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USV MODEL IDENTIFICATION AND NONLINEAR COURSE CONTROLLER

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Abstract. *The unmanned surface vehicle is an intelligent platform, which has important significance for the exploration of the marine resources, the collection of the hydrological data and the penetration of the military strategy. Its advantages come from the autonomous navigation, which is based on course autopilot. For a control system, if you want to achieve relatively accurate control, the parameters of the mathematical model of the controlled object need to determine firstly. So in this paper, the model parameters of unmanned surface vehicle are obtained by system identification and the identification results are verified by simulation. Secondly, under the premise that the model has been obtained, the algorithm of backstepping is applied to designing nonlinear course controller. Finally, to further demonstrate the effectiveness of the control law, the PID controller is compared with the backstepping controller. Simulation results show that under the case of presence interference, nonlinear course controller can meet the control requirements of course, which is better than PID.*
Keywords: Unmanned surface vehicle, Model identification, Course, Backstepping

1. **Introduction.** Unmanned surface vehicle (USV) is an intelligent equipment with the ability of autonomous navigation. It is mainly used to perform the tasks which are dangerous and unsuitable for manual operation. Because of having huge potential and broad application market, many experts and commercial organizations are forging ahead with USV and its course control is a hot and difficult research field. In the actual voyage, due to the existence of various kinds of interference, linear model is difficult to describe the characteristics of the system. So in [1], nonlinear Norrbin model is employed to describe the system characteristics of USV.

With the continuous development of science and technology, many advanced algorithms are used to design course autopilot. In [2], genetic algorithm is used to modify parameters of ADRC online and a ship course optimal ADRC controller is designed. Simulation results of ship course tracking and keeping show that the controller has good adaptabilities on the system nonlinearity. [3] presents an original ship course-keeping algorithm based on a knowledge base. Its integral part is a computer-borne ship movement dynamical model based on a set of signals obtained from the object's input and output. [4] presents a feedback linearization course controller with adaptive object model. The described method, consisting in current approximation of unknown object model functions by neuro-fuzzy approximators, represents a new generation of adaptive control method. [5] describes a manoeuvre based identification process and parameter analysis of a small unmanned surface vehicle. It is also shown that no thrust force measurements are required and the complete parameter set can be considered concurrently, avoiding the risk of suboptimal results when using a sequential approach. [6] presents the identification of non-linear ship manoeuvring models. It is a gray box approach in which some of the parameters of the model are known, and where a novel identification scheme for non-linear manoeuvring models based on two steps is proposed. These articles have not put forward a simple and effective solution to identify model and design controller. So the contribution of this paper is that linking theory with practice, a USV model is identified and according to the model, a course controller is designed.

This paper is organized as follows. The corresponding experiment and Norrbin model structure are described in the second chapter. In the third chapter, recursive least squares is used to identify the coefficients of model and simulation is carried out to verify the correctness of the identification result. In subsequent chapters, backstepping is employed to design course controller. Finally, by means of numerical simulation, backstepping controller is compared with PID controller to verify the performance of controller.

2. **Problem Statement and Preliminaries.**

In this paper, the USV of Dalian Maritime University "Lanxin" is used as experimental ship.

Figure 1. Lanxin USV

Equation (1) is the transfer function of the classical second order Nomoto model [7]. In engineering applications, it is often used to describe the characteristics of the ship. Here δ is rudder angle, ψ is course angle and r is yaw angle.

$$\frac{\psi(s)}{\delta(s)} = \frac{K(1+t_1 s)}{s(1+t_2 s)(1+t_3 s)} \tag{1}$$

Among them t_1, t_2 and t_3 are the time constants of Nomoto model and K is a gain coefficient. In the case of low frequency, second-order model can be simplified into a first order model.

$$\frac{\psi(s)}{\delta(s)} = \frac{K}{s(1+Ts)} \tag{2}$$

T is a time constant.

$$T = t_1 + t_2 - t_3 \tag{3}$$

In order to facilitate the identification of system and the design of course controller, Equation (2) is changed into a differential equation.

$$T\ddot{\psi} + \dot{\psi} = K\delta \tag{4}$$

Nomoto model is usually applied to describing the characteristics of ship, which operates with a small rudder angle. However, for USV, it often has a faster speed and need for frequent steering, so nonlinear characteristics should not be ignored. Taking account of the complexity of the system and fully reflecting the characteristics of model, Norrbin model is adopted to design controller.

$$T\ddot{\psi} + \alpha\dot{\psi}^3 + \dot{\psi} = K\delta \tag{5}$$

where K, T and α are model parameters and they will be identified in the following sections. Set state variables $x_1 = \psi$ and $x_2 = r = \dot{x}_1 = \dot{\psi}$. Then state space function can be got as Equation (6).

