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Abstract: With the development of unmanned ship technology, the intelligent control of ships is gradually used on large unmanned transport ships. In the course of navigation, ships are often disturbed by various nonlinear factors. Based on Norbbin nonlinear ship motion model, and adopting Lyapunov stability theorem to guarantee the stability of the closed-loop control system, *a new sliding mode control method is proposed*. Combined with backstepping, a backstepping sliding mode control method is designed to control the line track of ship on condition that the bound of disturbance is known. If the bound of disturbance is unknown, *an adaptive backstepping sliding mode control method is designed*. Simulation results with model of intelligent bulk carrier called Idolphin by Matlab demonstrate that this method is more stable and faster than PID controller.

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无人运输船舶的直线航迹反步自适应滑模控制

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摘要：随着无人船技术的发展，智能控制逐渐运用到大型无人运输船舶上。在船舶航行过程中，经常会受到一些非线性因素的干扰。基于船舶运动的 Norbbin 非线性数学模型和李雅普诺夫稳定性理论在闭环控制系统中的应用，*提出一种新型滑模控制方法，并和反步法相结合，在扰动界已知的前提下设计一种反步滑模控制器，控制船舶的航迹*。当扰动界未知时，提出一种自适应反步滑模的控制方法。最后运用 Matlab 对“大智”智能运输船模型进行仿真，控制方法和 PID 控制进行对比，结果表明自适应反步滑模控制比 PID 控制的稳定性更强，响应更快。

关键词：无人运输船舶；非线性因素；自适应反步滑模；直线航迹

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Introduction

In recent years, with the in-depth research and application of intelligent technology in the field of land transportation, the research and development of driver-less vehicles has achieved unprecedented success. As a result, people naturally associate with and correspond to the field of water transport. Given the intelligent technology in the field of water transport having a wide range of exploration and application, unmanned ship would be the future

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direction of development[1]. The control of unmanned transport ship has also become a hot topic.

At the 2017 China International Maritime Technology Conference and Exhibition, the iDolphin 38800 ton intelligent bulk carrier "Dazhi"[2], developed by China Shipbuilding Industry Group, was released, the intelligent ship can optimize the course and speed according to the ship's data and hydrometeorological information, and also has the ability to "check up" itself.

The linear motion track of a ship on the water surface is a control method adopted at present [3-4]. The control of some curved running of the ship in ocean can also be simplified into the linear tracking control of the ship which has been studied in this paper.

There are some shortcomings in the use of the ship's linear tracking method, such as there is no concern of impact of the environmental disturbance on the track and the ship's model perturbation, which cannot guarantee the stability of the whole operation process [5-6]. Considering these problems, this paper proposed an improved integrated ship backstepping adaptive sliding mode control method, which has been verified obvious advantage of overall asymptotic stability. Thus, the control stability of the ship is improved by this method. And at the same time, so is the "buffeting" shortcoming of the ship sliding mode controller obviously.

1 Motion model of unmanned transport ship

According to the motion of an unmanned transporting ship on the water surface shown in Fig. 1, the following formula can be used to express the motion model of the ship[7]:

$$\begin{cases}\dot{x}=u\cos\psi-v\sin\psi\\ \dot{y}=u\sin\psi+v\cos\psi\\ \dot{\psi}=r\end{cases}\tag{1}$$

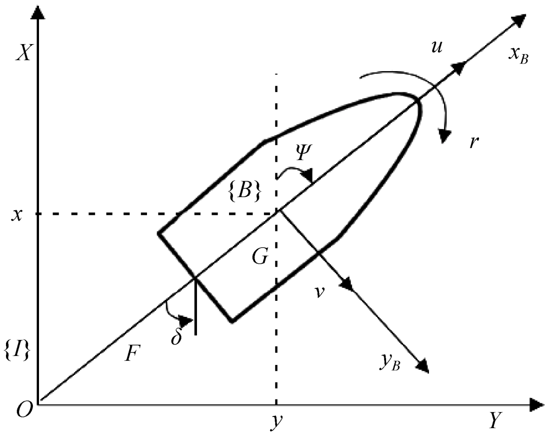

Fig. 1 Unmanned transport ship model diagram

Where *u*, *v*, *r* are the longitudinal, lateral and angular speeds of the unmanned transport ship; *x* and *y* are its center of mass-the ship's actual position in the inertial system; ψ is the course angle.

