Indian Journal of Geo Marine Sciences
Vol. 50 (11), November 2021, pp. 930-937

Dynamic positioning of ship using backstepping controller with nonlinear disturbance observer

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Received 31 August 2021; revised 30 November 2021

This paper studies the adaptive dynamic positioning control problem of the full-actuated ship with uncertain time-varying environmental disturbances. Considering the disturbances with unknown boundaries, the inversion control technique is combined with the disturbance observation compensation method to design the robust adaptive backstepping control law of the ship dynamic positioning system. The Lyapunov function is adopted to prove the errors of the ship's position and heading angle are uniformly ultimately bounded using the designed control law. The nonlinear disturbance observer can adaptively estimate and compensate for uncertain external disturbances caused by winds, waves and currents. Afterward, the verification of the proposed controller through a typical CyberShip II model subject to environmental disturbances is carried out using a hardware-in-the-loop simulation where a thrust distribution model is established. The simulation results show the effectiveness of the proposed control law.

[**Keywords**: Adaptive backstepping control, Dynamic positioning, Hardware-in-the-loop simulation, Nonlinear disturbance observer, Robust nonlinear control]

Introduction

Different from the traditional mooring system, the Dynamic Positioning (DP) system is capable of maintaining the ship at a certain position and angle under the interference of time-varying external disturbances (such as winds, waves and currents)[1].

The DP system has a variety of advantages such as low positioning cost, good maneuverability, easy operation and high control accuracy. It is widely used on offshore oil drilling platforms, salvage and rescue ships, engineering supply ships, firefighting ships and other marine ships[2]. The DP system plays an important role in maintaining normal operation of the floating platform and other marine vehicles. With the continuous expansion of ocean development to the deep sea[3-4], dynamic positioning technology has more and more important practical significance for ocean development and has received widespread attention[5].

As early as the 1960s, related research on ship dynamic positioning systems has already begun. The PID controller was used in the initial dynamic positioning system, which has achieved considerable success and has been used as a classic dynamic positioning system controller ever since[6]. Then came the advanced controller design based on modern control theory, which is based on the combination of multivariable linear optimal control and Kalman filter theory[7]. Since the ship's dynamic positioning system is a highly coupled complex nonlinear system, the Kalman filter needs to linearize the ship's nonlinear motion equation at each operating point, which can only prove the local stability of the system and the parameters adjustment workload is large. Moreover, it is difficult to ensure the control performance using this linear control methods[8-9]. Therefore, the design of the ship dynamic positioning controller based on the linear model can no longer meet the requirements of today's ship positioning performance.

Later, a larger number of scholars began to study intelligent control theories and methods, such as fuzzy control[10-11], reinforcement learning[12], bionic algorithms[13], optimized control[14], model predictive control[15-16], neural network control[17-18], etc., making the control of ship dynamic positioning systems tend to be intelligent and adaptive. However, the fuzzy control rules are formulated based on human intuition and experience. The "knowledge" of fuzzy logic control is provided by experts[19]. It lacks effective learning algorithms and adaptive capabilities. Simple fuzzy processing will reduce the control accuracy of the system. The dynamic quality deteriorates, and its robustness and stability are difficult to guarantee. The learning capabilities of neural networks, genetic algorithms, and reinforcement learning require sample data, and the learning process is time-consuming and difficult to apply to engineering practice[20].

Therefore, in order to avoid the problems caused by the above methods, Morishita[21] proposed a nonlinear backstepping method for ship dynamic positioning based on an adaptive observer, but it uses a simplified model, which only considers the system measurement noise without considering the environmental disturbances, and there is no hardware-in-the-loop simulation or actual ship verification.

This paper firstly presents a nonlinear observer and proves that the observer is capable of estimating then unknown external disturbances through Lyapunov stability theory. Then, using the filtered position signal, an observer-based adaptive backstepping controller is developed to achieve dynamic positioning control of a ship subject to input saturation and external disturbances. The stability of the closed-loop system is confirmed through Lyapunov theory. In addition, hardware-in-the-loop experiments are carried out to verify the performance of the proposed control scheme.