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\dfrac{1}{T}x_2 - \dfrac{\alpha}{T}x_2^3 + \dfrac{K}{T}\delta \\ y = x_1 \end{cases} \tag{6}$$

Assumption 2.1. *The USV's smooth reference trajectory ψ_d and its first 2 derivatives $\dot{\psi}_d$, $\ddot{\psi}_d$ are known and bounded.*

2.1. **Data collection.** The first step of identification is to perform acquisition experiment. When the sea condition is relatively stable (CALM-RIPPLED), keeping the speed about 8kn∼9kn (4.11m/s∼4.64m/s), z test (15°/15°) is carried out firstly. Due to the limit of space, a portion of the data are displayed in Table 1. For rotation test, 5, 8, 12, 15, 17, 18 and 20 degrees of rudder angle are used to carry out tests respectively. The corresponding data are displayed in Table 2.

Table 1. z test data

Marker	*Time*	*Rudder Angle*	*Speed*	*Course*
1	0.0s	−12.4°	9.01kn	235.04°
2	0.5s	−16.9°	9.01kn	224.64°
3	1.0s	−17.4°	9.05kn	220.78°
⋮	⋮	⋮	⋮	⋮
29	14.0s	13.3°	8.69kn	232.33°
30	14.5s	13.3°	8.69kn	237.52°

Table 2. Turning test data

Marker	*Rudder Angle*	r
1	5	3.38
2	8	6.261
3	12	7.543
4	15	8.832
5	17	9.421
6	18	9.811
7	20	11.201

3. Main Results.

3.1. **Identification method.** Recursive least squares is used to identify unknown coefficients and its algorithm is shown as Equation (7).

$$\begin{cases} \hat{\theta}(n) = \hat{\theta}(n-1) + K(n)\left[y(n) - \phi^T(n)\hat{\theta}(n-1)\right] \\ K(n) = \dfrac{P(n-1)\phi(n)}{1 + \phi^T(n)P(n-1)\phi(n)} \\ P(n) = \left[I - K(n)\phi^T(n)\right]P(n-1) \end{cases} \tag{7}$$

$\hat{\theta}$ is the estimation value of the ship, and $\phi(k)$ is the data vector [8].

3.2. **Parameter identification.** The essence of Norrbin model is a linear Nomoto model with a nonlinear term. So, in order to improve the accuracy of identification, K, T and α will be identified separately.

K and T are identified by z test data and α is fitted by rotation test data. When the rotation experiment is carried out, $\dot{r}$, $\ddot{r}$ and $\ddot{\delta}$ are equal to zero. As can be seen from Equation (8), α and δ are a pair of corresponding, so a simple fitting method (matlab toolbox) can be used to identify α.

$$\alpha\dot{\psi}^3 + \dot{\psi} = K\delta \tag{8}$$

The curves of identification and fitting results are displayed in Figures 2 and 3.

