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Fixed Time Control of Dynamic Positioning Ship with Unknown Interference

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Abstract

This paper proposes a fixed-time control scheme to ensure that the dynamic positioning can accurately reach the specified position under external interference. A fixed-time state observer was developed to accurately estimate the total external unknown interference. Based on the dynamic positioning ship motion model, the inversion design method is used to ensure the stability of the system and eliminate various uncertain effects. A fixed-time backstepping sliding mode controller is designed. Finally, the simulation results show that the method has good performance and advantages.

Keywords

Dynamic Positioning, Fixed-Time Observer, Sliding Mode Control

1. Introduction

Due to factors such as changeable marine environment, complicated operating conditions, and increasing water depth, the types of marine operating equipment are becoming more and more abundant. With the increase in offshore engineering operations, ships need to enter a more severe environment, and traditional anchorage positioning can no longer meet reality needs. Dynamic positioning has become an indispensable key technology for marine engineering equipment [1] [2]. At the same time, many ships have the characteristics of non-linearity and strong coupling as under-driven systems, so higher requirements are placed on the control system, and there is more and more research on this aspect in academia.

In recent years, nonlinear control theories such as pushback control and sliding mode control have attracted wide attention. Sliding mode control is based on the desired dynamic characteristics of the system to design the switching hyperplane of the system, so that the sliding mode controller makes the system state. The beam is switched to the hyperplane to overcome the uncertainty and external interference of the system, and the system can quickly reach the origin of the system along the hyperplane. However, SMC is prone to chattering, resulting in wear of actuators [3] [4]. However, the backstepping method [5] has no defects in this respect. It decomposes the nonlinear system into subsystems not exceeding the order, and designs virtual control to achieve global stability.

In the traditional method, the fastest form of convergence of the closed-loop system is exponential stability, and many problems in the backstepping method are discussed in the case where the closed-loop system satisfies the Lipschitz continuity and achieves gradual stability. The control results obtained in infinite time are not satisfied. Practical needs, and finite time stability are equivalent to the quantification of traditional control results. From the perspective of time optimization, the performance of the control system is analyzed, so that the closed-loop system's limited time convergence control method is the time-optimal control method [6] [7] [8]. In [9], a time-limited controller was developed by introducing an integral sliding mode manifold. The combination of non-singular fast terminal sliding mode control and backstepping control achieves finite time convergence. However, in finite-time control, the convergence time depends largely on the initial conditions of the system under consideration. At the same time, as the initial value changes, the convergence time may tend to be infinite, and in actual life many initial values cannot be obtained in advance, which limits the practical application. Therefore, fixed-time control occurs in actual demand. Fixed-time control can provide transition time independent of the operating domain and maintain convergence time without readjusting control parameters.

Polyakov *et al.* [10] first introduced fixed-time stability, and the upper bound of the convergence time no longer depended on the initial conditions of the system. A fixed-time non-singular terminal sliding mode control scheme with matching lumped disturbances is proposed. In [11], by designing a fixed-time controller to make multiple vehicles reach a fixed-time consistency on their respective scales, a class of multi-scale fixed-time coordinated control problems is realized. In [12], a fixed-time disturbance observer (FTDO) is proposed to deal with actuator dead zones and disturbances.

Based on the above conclusions, this paper solves the design problem of dynamic positioning ship controller under unknown interference, and makes the ship stable in a fixed-time. The main contributions of this article are:

1) Use fixed-time observer (FTXO) to estimate external interference, so that the estimation time is not limited by the initial error.

2) Based on the observer, a fixed-time sliding mode control method based on the Backstepping method is proposed to get rid of the constraints of the initial conditions on the system and achieve the ultimate bounded stability of the system.

2. Problem Formulation and Preliminaries

2.1. Preliminaries

Assume that there is a nonlinear system:

$$\dot{x}(t) = f(x(t)), \quad x(0) = 0, \quad f(0) = 0 \tag{1}$$

where $x = [x_1, x_2, \cdots, x_n]^{\mathrm{T}}$. $f(x)$ is a continuous nonlinear function.