Materials and Methods

Ship modeling and problem statement

For dynamic positioning ships, it assumes that the ship is symmetrical about the X-Z plane. Meanwhile, forward, lateral drift and bowing motions are decoupled, thus, the influence of the ship's heave, roll and pitch motions and their coupling effect on other directions of motion are ignored. The forward, horizontal drift and bow motion of the ship are considered as three degrees of freedom of the horizontal plane. A reference coordinate system is established for ship motion as shown in Figure 1, where $\{I\}$ is the geodetic coordinate system, $\{B\}$ is the ship-mounted coordinate system, and the origin of the ship-mounted coordinate system is at the center of gravity of the ship[22].

The position of the ship and the heading angle are defined in the geodetic coordinate system, where x and y are the lateral and longitudinal positions of the ship, respectively, and ψ is the heading angle. The velocity vector $v=[u,\upsilon,r]^T$ in the ship coordinate

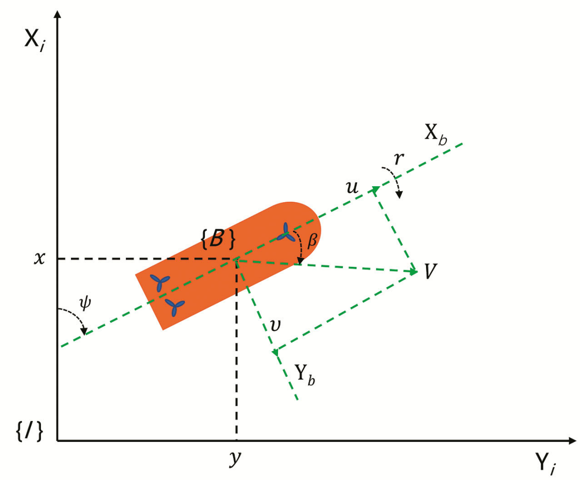

Fig. 1 — Coordinate system of ship motion

system $\{B\}$ is defined in the way of ship's forward speed u, the lateral drift speed υ and the heading angular velocity r. Considering the low speed of the ship during dynamic positioning, the coriolis and centripetal force matrix C can be ignored. Therefore, the nonlinear mathematical model of a dynamically positioned ship is usually described as[23-25].

$$\dot{\eta} = R(\psi)v \quad \ldots (1)$$

$$M\dot{v} = B\tau_c - D(v)v + d \quad \ldots (2)$$

In the equation, R is the rotation matrix, which is defined as:

$$R(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \ldots (3)$$

And satisfy the characteristic $R^{-1}(\psi) = R^T(\psi)$. B is the thrust distribution matrix[26], which is defined as:

$$B = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 0 & 1 \\ |l_{yT_1}| & -|l_{yT_2}| & |l_{xT_3}| \end{bmatrix} \quad \ldots (4)$$

M is the inertia matrix, which is a reversible positive definite symmetric matrix. Considering that the main diagonal terms have dominant effects, the asymmetric terms can be ignored. Specifically, M is defined as:

$$M = \begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & 0 \\ 0 & 0 & m_{33} \end{bmatrix} \quad \ldots (5)$$

Where, $m_{11} = m - X_{\dot{u}}$, $m_{22} = m - Y_{\dot{\upsilon}}$, $m_{33} = I_Z - N_{\dot{r}}$. D is the linear damping matrix, which can be expressed as follows:

$$D(v) = -\begin{bmatrix} d11 & 0 & 0 \\ 0 & d22 & 0 \\ 0 & 0 & d33 \end{bmatrix} \quad \ldots (6)$$

Where, $d_{11} = X_u$, $d_{22} = Y_\upsilon$, $d_{33} = N_r$. $\tau_c = [\tau_{c1}, \tau_{c2}, \tau_{c3}]^T$ is the control input vector, which is composed of the left stern control force τ_{c1}, the stern right control force τ_{c2}, and the bow control force τ_{c3}, $d = [d_1, d_2, d_3]^T \in R^3$ is an unknown disturbance term, which represents environmental factors such as winds, waves, and currents.