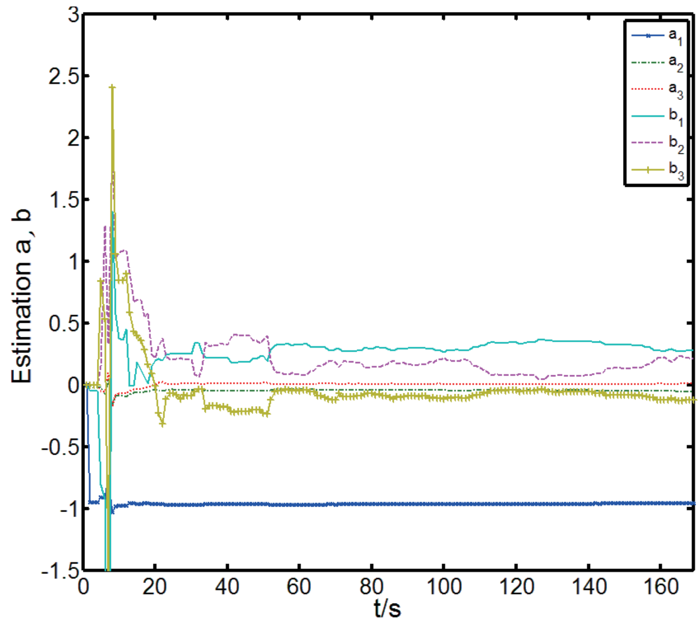


FIGURE 2. Identification curves

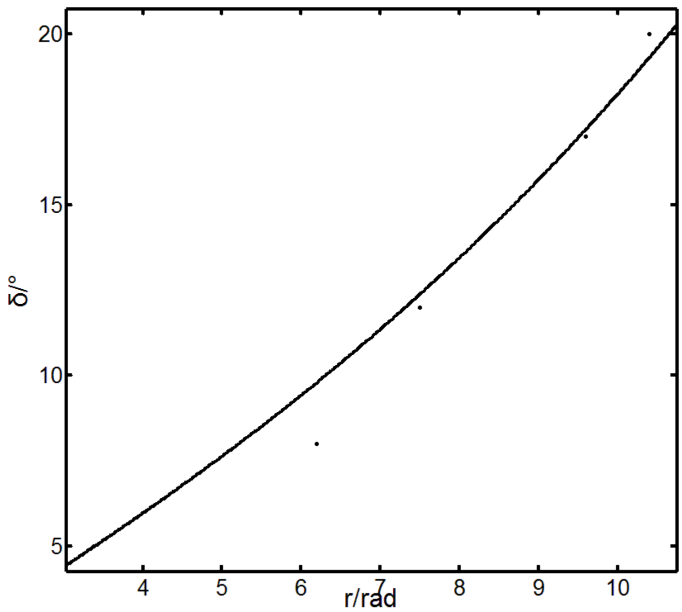


FIGURE 3. Fitting curve of δ and r

$a_1 \sim a_3$ and $b_1 \sim b_3$ are the coefficients of discrete transfer function. The discrete transfer function is

$$\frac{0.2743z^2 + 0.2122z - 0.118}{z^3 - 0.9537z^2 - 0.5476z + 0.007182} \tag{9}$$

The next step is to change Equation (9) into a continuous transfer function. The result of the conversion is shown in Equation (10).

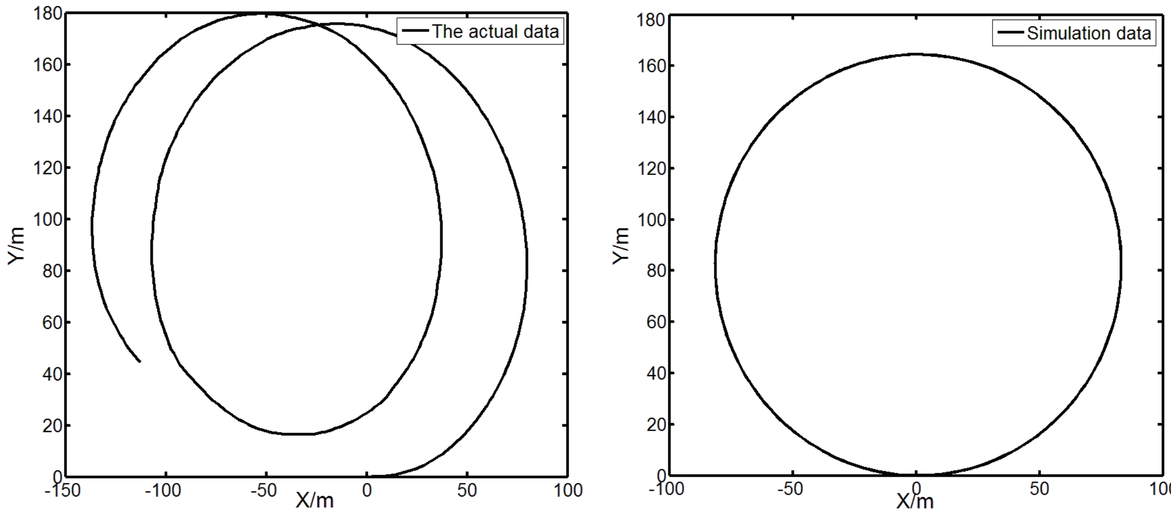
$$\frac{1.65s^3 - 10.63s^2 + 88.19s + 225.9}{s^4 + 14.26s^3 + 106.8s^2 + 322s - 0.7904} \tag{10}$$

Due to the fact that the coefficients of higher order and low order differ greatly, Equation (10) can be simplified as Equation (11).

$$\frac{225.9}{106.8s^2 + 332s} \tag{11}$$

Then K and T can be got. $K = 0.707$, $T = 0.332$. Meanwhile, as shown in Figure 3, the fitting result by matlab toolbox shows that α is equal to 0.001.