Definition If system $f(x)$ satisfies the following points, the equilibrium $x = 0$ of System (1) is fixed-time stable:

System $f(x)$ it has global finite time stability and $T(x)$ converges to the origin within a finite convergence time;

There is a stable time equation $T(x)$, Guaranteeing $T(x) \le T_{\max}$, where $T_{\max}$ is a constant.

Lemma 1 If there is a Lyapunov function $V(x)$ satisfied $\dot{V}(x) \le -\left(\alpha V(x)^p + \beta V(x)^q\right)^k$, it shows that the origin of the system is stable at a fixed-time, which means that $V(x)$ can converge to $V(x) = 0$ in a fixed time based on any initial value. The convergence time boundary is:

$$T \le \frac{1}{\alpha(1-p)} + \frac{1}{\beta(q-1)} \tag{2}$$

where α, β, p, q are positive constant, and $0 < p < 1, q > 1$.

Lemma 2 For any nonnegative real constants $[x_1, x_2, \cdots, x_n] \in R$, the following inequality we can holds: $\left(\sum_{i=1}^{n}|x_i|\right)^{\upsilon} \le \sum_{i=1}^{n}|x_i|^{\upsilon}$, where $\upsilon \in R^+, \upsilon \in (0,1]$.

If $\upsilon \in R^+, \upsilon > 1$, and $\left(\sum_{i=1}^{n}|x_i|\right)^{\upsilon} \le n^{\upsilon-1}\sum_{i=1}^{n}|x_i|^{\upsilon}$. (3)

Lemma 3 For arbitrary positive real constants *a*, *b*, and *c* and positive real constants *p* and q satisfying $1/p + 1/q = 1$, the following inequality holds:

$$ab \le c^p \frac{a^p}{p} + c^{-q}\frac{b^q}{q} \tag{4}$$

2.2. Ship Dynamic Positioning Mathematical Model

The ship's motions are described in two right-hand coordinate frames as shown in Figure 1. The earth-fixed frame indicated by $OX_0Y_0Z_0$ is an inertial frame and the ship-fixed frame indicated by $AXYZ$ is a non-inertial frame. The origin O of the earth-fixed frame can be chosen as any point on the earth's surface. The axis OX_0 is directed to the north, the axis OY_0 is directed to the east, and the axis OZ_0 points towards the center of the earth. When the ship is port-starboard symmetric, the origin A of the ship-fixed frame is located at the gravity center of the ship. The axis AX is directed from aft to fore, the axis AY is directed to starboard, and the axis AZ is directed from top to bottom. The planes X_0Y_0 and XY are parallel to the still water surface.

The mathematical model that describes the ship motions in DP mode is

$$\begin{aligned} &\dot{\eta} = R(\psi)\nu \\ &M\dot{\nu} + C(\nu)\nu + D(\nu)\nu = \tau + b \end{aligned} \tag{5}$$

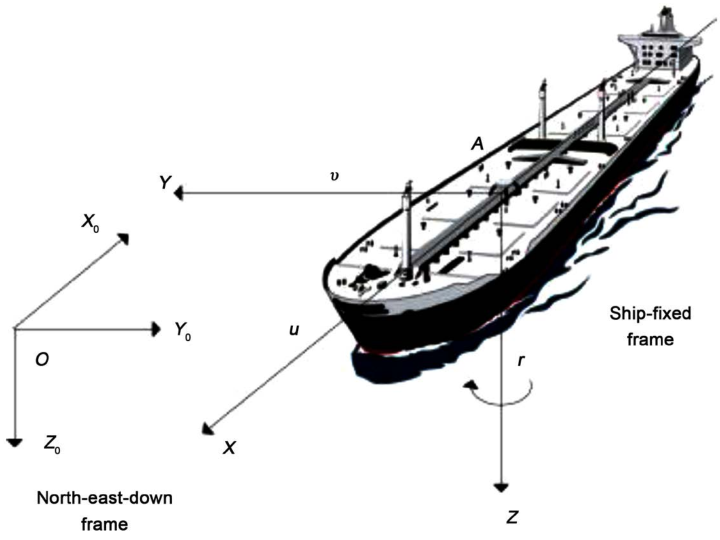

Figure 1. North-east-down frame and ship-fixed frame [13].