During the operation of the ship, $u \gg 0, v \approx 0$ [8], the equation of motion above can be simplified as:

$$\begin{cases}\dot{x}=U\cos\psi\\ \dot{y}=U\sin\psi\\ \dot{\psi}=r\end{cases}\tag{2}$$

It can be known that the summed speed of the unmanned transport ship is as follows:

$$U=\sqrt{u^2+v^2}\approx u$$

Because the unmanned transport ship will be affected by the nonlinear terms in the course of its motion, the corresponding nonlinear terms below can be added to the equations above[9]:

$$T\ddot{\psi}+\dot{\psi}+\alpha\dot{\psi}^3=K\delta\tag{3}$$

In this equation: δ is the rudder angle of the ship; *T* and *K* are ship maneuvering indexes as 2 constants; α is the correlative coefficient of the nonlinear terms in the system.

Due to the environmental disturbances and the modeling errors of the ship in the running process of the system, the dynamic model of the tracking control of linear track of the ship can be obtained by analysis of formula above as:

$$\begin{cases} \dot{y} = U\sin\psi \\ \dot{\psi} = r \\ \dot{r} = -\dfrac{r}{T} - \dfrac{\alpha r^3}{T} + \dfrac{K\delta}{T} + d(t) \end{cases} \tag{4}$$

2 Design of control system

In the practical applications of the linear track control, literatures[10-12] have done plenty of researches. The disadvantage is that it can only guarantee the local asymptotic stability of the linear track. Literature[13] uses the idea of redefining the output variable. It defines the output variable as $z = y + k\psi$. So a state feedback control law is proposed to insure the local asymptotical convergence of the system. In literature[14], an incremental sliding mode feedback control law is proposed by combining the iterative sliding mode design with incremental feedback technology.

In ship motion, the traditional method and boundary layer are generally used in the controller. This sliding mode control method is also used in inverted pendulum, robot, etc.[15]. With which the buffeting problem of the control system can be improved, but the steady state error will occur in the system which is solved by adding the integral term to the ship control system.

2.1 Design of backstepping sliding mode control system

According to the formula (4), the system is:

$$\dot{y} = U\sin\psi \tag{5}$$

In order to decrease the influence of the nonlinear term $\sin\psi$ of the ship control system, a feedback control law is designed as follow:

$$\psi_d = f(y) = \arctan(-ky) \tag{6}$$

Where k is a constant, formula (6) can be plugged into formula (5), and then rewritten as the formula (7):

$$\dot{y} = U\sin\psi = U\sin[\arctan(-ky)] = -\frac{Uky}{\sqrt{1+(ky)^2}} \tag{7}$$

The Lyapunov function is defined as[16]:

$$V_1 = \frac{1}{2}y^2 \tag{8}$$

By finding the derivative of V_1, in formula (8), we can obtain:

$$\dot{V}_1 = y\dot{y} = -\frac{Uky^2}{\sqrt{1+(ky)^2}}$$

Where ψ_d is not the actual controlled quantity of the ship. By defining the error variables z_1 and z_2 of the ship control system, the following formula can be obtained:

$$\begin{cases} z_1 = \psi - \psi_d = \psi - \arctan(-ky) \\ z_2 = r - \dfrac{Uk^2 y}{[1+(ky)^2]^{3/2}} \end{cases} \tag{9}$$

Cause the value of k is small so that the guidance to z_2 is r'. The guidance to z_1 and z_2 are

$$\begin{cases} \dot{z}_1 = z_2 \\ \dot{z}_2 = g(r) + b\delta + d(t) + \left(\dfrac{Uk^2 y}{[1+(ky)^2]^{3/2}}\right)' \end{cases} \tag{10}$$

In the formula, $g(r) = -(r + \alpha r^3)/T$, $b = K/T$.