The control goal of this paper is to design an adaptive control law τ_c for system (1) and (2), so that the actual position of the ship and the heading angle $\eta = [x, y, \psi]^T$ can arrive and remain at the desired position $\eta_d = [x_d, y_d, \psi_d]^T$.

Design of nonlinear disturbance observer

To address the adverse effect resulted from unknown external disturbances, in this paper, the nonlinear observer is adopted to achieve disturbance attenuation. The mathematical form of the observer is given as follows[27]:

$$\hat{d} = q + K_0 M v \quad \ldots (7)$$

$$\dot{q} = -K_0 q - K_0(-Dv + B\tau_c + K_0 M v) \quad \ldots (8)$$

In the above equation, $\hat{d} \in R^3$, is the estimated vector of d, $q \in R^3$ is the auxiliary vector of the disturbance observer, and $K_0 = K_0^{\ T} \in R^{3\times3}$ is the positive definite design matrix. The disturbance estimation error vector $\tilde{d} \in R^3$ of the disturbance observer is defined as:

$$\tilde{d} = \hat{d} - d \quad \ldots (9)$$

From equations 2, 7 and 8, it renders

$$\begin{aligned} \dot{\tilde{d}} &= \dot{\hat{d}} - \dot{d} \\ &= \dot{q} + K_0 M \dot{v} - \dot{d} \\ &= -K_0 q - K_0(-Dv + B\tau_c + K_0 M v) \\ &\quad + K_0(-Dv + B\tau_c + d) - \dot{d} \\ &= -K_0(q + K_0 M v - d) - \dot{d} \\ &= -K_0 \tilde{d} - \dot{d} \end{aligned} \quad \ldots (10)$$

To carry stability analysis of this observer, the Lyapunov function is selected as $V_o = \frac{1}{2}\tilde{d}^T\tilde{d}$. According to equation 10 and Young's inequality[28], the time derivative can be computed as:

$$\begin{aligned} \dot{V}_o &= \tilde{d}^T(-K_0\tilde{d} - \dot{d}) \\ &\le -\tilde{d}^T K_0 \tilde{d} + \frac{1}{2}\tilde{d}^T\tilde{d} + \frac{1}{2}\rho^2 \\ &= -2\alpha V_o + C \end{aligned} \quad \ldots (11)$$

In equation 11, $\alpha = \lambda_{\min}(K_0) - \frac{1}{2}$ and $C = \frac{1}{2}\rho^2$ (ρ is unknown constant, which is the upper bounding of the first time-derivative of the slow time-varying disturbance). Obviously $C \ge 0$ is always valid. If the design matrix K_0 satisfies $\lambda_{\min}(K_0) > \frac{1}{2}$, then V_o is uniformly ultimately bounded, and we know that $\|\tilde{d}\|$ is also uniformly ultimately bounded, which can ensure the convergence of the observation error.

Design of robust DP controller based on nonlinear observer

In this section, under the backstepping design framework, the robust controller will be developed with the aid of the nonlinear disturbance observer mentioned in the previous section. First, the position error vector is defined as $z_1 = \eta - \eta_d$, the first Lyapunov function is selected as $V_1 = \frac{1}{2}z_1^T z_1$, whose derivative can be calculated as follows:

$$\dot{V}_1 = z_1^T \dot{z}_1 = z_1^T J(\psi) v \quad \ldots (12)$$

Then, the virtual control law can be selected as:

$$\phi = -J^{-1}(\psi) K_1 z_1 \quad \ldots (13)$$

Where, $K_1 \in R^{3\times3}$ is the positive definite diagonal matrix to be designed. Then the error of the velocity variable is defined as $z_2 = v - \phi$, and the second Lyapunov function $V_2 = \frac{1}{2}z_2^T M z_2$ can be selected. In the light of the ship's dynamic equation, the second Lyapunov function can be calculated as:

$$\begin{aligned} \dot{V}_2 &= z_2^T M \dot{z}_2 \\ &= z_2^T\left(-Dv + d + B\tau_c - M\dot{\phi}\right) \end{aligned} \quad \ldots (14)$$

