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TRAJECTORY CONTROL OF DYNAMICALLY LOCATED VESSELS BASED ON ILOS GUIDANCE ALGORITHM

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Abstract. *This paper aims to solve the problem of ship track control, make the ship track converge to the expected track, improve the accuracy of the ship track, realize the economic track, and improve the practical value of the project. The ILOS (integrated line of sight) guidance algorithm is used to calculate the reference heading of the ship during navigation, the controller is designed to control the heading, and ESO (extended state observer) is used to observe the current state and disturbance, so as to realize the convergence of the actual track to the reference heading. The stability of the closed-loop system is proved by Lyapunov method. The control strategy proposed in this paper and the traditional ILOS-PID control method are used for simulation, respectively. The simulation results show that the control strategy proposed in this paper converges the reference heading better and produces less ship track error. The control strategy proposed in this paper can solve the problem of ship track control, so that the ship can save time and reduce costs in the process of navigation, achieve economic navigation, and have certain engineering practical value.*
Keywords: Smart ship, LOS guide, ILOS guide, PID control, ESO observer

1. **Introduction.** With the development of ship automation and intelligence, intelligent ships have become a hot spot in the field of ships, which leads to ship tracking control becoming a major problem in ship control technology. Most ships are underdrive systems, there are many control methods used in the control process, and the methods that are more studied mainly include the reverse foot method [1], fuzzy control [2], neural network control [3], and adaptive technology [4]. In recent years, since the LOS navigation algorithm can calculate the reference bow angle through the trajectory deviation, the ship can be controlled by the bow direction, that is, the ship bow angle is controlled to be consistent with the line of sight angle (LOS angle), the ship is guided to automatically sail along the calculated reference bow, and the ship can reach the destination along the planned reference path. The target position, thus achieving the effect of trajectory tracking, is widely used in the study of ship control [5]. In order to solve the problem of ocean current disturbance in the marine environment, [6] proposed a method based on internal mode control and LOS guidance algorithm for the problem of path tracking control, and experimentally verifies that the method has good control performance. [7] combined ADRC technology with sliding mode theory to design a path tracking controller that considers wind and current interference, which improves the convergence error of the

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system and reduces jitter. However, for the unknown perturbation and non-linear tracking problem, it has not been effectively solved. In view of this problem, [8] proposed the ship tracking control based on the ILOS guidance law, but the tracking effect is not good, so this paper is improved, the use of ILOS guidance algorithm, while combining with the addition of the expansion observer (ESO) PID control. Solving the track control of ship model uncertainty and unknown environmental disturbance, improves the accuracy of ship navigation.

2. Mathematical Model of the Ship.

2.1. Ship reference coordinate system. When building a mathematical model of a ship, the north-east-down (NED) coordinate system and the body coordinate system are usually chosen as reference coordinate systems [9].

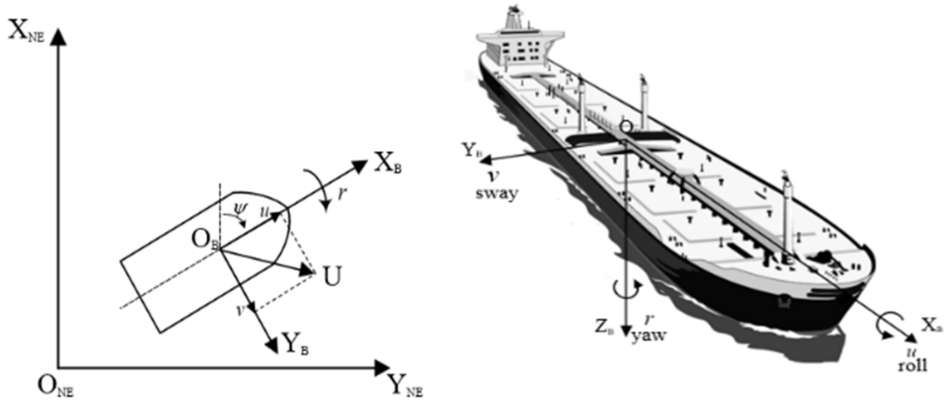

FIGURE 1. North-east coordinate system and hull coordinate system

2.2. Model of ship motion. The amount of motion of the ship is based on the north-east coordinate system of Figure 1, ignoring the movement of the ship's draping, vertical and horizontal rocking, and establishing a 3-DOF ship model as