$\eta=[x,y,\psi]^{\mathrm{T}}$ represents the ship position vector in the north-east-down frame; $v=[u,v,r]^{\mathrm{T}}$ represents the ship velocity vector in the ship-fixed frame; $\tau=[\tau_1,\tau_2,\tau_3]^{\mathrm{T}}$ and $b=[b_1,b_2,b_3]^{\mathrm{T}}$ respectively represent propeller thrust and external environmental force. $R(\psi)$ is a transformation matrix between coordinate systems. $M(v)$ is mass matrix, $C(v)$ is Coriolis centripetal matrix. $D(v)$ is damping coefficient matrix and the following equalities hold

$$M(v)=\begin{bmatrix} m-X_u & 0 & 0 \\ 0 & m-Y_v & mx_G-Y_r \\ 0 & mx_G-N_v & I_z-N_\tau \end{bmatrix} \tag{6}$$

$$C(v)=\begin{bmatrix} 0 & 0 & -m(x_G+v)+Y_v v+Y_r r \\ 0 & 0 & mu-X_u u \\ m(x_G r+v)-Y_v v-Y_r r & -mu+X_u u & 0 \end{bmatrix}$$

$$D(v)=\begin{bmatrix} -X_u & 0 & 0 \\ 0 & -Y_v & -Y_r \\ 0 & -N_v & -N_r \end{bmatrix}$$

2.3. Formula Conversion

Define dynamic positioning formula:

$$z=R(\psi)v \tag{7}$$

where $z=[z_1,z_2,z_3]^{\mathrm{T}}$.

So the formula can become:

$$\begin{cases} \dot{\eta}=z \\ \dot{z}=R(\psi)M^{-1}\tau+\delta \\ \dot{\eta}_d=z_d \\ \delta=R(\psi)s(r)v-R(\psi)M^{-1}C(v)v-R(\psi)M^{-1}D(v)v+R(\psi)M^{-1}b \end{cases} \tag{8}$$

where δ denotes unknown concentrated interference, and $\eta_d = [x_d, y_d, \psi_d]$ denotes the desired position.

Assume that the concentrated interference δ is continuously differentiable, that satisfies $\|\dot{\delta}\| \le H_n$, H_n is Upper limit constant.

2.4. Design of Fixed-Time State Observer

The fixed-time state observer obtains accurate information of speed and unknown disturbance in a comprehensive manner, so the observer can be designed as:

$$\begin{cases} \dot{\hat{\eta}} = \hat{z} - k_1 sig^{\alpha_1}(\eta - \hat{\eta}) - c_1 sig^{\beta_1}(\eta - \hat{\eta}) \\ \dot{\hat{z}} = R(\psi) M^{-1}\tau + \delta + k_2 sig^{\alpha_2}(\eta - \hat{\eta}) + c_2 sig^{\beta_2}(\eta - \hat{\eta}) \\ \dot{\hat{\delta}} = k_3 sig^{\alpha_3}(\eta - \hat{\eta}) + c_3 sig^{\beta_3}(\eta - \hat{\eta}) + \gamma sign(\eta - \hat{\eta}) \end{cases} \tag{9}$$

where $\hat{\eta}, \hat{z}, \hat{\delta}$ are estimated value, parameter $\alpha_i = i\alpha - (i-1), \beta_i = i\beta - (i-1), i = 1,2,3$. Where $\alpha \in (1-\varepsilon_1, 1), \beta \in (1, 1+\varepsilon_2)$ and $\varepsilon_1, \varepsilon_2$ are sufficiently small positive real number, and $H_n < \gamma$.

The state observer gain is Hurwitz matrix:

$$A = \begin{bmatrix} -k_1 & 1 & 0 \\ -k_2 & 0 & 1 \\ -k_3 & 0 & 0 \end{bmatrix} \tag{10}$$

$$k_1 > 0, k_2 > 0, k_3 > 0$$

The observation error of the observer converges to the origin within a fixed time, and convergence time is:

$$T_i \le \frac{1}{k_{i,1}} \frac{1}{1-\alpha_i} + \frac{1}{k_{i,2}} \frac{1}{1-\beta_i} \tag{11}$$