An improved integral sliding mode surface is used in this paper [17]:

$$\begin{cases} S = \dot{z}_1 + 2\lambda z_1 + \lambda^2, \\ \dot{\eta} = \dfrac{-\lambda^2 + \xi(1+\rho)sat(S/\xi) - \rho S - \dot{z}_1}{2\lambda} \end{cases} \tag{11}$$

Where $\lambda > 0$ is the slope of the sliding mode surface; $\rho \geq -1$ is the integral weakening degree regulator; $sat(S/\xi)$ is the saturation function, it is defined as[18]:

$$sat(S/\xi) = \begin{cases} S/\xi, & |S| \leq \xi \\ \operatorname{sgn}(S), & |S| > \xi \end{cases} \tag{12}$$

Where ξ is the thickness of boundary layer.

The Lyapunov function is defined as:

$$V_2 = V_1 + \frac{1}{2}S^2 \tag{13}$$

The derivation of V_2 can be obtained:

$$\dot{V}_2 = \dot{V}_1 + S\dot{S} = \dot{V}_1 + S[g(r) + b\delta + d(t) + 2\lambda z_2 + \lambda^2\dot{\eta}] \tag{14}$$

Design control law δ as follow:

$$\delta = (1/b)[-\beta\,\mathrm{sgn}(S) - k_s S - g(r) - 2\lambda z_2 - \lambda^2\dot{\eta} - D\,\mathrm{sgn}(S)] \tag{15}$$

Where δ is the rudder angle of the unmanned ship, β, k_s are positive constants. Put formula (15) into (14). So we can find out

$$\begin{aligned}\dot{V}_2 &= \dot{V}_1 + S[d(t) - k_s S - \beta\,\mathrm{sgn}(S) - D\,\mathrm{sgn}(S)] \le \\ &\dot{V}_1 + |S|[d(t) - D] - |S|\beta - k_s S \le \\ &-\frac{Uky^2}{\sqrt{1+(ky)^2}} - k_s S - |S|\beta \le -\theta V_2 \le 0\end{aligned} \tag{16}$$

$\theta = \max(2Uk/\sqrt{1+(ky)^2}, 2k_s)$. It is clear that the Lyapunov stability theory can prove that the feedback control law (16) can ensure that the original system (4) is a global exponential stability.

2.2 Design of adaptive backstepping sliding mode control system

Due to the nonlinear and time-varying characteristics of unmanned transport ship in the process of motion, the model is determined difficultly in the ship control system, and the operability is affected seriously by the external environment on the water. So when using the traditional controller, the related system parameters may not be known. In order to solve the problem of "buffeting" in the system, we added a disturbance. In this paper, the critical mass $d(t)$ of ship control system is calculated by using adaptive control algorithm.

Let $\hat{d}(t)$ be an estimated value of $d(t)$, the estimation error is $\tilde{d}(t) = d(t) - \hat{d}(t)$. The Lyapunov function is defined as:

$$V_3 = V_2 + \frac{1}{2\gamma}\tilde{d}(t)^2 \tag{17}$$

Finding the corresponding derivation of V_3, the following formula can be obtained:

$$\dot{V}_3 = \dot{V}_1 - \frac{\tilde{d}(t)[\dot{\hat{d}}(t) - \gamma S]}{\gamma} + S[g(r) + b\delta + \hat{d}(t) + 2\lambda z_2 + \lambda^2\dot{\eta}] \tag{18}$$

According to the above formula, the adaptive feedback control law δ of the unmanned ship can be designed as the following formula:

$$\hat{\delta} = [\hat{d}(t) + 2\lambda z_2 + \beta\,\mathrm{sgn}(S) + k_s S + g(r) + \lambda^2\dot{\eta}](-1/b) \tag{19}$$