$$\begin{cases} \dot{\eta} = J(\eta)\nu \\ M\dot{\nu} + D(\nu)\nu = \tau + \tau_{env} \end{cases} \tag{1}$$

where $\eta = [x, y, \psi]^T$ indicates the position and bow direction of the ship, $\nu = [u, v, r]^T$ represents the linear velocity of the ship; $J(\eta)$ is a coordinate transformation matrix, whose expression is as follows:

$$J(\eta) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

M is the inertia matrix and its expression is

$$M = \begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & 0 \\ 0 & 0 & m_{33} \end{bmatrix} = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & 0 \\ 0 & 0 & m - N_{\dot{r}} \end{bmatrix} \tag{3}$$

The input vector is $\tau = [\tau_u, \tau_v, \tau_r]$; $\tau_{env} = [\tau_{ud}, \tau_{vd}, \tau_{rd}]$ represents the marine environment; $D(\nu)$ is a hydrodynamic resistance matrix, in the following form:

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

where d_{ij} $(i = 1, 2, 3,\ j = 1, 2, 3)$ is

$$\begin{cases} d_{11} = -X_u - X_{|u|u}u \\ d_{22} = -Y_v - Y_{|v|v}v \\ d_{23} = -Y_r - X_{|v|r}v \\ d_{32} = -N_v - N_{|v|v}v \\ d_{33} = -N_r - X_{|v|r}v \end{cases} \tag{5}$$

where X_u, Y_v, Y_r, N_v, N_r, $X_{|u|u}$, $X_{|v|r}$, $Y_{|v|v}$, and $N_{|v|v}$ are the hydrodynamic coefficients. At the same time, combined with the environmental disturbances of wind, waves, and currents, we can establish a differential form of ship mathematics:

$$\begin{cases} \dot{x} = u\cos\psi - v\sin\psi \\ \dot{y} = u\sin\psi + v\cos\psi \\ \dot{\psi} = r \\ \dot{u} = \dfrac{(m_{22}vr - d_{11}u + \tau_u + \tau_{ud})}{m_{11}} \\ \dot{v} = -\dfrac{(m_{11}ur - d_{22} + \tau_{vd})}{m_{22}} \\ \dot{r} = \dfrac{((m_{11} - m_{22})\,uv - d_{33}r + \tau_r + \tau_{rd})}{m_{33}} \end{cases} \tag{6}$$

3. **Ship Guidance System.**

3.1. **LOS guidance law.**

The line of sight (LOS) guidance method is a guidance method suitable for straight paths. The principle is as follows: as shown in Figure 2, the straight line segment in the figure $p_{k-1}p_k$ is the expected trajectory of the current ship, ψ the real-time bow angle of the ship, ψ_{los} the bow angle that $p_{los}(x_{los}, y_{los})$ is the ship needs to adjust to the target point, and Δ the forward viewing distance (generally 2-6 times the captain), (x, y) representing the position of the ship in the NED coordinate system.