The resulting estimation error $\tilde{e}_1 = \eta - \hat{\eta}, \tilde{e}_2 = z - \hat{z}$ and $\tilde{e}_3 = \delta - \hat{\delta}$. Following equations hold:

$$\begin{cases} \dot{\tilde{e}}_1 = \tilde{e}_2 - k_1 sig^{\alpha_1}(\eta - \hat{\eta}) - c_1 sig^{\beta_1}(\eta - \hat{\eta}) \\ \dot{\tilde{e}}_2 = \tilde{e}_3 - k_2 sig^{\alpha_2}(\eta - \hat{\eta}) - c_2 sig^{\beta_2}(\eta - \hat{\eta}) \\ \dot{\tilde{e}}_3 = \dot{\delta} - k_3 sig^{\alpha_3}(\eta - \hat{\eta}) - c_3 sig^{\beta_3}(\eta - \hat{\eta}) - \gamma sign(\eta - \hat{\eta}) \end{cases} \tag{12}$$

If there are positive definite matrices P_1 and Q_1 make:

$$A_1^{\mathrm{T}} P_1 + P_1 A_1 = -Q_1 \tag{13}$$

where A_1 is Hurwitz matrix:

$$A_1 = \begin{bmatrix} -k_1 & 1 & 0 \\ -k_2 & 0 & 1 \\ -k_3 & 0 & 0 \end{bmatrix} \tag{14}$$

According to Lemma 1, we can conclude that the error converges to zero within a fixed time, and the boundary time is:

$$T_f = \frac{\lambda_{\max}^{(2-\alpha_i)}(P_1)}{\lambda_{\min}(Q_1)(1-\alpha_i)} + \frac{\lambda_{\min}(P_1)}{\lambda_{\min}(Q_2)(\beta_i - 1)\rho} \tag{15}$$

where ρ is positive and $\rho \le \lambda_{\min}(P_1)$

When $e_i = 0$ happen after T_f, e_i will remain zero. Then you can get $e_1 = \dot{e}_1 = 0, e_2 = e_3 = 0$. In other words, for all values of $t \ge T_1$, there is a upper limit time T_1.

$$\dot{e}_3 = \dot{\delta} - \gamma sign(\eta - \hat{\eta}) = 0, \quad t \ge T_1 \tag{16}$$

In reality, it is impossible to strictly implement $e_3 = 0$ due to defects such as noise, sampling steps, delay and interference. Therefore, a small range of convergence region $e_3|_\tau$ is proposed, Allow to reach the convergence area e_3 in a short time.

$$T_d = \frac{e_3|_\tau}{\gamma - H_n} \tag{17}$$

Therefore, the upper bound of the convergence time $T_u = T_f + T_d$ of the fixed-time extended state observer is obtained, completing the proof of the theorem.

3. Design of Fixed-Time Sliding Mode Controller with Backstepping

3.1. Controller Design

Using backstepping technology to solve the system status tracking problem, the design is as follows:

Make $s_1 = \eta - \eta_d$, therefore

$$s_1 = \dot{\eta} - \dot{\eta}_d = z - \dot{\eta}_d \tag{18}$$

Designing the virtual control rate:

$$z^* = -k_1 sig(s_1)^p - c_1 sig(s_1)^q + \hat{z} \tag{19}$$

where p, q, k_1 and c_1 are designing parameters.

We can get

$$s_2 = z - z^*. \tag{20}$$

Because $\dot{s}_2 = R(\psi) M^{-1}\tau + \delta - \dot{z}^*$, we can design control input:

$$\tau = \left(-k_2 sig(s_2)^p - c_2 sig(s_2)^q + \dot{z}^* - s_1 - \hat{\delta}\right) R(\psi)^{-1} M \tag{21}$$

where k_2, c_2 designing parameters.

The system can be summarized as follows:

$$\begin{cases} \dot{s}_1 = -k_1 sig(s_1)^p - c_1 sig(s_1)^q + s_2 + \hat{z} - \dot{\eta}_d \\ \dot{s}_2 = -k_2 sig(s_2)^p - c_2 sig(s_2)^q + \delta - s_1 - \hat{\delta} \end{cases} \tag{22}$$

As shown in the structural design shown in Figure 2, the impact of unknown interference on the ship is clearly reflected.

