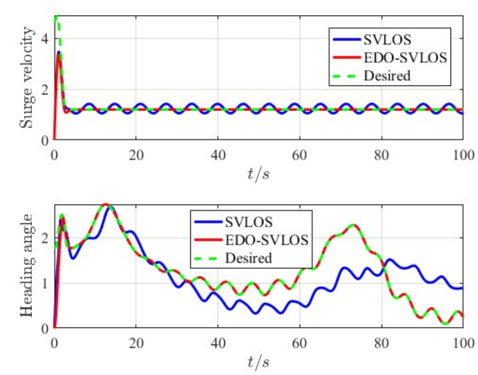

Fig. 7 — Surge and heading tracking.

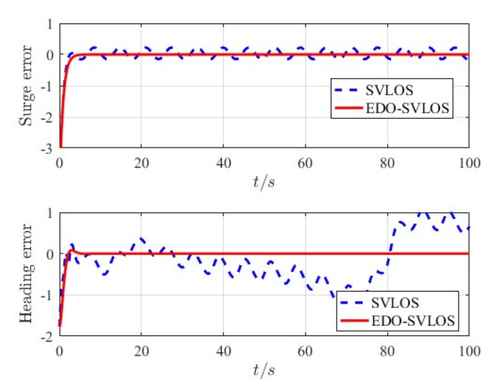

Fig. 8 — Surge and heading tracking errors.

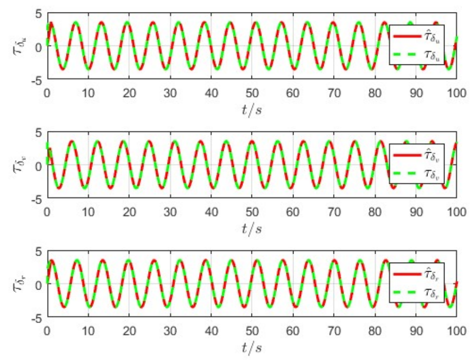

Fig. 9 — Estimates of external disturbances.

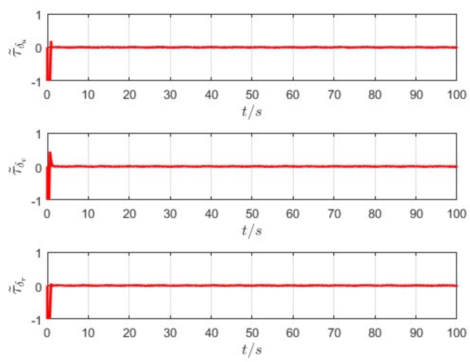

Fig. 10 — Disturbance estimate errors.

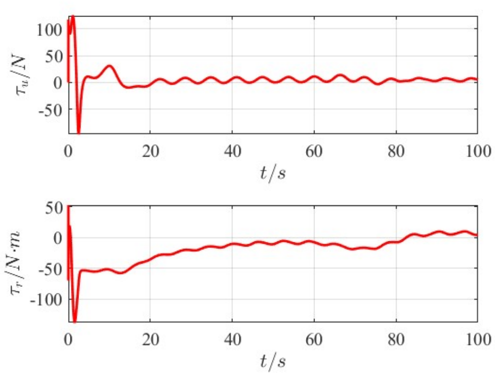

Fig. 11 — Control inputs.

estimated by the developed EDO with high precision. The control inputs of a USV are shown in Figure 11. The superiority of the EDO-SVLOS scheme can be comprehensively demonstrated.

Conclusion

In this paper, a novel EDO-SVLOS scheme with accurate guidance and high anti-disturbance ability for USVs has been developed. With the modified SVLOS guidance, the surge guidance law self-adjusts with cross-track error, which achieve double guidance of surge and heading, thereby accelerates the path following error convergence speed and flexibility. Unknowns are exactly estimated by the EDO. The EDO-based robust tracking controllers enable exact disturbance compensation and SVLOS signal tracking, which validates the EDO-SVLOS scheme can achieve accurate PFC of a USV in harsh ocean environment.

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