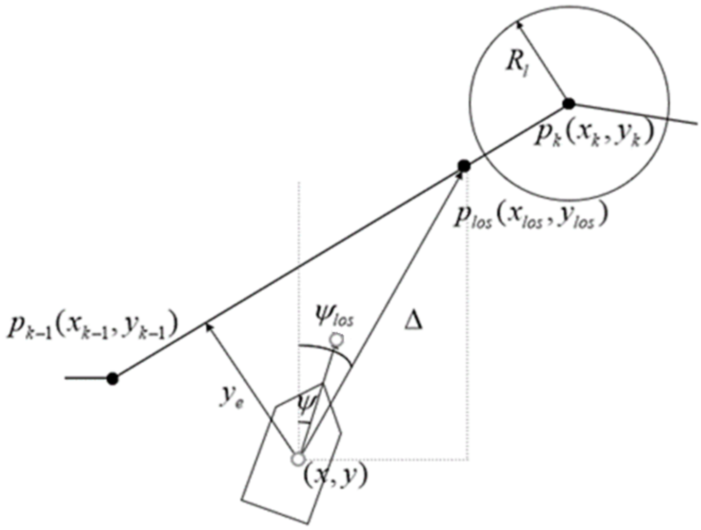

Figure 2. LOS introduction

The calculation formula of the target point $p_{los}(x_{los}, y_{los})$ can be obtained from the geometric relationship:

$$\begin{cases} (y_{los} - y)^2 + (x_{los} - x)^2 = \Delta^2 \\ \dfrac{y_k - y_{k-1}}{x_k - x_{k-1}} = \dfrac{y_{los} - y_{k-1}}{x_{los} - x_{k-1}} = \tan(\alpha_l) \end{cases} \tag{7}$$

where the forward viewing distance is $\Delta = nL_{pp}$, L_{pp} the actual length of the ship; At present, the angle α_l between the straight path and X_{NE} the axis is expected, and the switching conditions are as follows:

$$(x_k - x)^2 + (y_k - y)^2 \leq R_l^2, \quad R_l \leq \Delta \tag{8}$$

and the expected yaw angle is

$$\psi_{los} = \arctan\left(y_{los} - y, x_{los} - x\right) \tag{9}$$

3.2. **ILOS guidance.** For the current ship track control, more involved in the curve movement, for the curve movement, the traditional LOS navigation algorithm could not be accurately calculated, so it improved on the BASIS navigation algorithm by introducing integral variables and using the ILOS navigation algorithm [10-12]. Compared with the LOS navigation algorithm, the desired bow angle of the ILOS navigation algorithm is

$$\psi_d = \gamma_p - \arctan\left(\frac{y_e + \sigma y_{int}}{\Delta}\right) \tag{10}$$

$$\dot{y}_{int} = \frac{\Delta y_e}{\sqrt{\left(y_e + \Delta y_{int}\right)^2 + \Delta^2}} \tag{11}$$

$$\Delta = \left(\Delta_{\max} - \Delta_{\min}\right) e^{-\kappa|y_e|} + \Delta_{\min} \tag{12}$$

where $\Delta_{\max}$ and $\Delta_{\min}$ are the maximum and minimum forward viewing distances.

3.3. **Lyapunov stability analysis.** Define ship speed $U = \sqrt{u^2 + v^2}$, ship drift angle $\beta = \arctan(v/u)$, heading tracking error $\tilde{\psi} = \psi - \psi_d$, so there are

$$\begin{aligned}\dot{y}_e &= U \sin\left(\tilde{\psi} + \psi_d + \beta - \gamma_p\right) \\ &= U \sin\left(\tilde{\psi} + \psi_d - \gamma_p\right) \cos\beta + U \cos\left(\tilde{\psi} + \psi_d - \gamma_p\right) \sin\beta\end{aligned} \tag{13}$$

Because the drift angle β is usually smaller, there is $\sin\beta \approx \beta$, $\cos\beta \approx 1$, and thus

$$\begin{aligned}\dot{y}_e &= U \sin\left(\tilde{\psi} + \psi_d'\right) + U \cos\left(\tilde{\psi} + \psi_d'\right) \beta \\ &= U \sin\tilde{\psi} \cos\left(\psi_d - \gamma_p\right) + U \cos\tilde{\psi} \sin\left(\psi_d - \gamma_p\right) \\ &\quad + U\beta \cos\tilde{\psi} \cos\left(\psi_d - \gamma_p\right) - U\beta \sin\tilde{\psi} \sin\left(\psi_d - \gamma_p\right)\end{aligned} \tag{14}$$