3.3. **Model validation.** Parameters have been identified in the previous section. To ensure the control effect of the controller, the correctness of the model needs to be verified. According to international practice, rotation test is hired to verify model. Because the rudder performance is not considered in this paper, the verification of z test is not required. When rudder angle is 15 degrees, the results are shown in Figure 4.



(a) Actual radius of gyration (b) Simulation radius of gyration

Figure 4. Verification curves

As can be seen from Figure 4, the actual radius of gyration is 85.25m and the simulation is 86.11m. The results of the numerical simulations and tests are very close. This is to say, the result of the identification is correct and reliable.

4. **Control Design.** Backstepping is a nonlinear control algorithm which aims at strict feedback control system [9]. The essence of backstepping is gradually recursive making the system uniformly asymptotically stable at balance point.

Firstly, a new state variable is introduced which is defined by the following equation.

$$z_1 = x_1 - \psi_d \tag{12}$$

where ψ_d is the desired ship course. The derivative of Equation (12) is

$$\dot{z}_1 = x_2 - \dot{\psi}_d \tag{13}$$

Define another state variable z_2 and its expression is

$$z_2 = x_2 - \beta(z_1) \tag{14}$$

The role of $\beta(z_1)$ is to stabilize Equation (13). This has been done by considering the first Lyapunov function.

$$V_1 = \frac{1}{2}z_1^2 \tag{15}$$

Its derivative, with respect to time, is given by

$$\dot{V}_1 = z_1\left(z_2 + \beta(z_1) - \dot{\psi}_d\right) \tag{16}$$

In order to ensure the convergence to zero of the error z_1, $\beta(z_1)$ takes the following form

$$\beta(z_1) = -k_1 z_1 + \dot{\psi}_d \tag{17}$$

where $k_1 > 0$ is a tuned parameter. Finally, the derivative of V_1 is expressed by

$$\dot{V}_1 = -k_1 z_1^2 + z_1 z_2 \tag{18}$$

When $z_2 \to 0$, subsystem of z_1 is stabilization. Secondly, the derivative of Equation (14) takes the form

$$\dot{z}_2 = -\frac{1}{T}x_2 - \frac{\alpha}{T}x_2^3 + \frac{K}{T}\delta - \dot{\beta}(z_1) \tag{19}$$

The second Lyapunov function is defined by

$$V_2 = V_1 + \frac{1}{2}z_2^2 \tag{20}$$

The derivative of V_2 is expressed by

$$\dot{V}_2 = \dot{V}_1 + z_2\dot{z}_2 \tag{21}$$

Substituting Equations (18) and (19) into Equation (21), we can obtain

$$\dot{V}_2 = -k_1 z_1^2 + z_2\left(-\frac{1}{T}x_2 - \frac{\alpha}{T}x_2^3 + \frac{K}{T}\delta - \dot{\beta}(z_1) + z_1\right) \tag{22}$$

The desired control low δ is given by

$$\delta = \frac{T}{K}\left(-k_2 z_2 - z_1 + \frac{1}{T}x_2 + \frac{K}{T}x_2^3 + \dot{\beta}(z_1)\right) \tag{23}$$

where k_2 is a positive constant. Substituting Equation (23) into Equation (22), we can obtain

$$\dot{V}_2 = -k_1 z_1^2 - k_2 z_2^2 \leq 0 \tag{24}$$

It can be seen that from the theoretical analysis, the system is stable when the control law is Equation (23).

5. **Numerical Simulations.** In order to prove the correctness of the control strategy, backstepping controller is compared with traditional PID controller. The control law of PID is

$$\delta = K_p e + K_i \int_0^t e d\tau + K_d \dot{e} \tag{25}$$

where K_p, K_i and K_d are the parameters of PID, and e is the difference between the actual course and the target value.

In order to further prove backstepping controller having a good anti-interference ability, a certain interference is added in the simulation. The transfer function of interference is shown as Equation (26) and it is driven by a white noise.

$$\frac{0.42s}{s^2 + 0.3637s + 0.3675} \tag{26}$$

The parameters of backstepping controller $k_1 = 20$ and $k_2 = 13$, the parameters of PID controller $K_p = 20$, $K_i = 0.1$ and $K_d = 5$.

The results of simulation are shown in Figures 5 and 6.