By virtue of the nonlinear observer, the robust control law can be selected as follows:

$$\tau_c = B^{-1}(-K_2 z_2 + Dv - \hat{d} + M\dot{\phi}) \quad \ldots (15)$$

At this time, the final Lyapunov function can be selected as $V = V_1 + V_2 + \frac{1}{2}\tilde{d}^T\tilde{d}$. Differentiating the final Lyapunov function with respect to time yields, one has

$$\begin{aligned}\dot{V} &= z_1^T\dot{z}_1 + z_2^T M\dot{z}_2 + \tilde{d}^T\dot{\tilde{d}} \\ &\le z_1^T J(\psi)(z_2+\phi) \\ &\quad + z_2^T(-Dv + d + B\tau_c - M\dot{\phi}) \\ &\quad - \tilde{d}^T K_0\tilde{d} + \frac{1}{2}\tilde{d}^T\tilde{d} + \frac{1}{2}\rho^2\end{aligned} \quad \ldots (16)$$

Substituting the virtual control law and equation 15 into 16, we can get

$$\begin{aligned}\dot{V} &\le -z_1^T K_1 z_1 + z_1^T J(\psi) z_2 \\ &\quad - z_2^T K_2 z_2 - z_2^T\tilde{d} - \tilde{d}^T K_0\tilde{d} \\ &\quad + \frac{1}{2}\tilde{d}^T\tilde{d} + \frac{1}{2}\rho^2\end{aligned} \quad \ldots (17)$$

Furthermore, based on Young's inequality, we have

$$\begin{aligned}\dot{V} &\le -z_1^T\left(K_1 - \frac{1}{2}I\right)z_1 - z_2^T(K_2 - I)z_2 \\ &\quad - \tilde{d}^T(K_0 - I)\tilde{d} + \frac{1}{2}\rho^2 \\ &\le -2\mu V + C\end{aligned} \quad \ldots (18)$$

Where,

$$\begin{aligned}\mu &= \min\left\{\lambda_{\min}\left(K_1 - \frac{1}{2}I\right),\right. \\ &\quad \left.\lambda_{\min}\left((K_2 - I)M^{-1}\right), \lambda_{\min}(K_0 - I)\right\} \\ C &= \max\left\{\frac{1}{2}\rho^2\right\}\end{aligned} \quad \ldots (19)$$

After solving the above in equality, we have the following result

$$0 \le V \le \frac{C}{2\mu} + \left[V(0) - \frac{C}{2\mu}\right]e^{-2\mu t} \quad \ldots (20)$$

It can be seen that for all bounded initial conditions, V is uniformly ultimately bounded. Moreover, since $V = \frac{1}{2}z_1^T z_1 + \frac{1}{2}z_1^T M z_1 \frac{1}{2}\tilde{d}^T\tilde{d}$, it is known that $\|z_1\|$, $\|z_2\|$ and $\|\tilde{d}\|$ are uniformly ultimately bounded. Furthermore, we can obtain that all signals in the closed-loop system are uniformly ultimately bounded.