From the above, we can see

$$\begin{cases} \sin\left(\psi_d - \gamma_p\right) = -\dfrac{y_e + y_{int}}{\sqrt{\left(y_e + \Delta y_{int}\right)^2 + \Delta^2}} \\ \cos\left(\psi_d - \gamma_p\right) = \dfrac{\Delta}{\sqrt{\left(y_e + \Delta y_{int}\right)^2 + \Delta^2}} \end{cases} \tag{15}$$

Get the following formula:

$$\dot{y}_e = -\frac{U\left(y_e + y_{int}\right)}{\sqrt{\left(y_e + \Delta y_{int}\right)^2 + \Delta^2}} + \frac{U\beta\Delta}{\sqrt{\left(y_e + \Delta y_{int}\right)^2 + \Delta^2}} + U\phi\left(y_e, \tilde{\psi}, \beta\right)\tilde{\psi} \tag{16}$$

where

$$\begin{aligned}\phi\left(y_e, \tilde{\psi}, \beta\right) =& \frac{\sin\tilde{\psi}}{\tilde{\psi}} \cos\left(\psi_d - \gamma_p\right) + \frac{\cos\tilde{\psi} - 1}{\tilde{\psi}} \sin\left(\psi_d - \gamma_p\right) \\ &+ \beta\left[-\frac{\sin\tilde{\psi}}{\tilde{\psi}} \sin\left(\psi_d - \gamma_p\right) + \frac{\cos\tilde{\psi} - 1}{\tilde{\psi}} \sin\left(\psi_d - \gamma_p\right)\right]\end{aligned} \tag{17}$$

Because $\left|\sin\tilde{\psi}\big/\tilde{\psi}\right| \le 1 \left|\left(\cos\tilde{\psi}-1\right)\big/\tilde{\psi}\right| \le 0.73$, the function $\phi\left(y_e,\tilde{\psi},\beta\right)$ is bounded. Assuming that the ship can accurately track the reference course ψ_d, that is $\tilde{\psi}\to 0$, it should converge to the ship drift angle β, that is $y_{int}=\hat{\beta}$. Define the Lyapunov function:

$$V\left(y_e,\tilde{\beta}\right)=\frac{1}{2}y_e^2+\frac{1}{2k}\tilde{\beta}^2>0,\quad k>0 \tag{18}$$

Seek to obtain:

$$\dot{V}\left(y_e,\tilde{\beta}\right)=-\frac{Uy_e^2}{\sqrt{\left(y_e+\Delta y_{int}\right)^2+\Delta^2}}+\frac{U\Delta y_e}{\sqrt{\left(y_e+\Delta y_{int}\right)^2+\Delta^2}}+\frac{1}{k}\dot{\tilde{\beta}} \tag{19}$$

Usually we think that the drift angle changes very slowly, $\dot{\beta}\approx 0$, therefore, $\dot{\tilde{\beta}}\approx-\dot{\hat{\beta}}$, there exists $k>0$, so that

$$\frac{U\Delta y_e}{\sqrt{\left(y_e+\Delta y_{int}\right)^2+\Delta^2}}=-\frac{1}{k}\dot{\tilde{\beta}} \tag{20}$$

$$\dot{V}\left(y_e,\tilde{\beta}\right)=-\frac{Uy_e^2}{\sqrt{\left(y_e+\Delta y_{int}\right)^2+\Delta^2}}<0 \tag{21}$$

Therefore, the above ILOS guidance is asymptotic and stable.

4. **Design and Simulation of the Controller.**

4.1. **Design of the controller.**

4.1.1. *Traditional PID control.* Based on the PID control of ILOS guidance algorithm, and controlling it through the most traditional PID control, the specific schematic diagram is as follows.