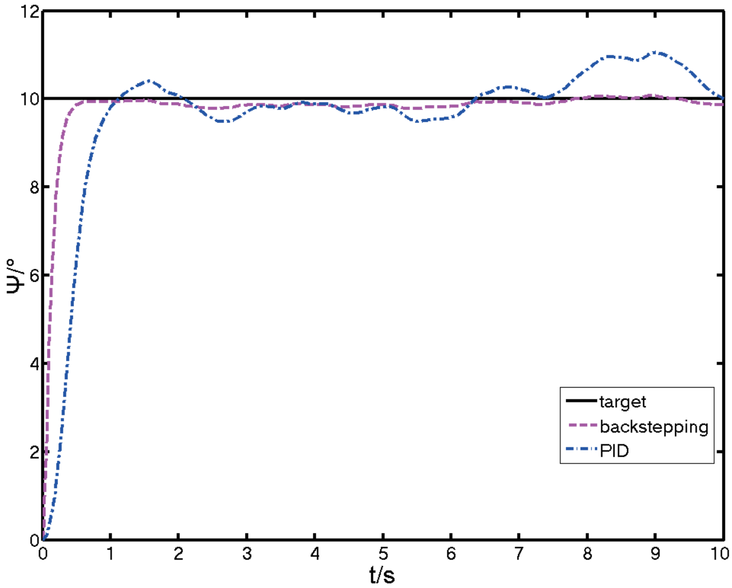


Figure 5. Course curves

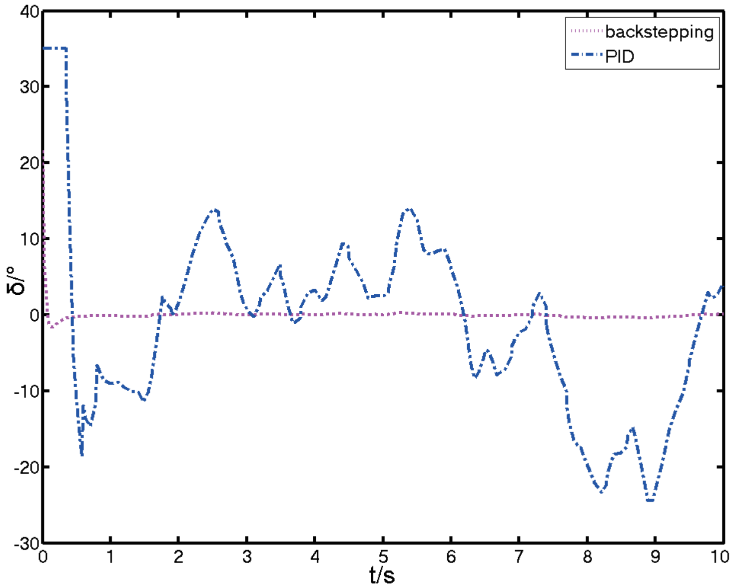


Figure 6. Rudder curves

It can be seen from Figure 5 that under the same disturbance, both backstepping controller and PID controller are able to ensure that the course is maintained near the target value. However, backstepping controller has a faster response speed than PID controller, and it can be clearly seen that the fluctuation range of backstepping controller is 9.8$\sim$10.1 and the fluctuation range of PID controller is 9.3$\sim$11.1. Thus, from the point of view of the control effect, backstepping controller has more obvious advantages than PID controller. It can be seen from Figure 6, the fluctuation range of PID automatic rudder is $-20\sim 10$ larger than backstepping controller. This is to say, PID controller needs more energy and has more mechanical wear. Thus, from the point of saving energy, backstepping controller has more obvious advantages than PID controller.

6. **Conclusions.** Model is the basis of control, so it is very important to choose a model which is relatively simple and can fully describe the system characteristics. In this article, Norrbin model is employed to describe the characteristics of USV, and in order to obtain a relatively accurate mathematical model, RLS is used to identify the parameters of model. Subsequently, the identified model is used to carry out simulation experiment, and the result of simulation has proved that the difference between the actual radius of gyration and the simulation radius of gyration is 0.86m. In other words, the identified model satisfies the requirement of accuracy. Finally, the comparison results of backstepping controller and PID controller can illustrate that from the angle of control, backstepping controller has a faster tracking speed and a good anti-jamming capability; from the angle of energy saving, backstepping controller has a smaller power consumption and automatic rudder wear than PID controller. In the next work, in order to be more in line with the actual project, speed and course should be considered at the same time. Meanwhile, advanced algorithms will be employed to design course controller.

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