Design of input saturation robust DP controller based on nonlinear observer

Considering that the ship's propulsion system can only provide limited thrust. Hence, when the given command is too large, there will be a deviation $\Delta\tau$ between actual control input and control command. The calculated control command is defined as τ_c, and the actual control input that can be provided is τ_p. The relationship between them can be expressed as follows[29]:

$$\tau_p = \tau_c + \Delta\tau \quad \ldots (21)$$

Where, τ_p can be more specifically defined as the following saturation constraint form

$$\tau_{pi} = sat(\tau_{ci}) = \begin{cases}\tau_{ci}, & |\tau_{ci}| \le \tau_{Mi} \\ \tau_{Mi}, & |\tau_{ci}| > \tau_{Mi}\end{cases} \quad \ldots (22)$$

In the equation, τ_{Mi} is the maximum available force/torque of the actuator.

Considering the dynamic model of actuator saturation, the equation 2 can be reformulated as

$$M\dot{v} = -D(v)v + B\tau_c + B\Delta\tau + d \quad \ldots (23)$$

The adaptive law of the disturbance observer is modified to

$$\begin{aligned}\hat{d} &= q + K_0 M v \\ \dot{q} &= -K_0 q - K_0(-Dv + B\tau_p + K_0 M v)\end{aligned} \quad \ldots (24)$$

Considering that the unknown deviation $\Delta\tau$ will adversely affect the stability of the system, and even make the system unstable in severe cases, we need to seek proper solution deal with it. In this paper, the following fuzzy system is used to approximate it

$$B\Delta\tau = \omega^{*T}\xi(e) + \varepsilon \quad \ldots (25)$$

Where, ε is the bounded approximation error, ω^* is the ideal weight, and $\xi(e)$ is the bounded Gaussian function. Define the optimal estimation weight as $\hat{\omega}$ and the estimation error as $\tilde{\omega} = \hat{\omega} - \omega^*$. The adaptive update law for fuzzy weight can be given as follows:

$$\dot{\hat{\omega}}_i = \gamma_{\omega i}(z_{2i}\xi - K_3\hat{\omega}_i) \quad \ldots (26)$$

The robust control law can be re-selected as follows:

$$\tau_p = B^{-1}(-k_2 z_2 + Dv - \hat{d} + M\dot{\phi} - \hat{\omega}^T \xi - \hat{\varepsilon}) \quad \ldots (27)$$

In the equation, $\hat{\varepsilon}$ is the adaptive term introduced in order to eliminate the influence of the approximation error, the adaptive error is $\tilde{\varepsilon} = \hat{\varepsilon} - \varepsilon$, and the adaptive law is as follows:

$$\dot{\hat{\varepsilon}} = \gamma_\varepsilon \left(z_2 - K_4 \hat{\varepsilon} \right) \quad \ldots (28)$$

Choose the Lyapunov function as

$$\begin{aligned} V_s &= V_1 + V_2 + \frac{1}{2}\tilde{d}^T \tilde{d} \\ &+ \frac{1}{2}\sum_{i=1}^{3} \tilde{\omega}_i^T \gamma_{\omega i}^{-1} \tilde{\omega}_i \\ &+ \frac{1}{2}\tilde{\varepsilon}^T \gamma_\varepsilon^{-1} \tilde{\varepsilon} \end{aligned} \quad \ldots (29)$$

The time derivative of this function can be calculated as follows:

$$\begin{aligned} \dot{V}_s &= z_1^T \dot{z}_1 + z_2^T M \dot{z}_2 + \tilde{d}^T \dot{\tilde{d}} \\ &+ \sum \tilde{\omega}^T \gamma_\omega^{-1} \dot{\hat{\omega}} + \frac{1}{2}\tilde{\varepsilon}^T \gamma_\varepsilon^{-1} \dot{\hat{\varepsilon}} \\ &\le z_1^T J(\psi)(z_2 + \phi) \\ &+ z_2^T \left(-Dv + d + B\tau_p - M\dot{\phi} \right) \\ &- \tilde{d}^T K_0 \tilde{d} + \frac{1}{2}\tilde{d}^T \tilde{d} + \frac{1}{2}\rho^2 \\ &+ \sum_{i=1}^{3} \tilde{\omega}_i^T \gamma_{\omega i}^{-1} \dot{\hat{\omega}}_i + \tilde{\varepsilon}^T \gamma_\varepsilon^{-1} \dot{\hat{\varepsilon}} \end{aligned} \quad \ldots (30)$$