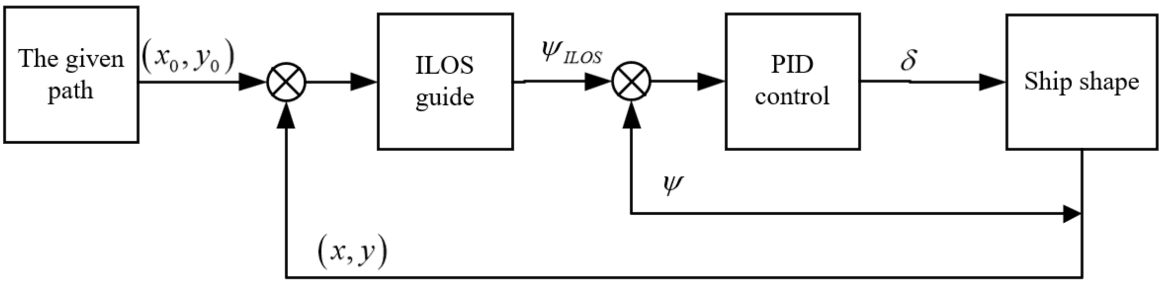

FIGURE 3. ILOS-based ship track PID control schematic

4.1.2. *Improved PID control.*

1) Based on the traditional PID control, the ESO expansion observer is added to protect against environmental interference [12,13], which is mainly the interference of the ocean current, and the interference is estimated by adding ESO to control it.

2) ESO estimates interference

As can be seen from the ship motion equation, under the interference of the current, the ship motion equation becomes

$$\begin{cases}\dot{x}=u\cos\psi-v\sin\psi+\omega_{\dot{x}}\\ \dot{y}=u\sin\psi+v\cos\psi+\omega_{\dot{y}}\\ \dot{\psi}=r\end{cases} \tag{22}$$

where ψ is the bow angle; u and v are the relative velocity along x_b axis and y_b axis respectively in the ship's coordinate system; (x,y) represents the position of ships in the

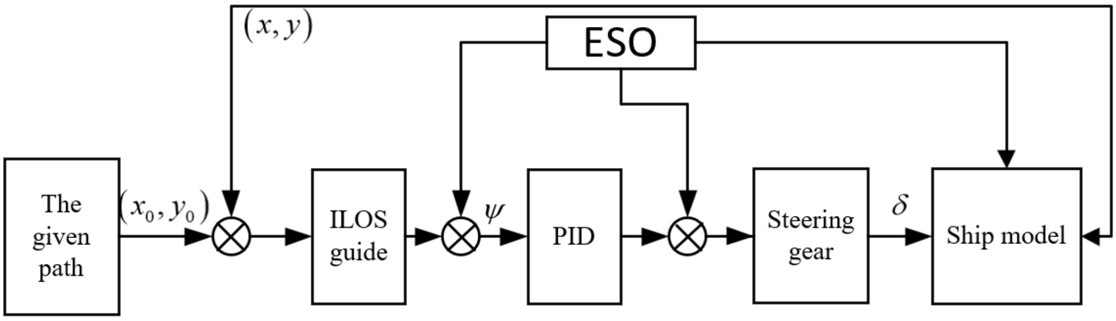

FIGURE 4. ILOS-based ship track improvement PID control schematic

NED coordinate system; $\omega_{\dot{x}}$ and $\omega_{\dot{y}}$ are ocean current velocity components along x_b axis and y_b axis. Mathematical model of ship steering is as follows:

$$\ddot{\psi} = -\frac{\alpha_1}{T}\dot{\psi} - \frac{\alpha_3}{T}\dot{\psi}^3 + \frac{K}{T}\delta \tag{23}$$

where α_1, α_3, K, and T in the equation are the manipulation parameters; δ is the rudder angle.

The steering characteristic equation is

$$\dot{\delta} = -\frac{K_\delta}{T_\delta}\delta + \frac{K_\delta}{T_\delta}\delta_c \tag{24}$$

where δ_c is command rudder angle, K_δ and T_δ are respectively open loop gain and time constant.