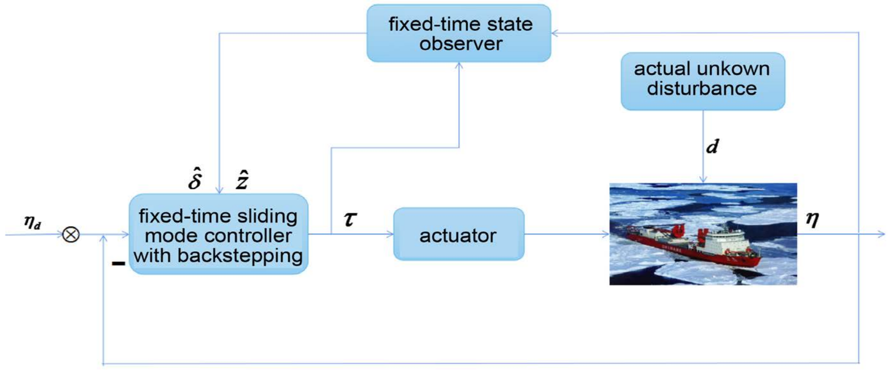

Figure 2. Controller structure of the dynamic positioning.

3.2. Stability Analysis

System Lyapunov function $V = \frac{1}{2}s_1^2 + \frac{1}{2}s_2^2$.

We have:

$$\begin{aligned}\dot{V} &= s_1\dot{s}_1 + s_2\dot{s}_2 \\ &= -\left(k_1|s_1|^{p+1} + c_1|s_1|^{q+1}\right) - \left(k_2|s_2|^{p+1} + c_2|s_2|^{q+1}\right) + s_1\left(\hat{z} - \dot{\eta}_d\right) + s_2\left(\delta - \hat{\delta}\right) \\ &\le -\left(k_1|s_1|^{p+1} + c_1|s_1|^{q+1}\right) - \left(k_2|s_2|^{p+1} + c_2|s_2|^{q+1}\right) + |s_1||\hat{z} - \dot{\eta}_d| + |s_2||\delta - \hat{\delta}|\end{aligned} \quad (23)$$

According to the lemma 3:

$$\begin{cases}|s_1||\hat{z} - \dot{\eta}_d| \le l^{p+1}\dfrac{s_1^{p+1}}{p+1} + l^{-(q+1)}\dfrac{|\hat{z} - \dot{\eta}_d|^{q+1}}{q+1} \\ |s_2||\delta - \hat{\delta}| \le h^{p+1}\dfrac{s_2^{p+1}}{p+1} + h^{-(q+1)}\dfrac{|\delta - \hat{\delta}|^{q+1}}{q+1}\end{cases} \quad (24)$$

where $H > 0$ Represents the upper limit of $|\dot{z}^*|$.

From the above formula:

$$\begin{aligned}\dot{V} \le &-\left(k_1 - \frac{l^{p+1}}{p+1}\right)|s_1|^{p+1} - c_1|s_1|^{q+1} - \left(k_2 - \frac{h^{p+1}}{p+1}\right)|s_2|^{p+1} - c_2|s_2|^{q+1} \\ &+ \frac{l^{-(q+1)}}{q+1}|\hat{z} - \dot{\eta}_d|^{q+1} + \frac{h^{-(q+1)}}{q+1}|\delta - \hat{\delta}|^{q+1}\end{aligned} \quad (25)$$

Choosing design parameters such that

$$k_1 > \frac{l^{p+1}}{p+1},\ c_1 > 0,\ k_2 > \frac{h^{p+1}}{p+1},\ c_2 > 0. \quad (26)$$