Substituting the virtual control law and equation 27 into the above inequality, we can get

$$\begin{aligned} \dot{V}_s &\le -z_1^T \left(K_1 - \frac{1}{2}I \right) z_1 - z_2^T (K_2 - I) z_2 \\ &- \tilde{d}^T (K_0 - I)\tilde{d} + \frac{1}{2}\rho^2 \\ &+ z_2^T \left(\omega^{*T}\xi + \varepsilon - \hat{\omega}^T \xi - \hat{\varepsilon} \right) \\ &+ \sum_{i=1}^{3} \tilde{\omega}_i^T \gamma_{\omega i}^{-1} \dot{\hat{\omega}}_i + \tilde{\varepsilon}^T \gamma_\varepsilon^{-1} \dot{\hat{\varepsilon}} \\ &\le -z_1^T \left(K_1 - \frac{1}{2}I \right) z_1 - z_2^T (K_2 - I) z_2 \\ &- \tilde{d}^T (K_0 - I)\tilde{d} \\ &+ \frac{1}{2}\rho^2 + \sum_{i=1}^{3} \tilde{\omega}_i^T \left(\gamma_{\omega i}^{-1} \dot{\hat{\omega}}_i - z_{2i}\xi \right) \\ &+ \tilde{\varepsilon}^T \left(\gamma_\varepsilon^{-1} \dot{\hat{\varepsilon}} - z_2 \right) \end{aligned} \quad \ldots (31)$$

Substituting the adaptive law into the above inequality yields, we have

$$\begin{aligned} \dot{V}_s &\le -z_1^T \left(K_1 - \frac{1}{2}I \right) z_1 - z_2^T (K_2 - I) z_2 \\ &- \tilde{d}^T (K_0 - I)\tilde{d} + \frac{1}{2}\rho^2 \\ &- \sum_{i=1}^{3} \tilde{\omega}_i^T K_{3i} \hat{\omega}_i - \tilde{\varepsilon}^T K_4 \hat{\varepsilon} \end{aligned} \quad \ldots (32)$$

From Young's inequality and the definition of $\tilde{\omega}_i^T$ and $\tilde{\varepsilon}^T$, we have

$$\begin{aligned} &-\sum_{i=1}^{3} \tilde{\omega}_i^T K_{3i} \hat{\omega}_i \\ &= -\sum_{i=1}^{3} \tilde{\omega}_i^T K_{3i} \left(\tilde{\omega}_i + \omega_i^* \right) \\ &\le -\frac{1}{2}\sum_{i=1}^{3} \tilde{\omega}_i^T K_{3i} \tilde{\omega}_i + \frac{1}{2}\sum_{i=1}^{3} \omega_i^{*T} K_{3i} \omega_i^* \end{aligned} \quad \ldots (33)$$

$$\begin{aligned} -\tilde{\varepsilon}^T K_4 \hat{\varepsilon} &= -\tilde{\varepsilon}^T K_4 \left(\tilde{\varepsilon} + \varepsilon \right) \\ &\le -\frac{1}{2}\tilde{\varepsilon}^T K_4 \tilde{\varepsilon} + \frac{1}{2}\varepsilon^T K_4 \varepsilon \end{aligned} \quad \ldots (34)$$

In the light of inequalities 33 and 34, inequality 32 can be reformulated as

$$\begin{aligned} \dot{V}_s &\le -z_1^T \left(K_1 - \frac{1}{2}I \right) z_1 - z_2^T (K_2 - I) z_2 \\ &- \tilde{d}^T (K_0 - I)\tilde{d} + \frac{1}{2}\rho^2 \\ &- \frac{1}{2}\sum_{i=1}^{3} \tilde{\omega}_i^T K_{3i} \tilde{\omega}_i + \frac{1}{2}\sum_{i=1}^{3} \omega_i^{*T} K_{3i} \omega_i^* \\ &- \frac{1}{2}\tilde{\varepsilon}^T K_4 \tilde{\varepsilon} + \frac{1}{2}\varepsilon^T K_4 \varepsilon \\ &\le -2\mu V_s + C \end{aligned} \quad \ldots (35)$$