The following vectors are defined for ESO design:

$$\boldsymbol{x} = \begin{bmatrix} x_{1,1} & x_{2,1} & x_{3,1} & x_{3,2} & x_{4,1} \end{bmatrix}^T = \begin{bmatrix} x & y & \psi & \dot{\psi} & \delta \end{bmatrix}^T \tag{25}$$

$$\boldsymbol{y} = \begin{bmatrix} y_1 & y_2 & y_3 & y_4 \end{bmatrix}^T = \begin{bmatrix} x_{1,1} & x_{2,1} & x_{3,1} & x_{4,1} \end{bmatrix}^T \tag{26}$$

$$u = u_1 = \delta_d \tag{27}$$

The expansion vector shown as follows is used to represent the external disturbance of the system:

$$\begin{bmatrix} x_{1,2} & x_{2,2} & x_{3,3} & x_{4,2} \end{bmatrix}^T = \begin{bmatrix} \omega_1 & \omega_2 & \omega_3 & \omega_4 \end{bmatrix}^T \tag{28}$$

In the formula, $\omega_1 = \omega_{\dot{x}}$, $\omega_2 = \omega_{\dot{y}}$ are the disturbance of the arrival of the current to the ship; model noise for a mathematical model of ship steering ω_3; model noise for the servo mathematical model ω_4. Define the estimation error vector:

$$\boldsymbol{e} = \begin{bmatrix} e_1 & e_2 & e_3 & e_4 \end{bmatrix}^T = \begin{bmatrix} \hat{x}_{1,1} - y_1 & \hat{x}_{2,1} - y_2 & \hat{x}_{3,1} - y_3 & \hat{x}_{4,1} - y_4 \end{bmatrix}^T \tag{29}$$

and the expression of NLESO is

$$\begin{cases} \dot{\hat{x}}_{1,1} = \hat{x}_{1,2} - \beta_{1,1}e_1 + (u\cos\hat{x}_{3,1} - v\sin\hat{x}_{3,1}) \\ \dot{\hat{x}}_{1,2} = -\beta_{1,2}\,\mathrm{fal}\,(e_1, \alpha, \gamma) \\ \dot{\hat{x}}_{2,1} = \hat{x}_{2,2} - \beta_{2,1}e_2 + (u\sin\hat{x}_{3,1} + v\cos\hat{x}_{3,1}) \\ \dot{\hat{x}}_{2,2} = -\beta_{2,2}\,\mathrm{fal}\,(e_2, \alpha, \gamma) \\ \dot{\hat{x}}_{3,1} = \hat{x}_{3,2} - \beta_{3,1}e_3 \\ \dot{\hat{x}}_{3,2} = \hat{x}_{3,3} - \beta_{3,2}\,\mathrm{fal}\,(e, \alpha, \gamma) + \left(-\frac{\alpha_1}{T}\hat{x}_{3,2} - \frac{\alpha_3}{T}\hat{x}_{3,2}^3 + \frac{K}{T}\hat{x}_{4,1}\right) \\ \dot{\hat{x}}_{3,3} = -\beta_{3,3}\,\mathrm{fal}\,(e_3, \alpha^2, \gamma) \\ \dot{\hat{x}}_{4,1} = \hat{x}_{4,2} - \beta_{4,1}e_4 + \frac{K_\delta}{T_\delta}u \\ \dot{\hat{x}}_{4,2} = -\beta_{4,2}\,\mathrm{fal}\,(e_4, \alpha, \gamma) \end{cases} \tag{30}$$

where α and γ are design parameters, the expression of function $\mathrm{fal}(e, \alpha, \gamma)$ is

$$\mathrm{fal}\left(e, \alpha, \gamma\right) = \begin{cases} |e|^{\alpha} \cdot \mathrm{sign}(e), & |e| > \gamma \\ \dfrac{e}{\gamma^{\alpha}}, & |e| \le \gamma \end{cases} \tag{31}$$

5. **Simulation Results.** In the simulation process, we take ship 299 as an example, and design a curved track at the same time, here we set the ship track as a circular trajectory: $(x - 2000)^2 + (y - 2000)^2 = 1500^2$, set the ship speed to 3 m/s, PID control parameters of $k_i = 1$, $k_d = 30$ and perform the corresponding simulation to obtain the following simulation diagram.