According to the lemma 4:

$$\begin{aligned}\dot{V} &\le -\zeta_1\left(|s_1|^{p+1} + |s_2|^{p+1}\right) - \zeta_2\left(|s_1|^{q+1} + |s_2|^{q+1}\right) + \zeta_3 \\ &= -\zeta_1\left(|s_1^2|^{\frac{p+1}{2}} + |s_2^2|^{\frac{p+1}{2}}\right) - \zeta_2\left(|s_1^2|^{\frac{q+1}{2}} + |s_2^2|^{\frac{q+1}{2}}\right) + \zeta_3 \\ &\le -3^{\frac{1-p}{2}}V^{\frac{p+1}{2}} - 3^{\frac{1-q}{2}}V^{\frac{q+1}{2}} + \zeta_3\end{aligned} \quad (27)$$

where

$$\begin{cases} \zeta_1 = \min\left\{\left(k_1 - \dfrac{l^{p+1}}{p+1}\right), \left(k_2 - \dfrac{h^{p+1}}{p+1}\right)\right\} \\ \zeta_2 = \min\{c_1, c_2\} \\ \zeta_3 = \dfrac{l^{-(q+1)}}{q+1}\left|\hat{z} - \dot{\eta}_d\right|^{q+1} + \dfrac{h^{-(q+1)}}{q+1}\left|\delta - \hat{\delta}\right|^{q+1} \end{cases} \tag{28}$$

Because the global scope of $\left|\hat{z} - \dot{\eta}_d\right|$ and $\left|\delta - \hat{\delta}\right|$ are bounded, ζ_3 is bounded, so:

$$\dot{V} \le -3^{\frac{1-p}{2}} V^{\frac{p+1}{2}} - 3^{\frac{1-q}{2}} V^{\frac{q+1}{2}} + \zeta_3 \tag{29}$$

For all $t \ge \max\{T_1, T_2\}$ cases, the limit range of the system can be calculated:

$$-3^{\frac{1-p}{2}} V^{\frac{p+1}{2}} - 3^{\frac{1-q}{2}} V^{\frac{q+1}{2}} + \zeta_3 = 0 \tag{30}$$

So we can get the equations:

$$\begin{cases} -3^{\frac{1-p}{2}} V^{\frac{p+1}{2}} + \dfrac{\zeta_3}{2} = 0 \\ -3^{\frac{1-q}{2}} V^{\frac{q+1}{2}} + \dfrac{\zeta_3}{2} = 0 \end{cases} \tag{31}$$

We have:

$$\lim_{t\to\infty} V(t) \le 2\min\left\{\left(\frac{\zeta_3}{2\times 3^{\frac{1-p}{2}}}\right)^{\frac{2}{1-p}}, \left(\frac{\zeta_3}{2\times 3^{\frac{1-q}{2}}}\right)^{\frac{2}{1-q}}\right\} \tag{32}$$

$$T_3 \le \frac{1}{3^{\frac{1-p}{2}}\left(\dfrac{p-1}{2}\right)} + \frac{1}{3^{\frac{1-q}{2}}\left(\dfrac{q-1}{2}\right)}$$

Because of the fixed-time observer, all state errors are limited and the formulas show that $\left|\hat{z} - \dot{\eta}_d\right|$ and $\left|\delta - \hat{\delta}\right|$ can converge to zero in finite times T_1 and T_2. Therefore, the final settling time of the system is $T = \max\{T_1, T_2, T_3\}$.

4. Simulation

In order to verify the effect of the controller under unknown interference and the accuracy of estimation of external interference, assuming the initial position of the ship, $\eta(0) = [0\text{ m}, 0\text{ m}, 0\text{ rad}]^{\mathrm{T}}$, $v(0) = [0\text{ m/s}, 0\text{ m/s}, 0\text{ rad/s}]$, desired position $\eta_d = [10\text{ m}, 20\text{ m}, \pi/3\text{ rad}]^{\mathrm{T}}$, observer parameter selection: $k_2 = c_2 = 216$, $k_3 = c_3 = 864$. $\alpha_1 = 0.8$, $\alpha_2 = 0.6$, $\alpha_3 = 0.6$, $\beta_1 = 1.2$, $\beta_2 = 1.4$, $\beta_3 = 1.6$. The controller parameters are: $p = \dfrac{1}{q} = 9/5$, $k_1 = c_1 = 50$, $k_2 = c_2 = 25$.

External interference is: $d = \begin{bmatrix} 1.1 + 2\sin(0.05t) + 1.3\sin(0.1t) \\ -0.5 + 1.6\sin(0.03t) + 2.1\cos(0.02t) \\ 4\sin(0.06t) - 3\sin(0.04t) \end{bmatrix}$, and includes white noise in the range [−0.5, 0.5].