Where,

$$\begin{aligned} \mu = \min\Big\{ &\lambda_{\min}\left(K_1 - \frac{1}{2}I \right), \\ &\lambda_{\min}\left((K_2 - I)M^{-1} \right), \lambda_{\min}(K_0 - I) \\ &\lambda_{\min}(\gamma_{\omega i} K_{3i}), \lambda_{\min}(\gamma_\varepsilon K_4) \Big\} \end{aligned} \quad \ldots (36)$$

$$\begin{aligned} C = \max\Big\{ &\frac{1}{2}\rho^2 + \frac{1}{2}\sum_{i=1}^{3} \omega_i^{*T} K_{3i} \omega_i^* \\ &+ \frac{1}{2}\varepsilon^T K_4 \varepsilon \Big\} \end{aligned} \quad \ldots (37)$$

Analyzing the above inequality, one has

$$0 \le V_s \le \frac{C}{2\mu} + \left[V_s(0) - \frac{C}{2\mu} \right] e^{-2\mu t} \quad \ldots (38)$$

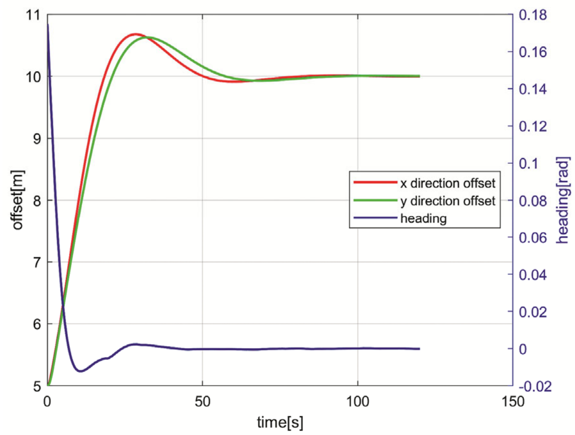

Fig. 2 — Dynamic positioning offsets

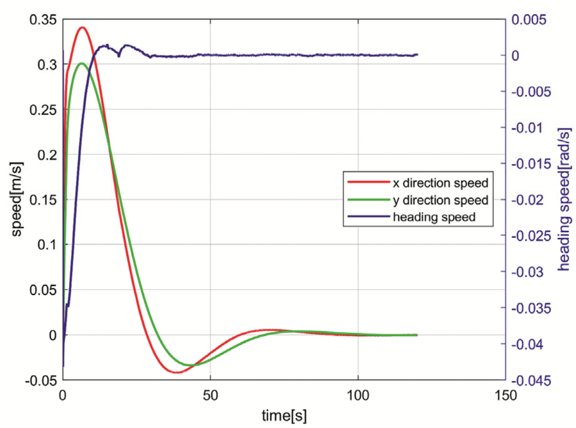

Fig. 3 — Ship speed

It can be seen that all signals in the closed-loop system are uniformly ultimately bounded.

Hardware-in-the-loop simulation and analysis

This paper takes a typical CyberShip II ship model as a simulation example to verify the performance of the designed observer-based robust dynamic positioning controller. The mass of the experimental ship is m = 23.8 kg and the length L = 1.255 m. The parameters of the inertia matrix and damping matrix of the experimental ship are $m_{11} = 25.8$, $m_{22} = 33.8$, $m_{33} = 2.76$, $d_{11} = 2$, $d_{22} = 7$, and $d_{33} = 0.5$, respectively.