It can be seen from the ship curve track in Figure 5 and in Figure 7 that in the two control strategies, the control strategy with the addition of the ESO expansion observer is more effective, and it almost coincides with the desired track, and the results of Figure 6 are further verified.

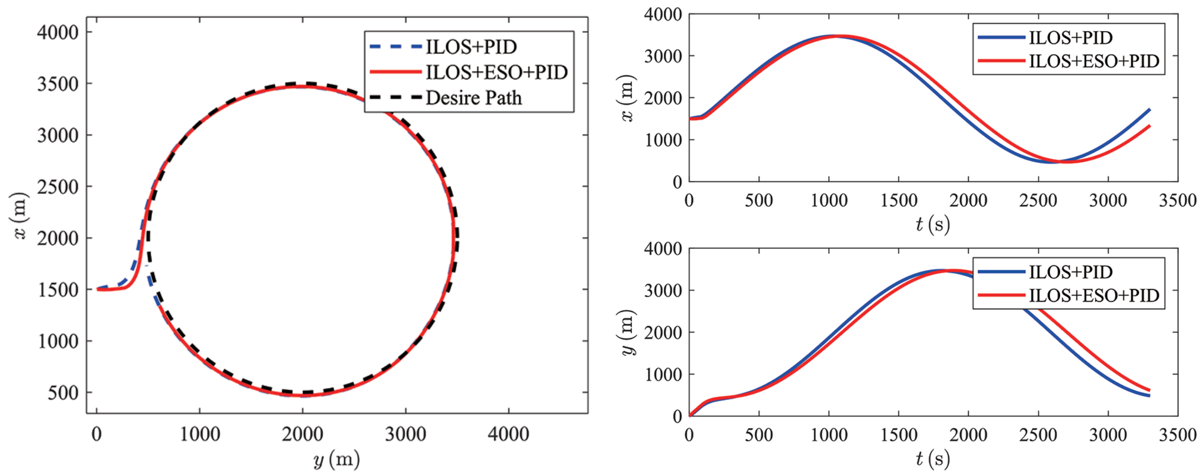

Figure 5. Ship track

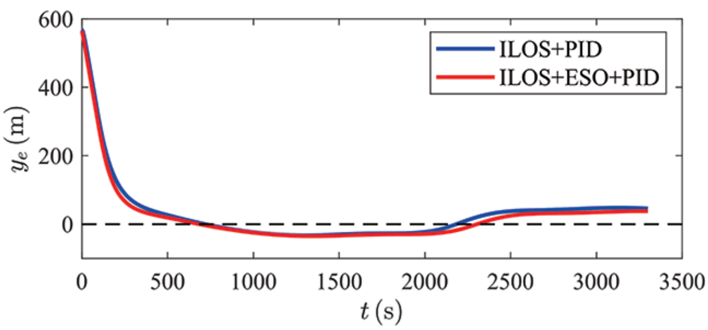

Figure 6. Ship track error

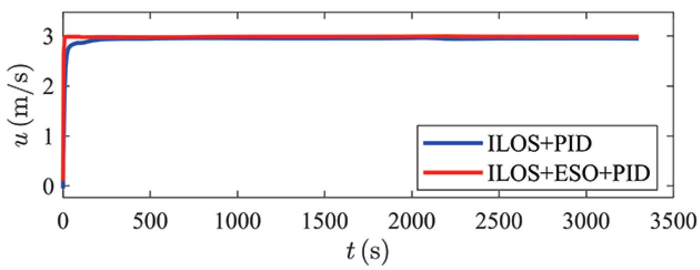

Figure 7. Ship velocity

6. **Conclusion.** Through simulation experiment, comparing the control effect of the two control algorithms, we can see that the improved control algorithm is far better than the problem in the ship model uncertainty and unknown environmental disturbance, improves the accuracy of ship navigation, and has practical engineering value, laying the foundation for the future control algorithm research.

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