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MODELING AND IDENTIFICATION OF PODDED PROPULSOR UNMANNED SURFACE VEHICLE

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Abstract. *According to podded propulsor unmanned surface vehicle, the idea of MMG separation model is employed to establish mathematical model of plane motion with three degrees of freedom. Then by analysing and hypothesizing the force of acting on the hull and propulsor, mathematical model of plane motion is simplified as a response model. Because model is the key to further studying the unmanned vehicle, the next step is to identify the response model. Meanwhile, the identified model is simulated and compared with the actual experiment to verify the correctness of the model. The final comparison results show that the errors of simulation results with the actual experiments are in the range of confidence. In other words, it proves the correctness of the modeling of unmanned surface vehicle and the feasibility of identification scheme.*

Keywords: Unmanned surface vehicle, POD, MMG, Response model, Identification

1. **Introduction.** Unmanned Surface Vehicle (USV) is a piece of intelligent equipment with the functions of autonomous navigation, target detection and identification, etc. In the complex and changeable marine environment, USV requires a faster speed and a good maneuverability, which puts forward a higher requirement for the performance of its propulsor. POD propulsor is a new type of ship propulsion device developed in recent years, which can generate vector thrust in any direction. In a nutshell, without need rudder and lateral thruster, ship can achieve rotation, reverse, horizontal movement and other driving operations. So POD propulsor is not only to meet its basic operation requirements, but also to improve the integrated navigation performance.

Several authors have studied the handling performance of POD propulsor ship. British scholar Woodward et al. [1] predict the performance of the POD propulsion ship. [2] takes the POD propulsor as the research object, and two methods of numerical calculation and model test are used to analyze its hydrodynamic performance. Based on the analysis of mechanical characteristics of electrical podded propulsor ship, [3] establishes an MMG three degrees of freedom model, and to a certain extent explains the maneuvering characteristics of the podded propulsor ship. For the study of the control technology of podded propulsor ship, accurate maneuvering model needs to be established firstly. In [4], the partial model parameters of MMG are identified by least square method, and the residual parameters are identified by inverse adaptive method. The results are accurate and effective, but this method can only be used in the model ship. [5] uses different operation methods to identify model parameters, and the identification results are evaluated by using fisher matrix. For a high speed three body model ship, under the premise of known partial ship model parameters, [6] uses stepwise regression method to identify the rest unknown coefficients. Based on the approximation ability of radial basis function neural network, in the unknown ocean environment, [7] proposes a set of method to precisely identify, but this method is relatively complex.

According to the existing articles, only a few articles research on the modeling and identification of POD propulsion ship; however, their methods are not easy to implement. Therefore, the contribution of this paper is that from modeling to identification, a simple and feasible scheme is proposed in this paper. The principle of separation modeling is used to analyze the force of hull, and then it is simplified as a response model. Model is the basis for further research on intelligent control, so the response model and the servo system model are identified in the next step. In order to verify the correctness of the identification results, z type experiment and turning experiment are carried out by simulation to compare with the actual experiment data.

The remainder of this paper is organized as follows. In the second chapter, on the basis of the analysis of the viscous hydrodynamic force and moment of USV and the thrust allocation of POD, three degrees of freedom MMG model is simplified as a response model. In the third chapter, on the basis of collecting experimental data, the response model of USV and the servo model of POD are identified by recursive least squares. The results of identification are verified in subsequent chapter. In the last chapter, the full text is summarized and the future research direction is introduced.

2. **USV Model.**

2.1. **USV and its propulsion system.**

The USV and its propulsor are shown in Figures 1 and 2. When the propulsion angle is changed, the vector thrust produced by the propulsor can be decomposed into two directions in the attached body coordinate system: maintains the longitudinal thrust of keeping ship forward and produces the transverse thrust of the steering effect.

Figure 1. USV

Figure 2. The structure of propulsor

2.2. **Model derivation and simplification.**

Assuming that the ship is symmetrical and the center of gravity is located in the origin of the attached coordinate system, the motion model with three degrees of freedom can be expressed as

$$\begin{cases} (m+m_x)\dot{u} - (m+m_y)vr = X = X_H + X_P \\ (m+m_y)\dot{v} + (m+m_x)ur = Y = Y_H + Y_P \\ (I_{zz}+J_{zz})\dot{r} = N = N_H + N_P \end{cases} \tag{1}$$

where u is surge velocity, v is sway velocity, r is yaw rate, m is the weight of ship, m_x is the additional mass in the x axis direction, m_y is the additional mass in the y axis direction, I_{zz} is the moment of inertia of the o_x axis, J_{zz} is the additional moment of inertia in the direction of the z axis, X, Y and N are the hydrodynamic forces and moments acting on the hull, H is the hydrodynamic force acting on the bare hull, and P is the propulsor thrust. According to [8], the hydrodynamic forces acting on the bare hull are

$$\begin{cases} X_H = X(u) + X_{Hvv}v^2 + X_{Hvr}vr + H_{Hrr}r^2 \\ Y_H = Y_{Hv}v + Y_{Hr}r + Y_{NL} \\ N_H = N_{Hv}v + N_{Hr}r + N_{NL} \end{cases} \tag{2}$$

where Y_{NL} and N_{NL} are nonlinear fluid dynamics, and compared with the linear hydrodynamic force, they can be considered as a high order small quantity, which can be ignored. According to [9], the propulsor thrust of POD is