In the simulation, the initial position of the ship is set to $\eta_d = [5m, 5m, 10^{\circ}]^T$, the desired position is $\eta_d = [10m, 10m, 0^{\circ}]^T$, the disturbance is set to $d = [1, 1, 0.1]^T$, and the design parameter matrix in the ship dynamic positioning control law is chosen as K_0 = diag (5, 5, 5), K_1 = diag(2, 2, 2), and K_2 = diag(7, 7, 7), the hardware-in-the-loop experimental results are shown in Figures 2 – 5.

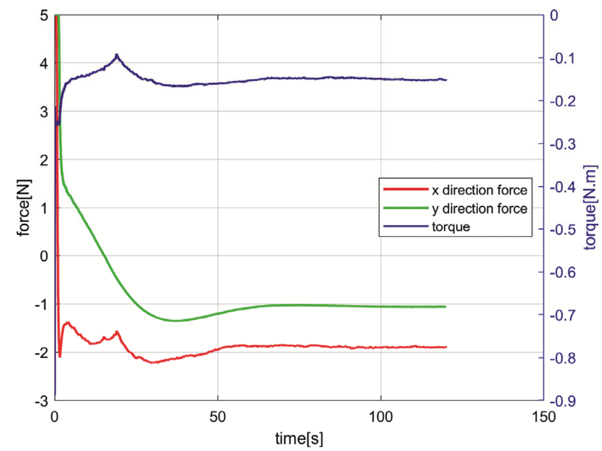

Fig. 4 — Ship force/torque efforts

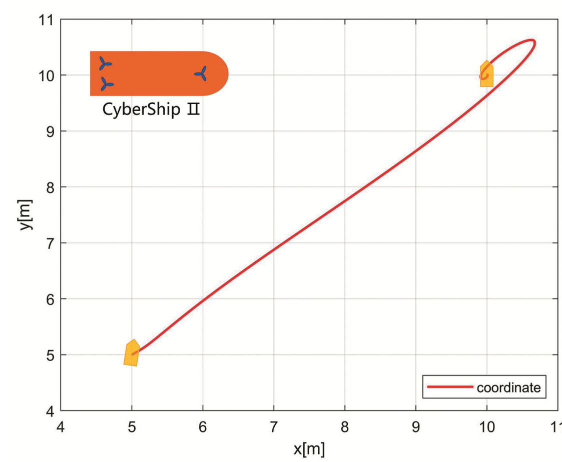

Fig. 5 — Ship dynamic positioning evolution

As shown in the above figures, the designed nonlinear disturbance observer is capable of estimating unknown disturbances. As a consequence, the observer-based controller can achieve accurate compensation for the interference of external disturbances. As shown in Figure 2, by virtue of the proposed control scheme, the position and heading of the DP ship can be quickly regulated to the desired states. In summary, the simulation results shown in Figures 2 – 5 verified the effectiveness of the proposed controller.

Conclusion

In this paper, a nonlinear disturbance observer-based adaptive controller with control allocation taking into consideration is proposed to achieve dynamic position control of a ship subject to external disturbances and input saturation. By employing the nonlinear disturbance observer, external disturbances can be estimated through feedback states. Meanwhile, the fuzzy approximation technique is adopted to tackle the input saturation problem. Subsequently, the adaptive technique is introduced to eliminate the negative effect of unknown approximation error. Finally, theoretical analysis and simulation results illustrate the performance of the proposed scheme.

Acknowledgment

This work is supported by the Hubei Provincial Natural Science Foundation for Innovation Groups (No. 2021CFA026), National Natural Science Foundation of China (under Grant 52071153) and the Fundamental Research Funds for the Central Universities (under Grant 2021yjsCXCY007).

Conflict of Interest

The authors declare that they have no competing or conflict of interest.

Author Contributions

DD: Methodology, simulation, experiment, and writing - original draft. JL: Methodology, simulation, and writing - original draft; SY: Methodology, co-supervision, and writing – review & editing and XX: Conceptualization, supervision, resources, and writing – review & editing.

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