The definition of the $d(t)$ adaptive law for the key quantity in the ship controller is:

$$\dot{\hat{d}}(t) = \gamma S \tag{20}$$

Finally, plugging formula (19)-designed adaptive feedback control law for undermanned ships and formula (20)-defined adaptive law into derivatived formula (18), it can be concluded:

$$\dot{V}_3 = -\frac{Uky^2}{\sqrt{1+(ky)^2}} - k_s S^2 - \beta|S| \le 0 \tag{21}$$

2.3 Analysis of system stability

By using backstepping method, the Lyapunov function testifies that the system error can be stabilized exponentially and asymptotically. The system finally realized the global asymptotic stabilization. The sliding mode control theory proves that the system can reach the sliding surface in finite time (i.e. satisfied reachable condition), and it ensures that the stability of the whole system is controllable[19].

Considering the influence of uncertainty on the ship's linear trajectory control system (4), under the action of feedback control law (19) and adaptive rule (20), the system type (4) is globally asymptotically stable[20]. We can prove it from the 2.1 and 2.2 sections.

3 Numerical simulations

In order to verify the correctness and validity of the control strategy, simulation is carried out. Before the simulation, the control system needs to be set up. The object is "IDolphin-Dazhi" unmanned transport ship. Its basic parameters are as follows: the length of the ship is L=179 m; the basic width is B=32 m; the square coefficient is C_b = 0.680; the speed is set at V=7.9 m/s, and the draft of the ship is d =15 m under full load.

The control law parameters of unmanned transport ship is set: λ=0.04, k=0.002 2, γ=0.001, k_s=0.01, β=0.001, ρ= 9.9, ξ= 0.015; the nominal model of the corresponding steering setting: T=216, K=–0.478, α=30. The initial value in the experiment is taken as: y_0=1 000 m, ψ_0=–60°, $v_0 = r_0 = 0$, and considering the limiting condition of rudder angle saturation: $-30^{\circ} \leq \delta \leq +30^{\circ}$. Using Matlab for numerical simulation, and compared with the effect of PID controller. The results of the simulation experiment are shown in the following diagrams.

The experiment results are shown in Fig. 2~6. It shows that the satisfied effect in performance such as overshoot, stable-time and steady-error. The curve is smooth and there are no bad phenomena such as oscillation. Fig. 2 shows that the unmanned transporting ship can move along a straight line due north. Fig. 5~6 are the comparisons of the traditional PID control algorithm with adaptive backstepping sliding mode control algorithm, which show that the adaptive backstepping sliding mode control algorithm has large benefits and strong stability.