In **Figure 3** and **Figure 4**, the ship's tracking to the target position under unknown interference and the actual interference under white noise interference are shown.

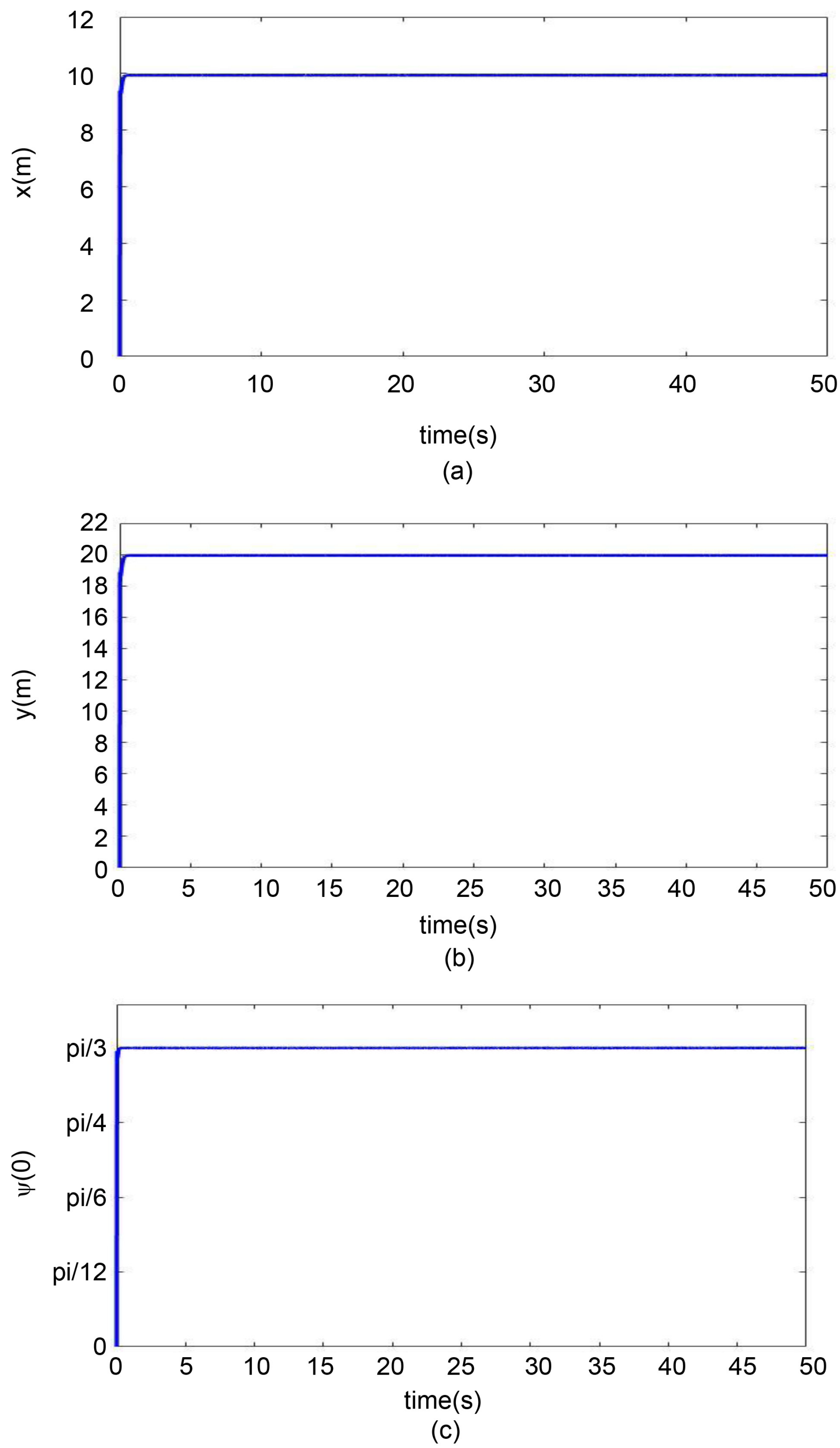

Figure 3. Ship's desired position η_d

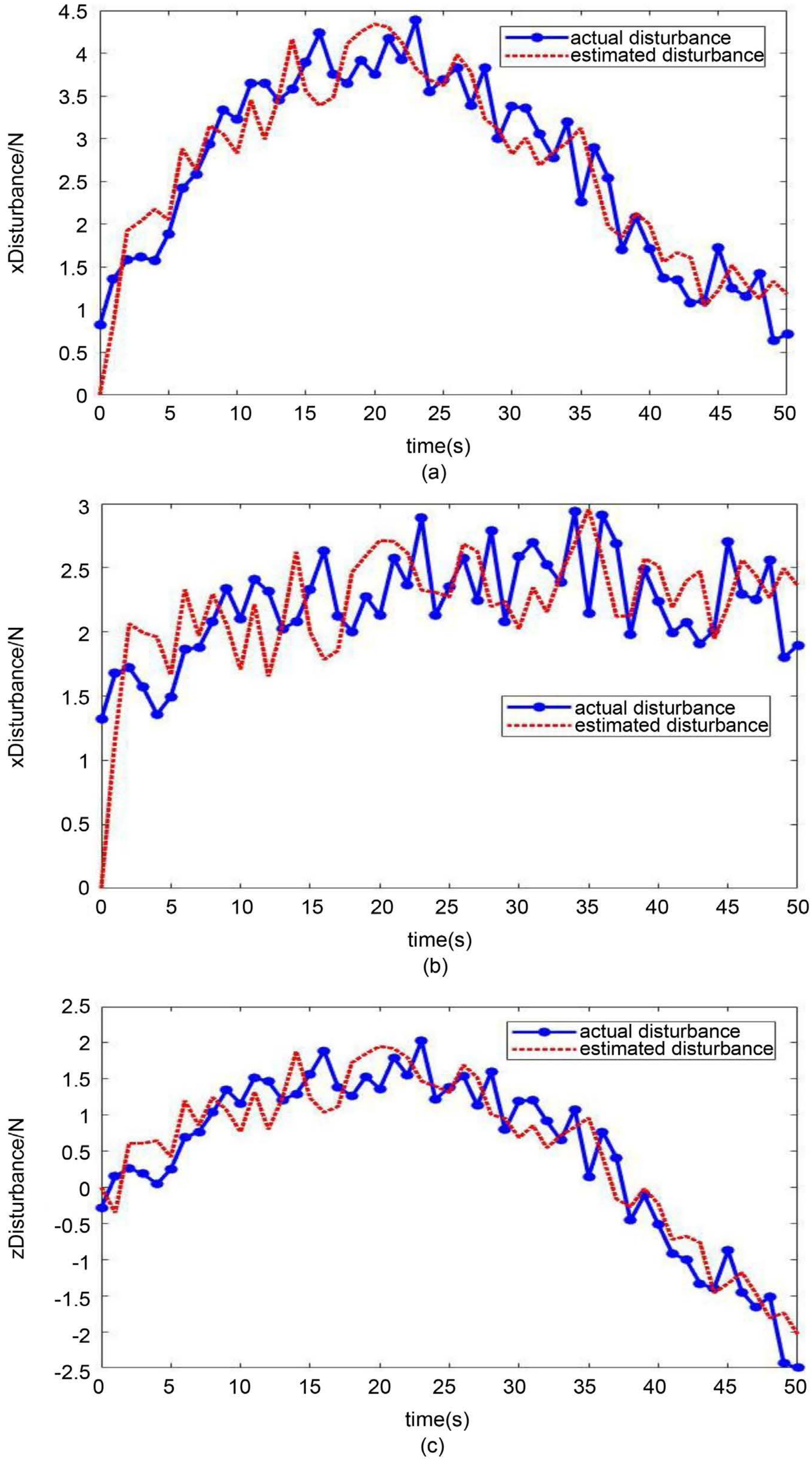

Figure 4. Estimated and actual values of external interference.

5. Conclusion

This paper studies the problem of dynamic positioning control with unknown external disturbances. The conclusion shows that using a fixed-time observer to estimate the unknown disturbance force outside the ship can help improve the accuracy and response speed of the ship control, and make the ship control stable in a short time. In the future, further research can be conducted on the basis of under drive.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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