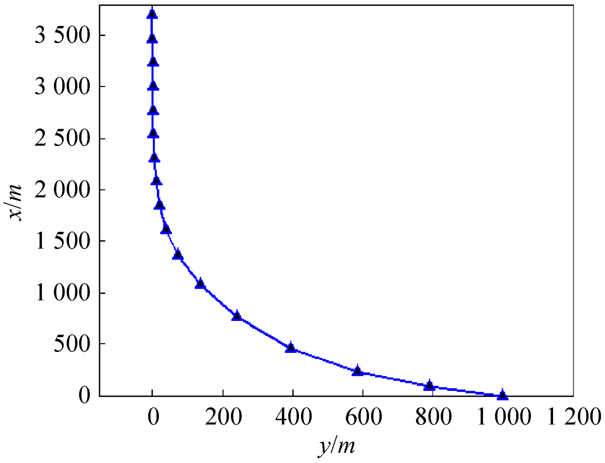

Fig.2 Track of unmanned transport ship

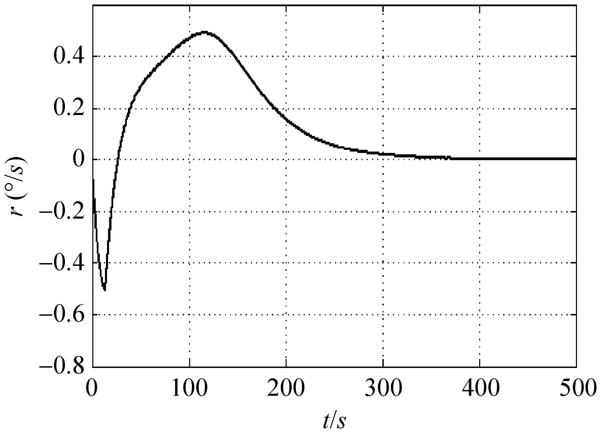

Fig. 3 Response curve of angular velocity

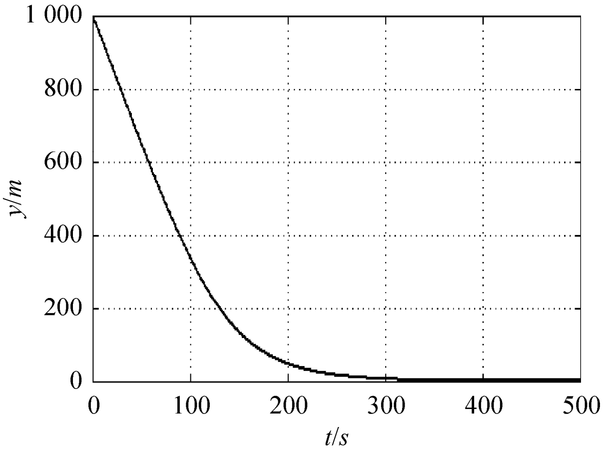

Fig. 4 Response curve of lateral displacement

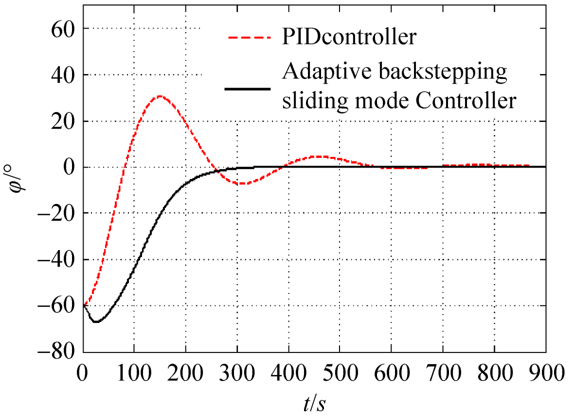

Fig. 5 Comparison simulation result of two systems (ψ)

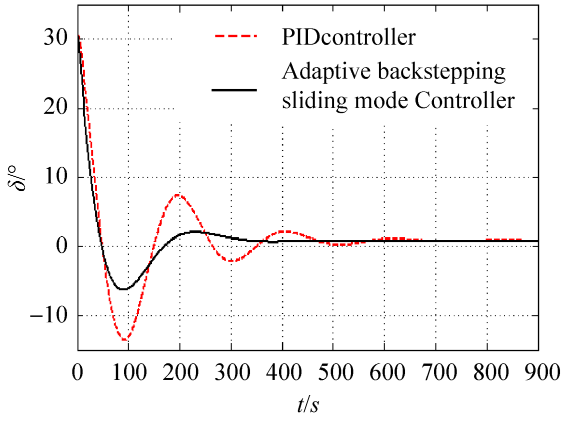

Fig. 6 Comparison simulation result of two systems (δ)

4 Conclusions

The unmanned transport ship is the main direction of ship development in the future, which realizes automation and intelligence, saves manpower, improves the efficiency of cargo transportation, and enhances the safety of the ship. In this paper, the control methods to be used in the unmanned ship control system are analyzed. The common methods do not deal with the environmental disturbance on the water and the model perturbation of the ship. The improved control method is applied to the ship control system, and the "Dazhi" ship is simulated. The results show that the control method can improve the control stability of the ship. At the same time, the "buffeting" shortcoming of ship sliding mode controller is ameliorated obviously.

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