$$T = cV\delta_n + d\left|\delta_n\right|\delta_n \tag{3}$$

where T is propulsor thrust, V is the speed of ship, δ_n is the speed of propeller, and c and d are the coefficients greater than zero. When the propulsion angle is δ, the vector thrust in different directions are

$$\begin{cases} X_P = (cV\delta_n + d\left|\delta_n\right|\delta_n)\cos\delta \\ Y_P = (cV\delta_n + d\left|\delta_n\right|\delta_n)\sin\delta \\ N_P = x_{\delta s}(cV\delta_n + d\left|\delta_n\right|\delta_n)\sin\delta \end{cases} \tag{4}$$

where $x_{\delta s}$ is the length of vertical arm from the center of rotation to the fulcrum of the propulsor. Assume that the outside interference is small, that is to say, it is always moving in the vicinity of the initial equilibrium state. At this point the linear hydrodynamic force acting on USV occupies a dominant position, and the higher order terms can be ignored. In the field of ship model research, the uniform linear motion of the ship is generally regarded as an initial equilibrium state. Assume $u = u_0$, $v = v_0 = 0$, $r = r_0 = 0$ and $\delta = \delta_0 = 0$, where u_0 is the longitudinal initial velocity of USV. When the USV is disturbed by interference, the changes of motion state are Δu, $\Delta v = v$, $\Delta r = r$ and $\Delta\delta = \delta$. Then $u = u_0 + \Delta u$, $v = v_0 + \Delta v$, $r = r_0 + \Delta r$ and $\delta = \delta_0 + \Delta\delta$. Formula (1) is simplified as

$$\begin{cases} (m + m_x)\Delta\dot{u} = X \\ (m + m_y)\dot{v} + (m + m_x)u_0 r = Y \\ (I_{zz} + J_{zz})\dot{r} = N \end{cases} \tag{5}$$

Keep first order small quantities Δu, v, r, δ and ignore high order small quantities of two and above.

$$\begin{cases} X_H = X(u_0 + \Delta u) \\ Y_H = Y_{Hv}v + Y_{Hr}r \\ N_H = N_{Hv} + N_{Hr}r \end{cases} \tag{6}$$

where $X(u_0 + \Delta u)$ is the direct resistance of USV which can be expressed as

$$X(u_0 + \Delta u) = -\frac{1}{2}\rho SC_t(u_0 + \Delta u)^2 \tag{7}$$

where S is the wetted area of ship, ρ is water density, C_t is the total drag coefficient, and its essence is a function of speed. Formula (7) can be expanded as

$$X(u_0 + \Delta u) = -\frac{1}{2}\rho S\left[C_{t0} + \left(\frac{\partial C_t}{\partial\Delta u}\right)_{u0}\Delta u\right](u_0 + \Delta u)^2 \tag{8}$$

When the speed is u_0, its total resistance coefficient is C_{t0}. Δu of Formula (8) is linearized as

$$X_H = -\frac{1}{2}\rho SC_{t0}u_0^2 - \frac{1}{2}\rho S\left[2C_{t0}u_0 + \left(\frac{\partial C_t}{\partial\Delta u}\right)_{u0}u_0^2\right]\Delta u \tag{9}$$

Make $X_0 = -\frac{1}{2}\rho SC_{t0}u_0^2$ and $X_{Hu} = -\frac{1}{2}\rho S\left[2C_{t0}u_0 + \left(\frac{\partial C_t}{\partial\Delta u}\right)_{u0}u_0^2\right]$, where X_0 is the straight line resistance of the unmanned vehicle in the initial state. Then $X_H = X_0 +$

$X_{Hu}\Delta u$. So Formula (6) can be converted to

$$\left\{\begin{array}{l} X_H = X_0 + X_{Hu}\Delta u \\ Y_H = Y_{Hv}v + Y_{Hr}r \\ N_H = N_{Hv} + N_{Hr}r \end{array}\right. \tag{10}$$

Taking account that δ is small, so $\sin\delta \approx \delta$ and $\cos\delta \approx 1$. Then the thrust of the propeller can be simplified as

$$\left\{\begin{array}{l} X_P = cV\delta_n + d\left|\delta_n\right|\delta_n \\ Y_P = (cV\delta_n + d\left|\delta_n\right|\delta_n)\delta \\ N_P = x_{\delta s}(cV\delta_n + d\left|\delta_n\right|\delta_n)\delta \end{array}\right. \tag{11}$$

So Formula (1) can be expressed as

$$\left\{\begin{array}{l} X = X_0 + X_{pu}\Delta u + X_p \\ Y = Y_H + Y_p = Y_{Hv}v + Y_{Hr}r + X_p\delta \\ N = N_H + M_p = N_{Hv}v + N_{Hr}r + x_{\delta s}X_p\delta \end{array}\right. \tag{12}$$

Because in the initial state, the resistance of the unmanned vehicle is equal to the thrust of the propulsor. Then $X_0 + X_P = 0$, so

$$\left\{\begin{array}{l} (m + m_x)\Delta\dot{u} = X_u\Delta u \\ (m + m_y)\dot{v} + (m + m_x)u_0 r = Y_{Hv}v + Y_{Hr}r + X_p\delta \\ (I_{zz} + J_{zz})\dot{r} = N_{Hv}v + N_{Hr}r + x_{\delta s}X_p\delta \end{array}\right. \tag{13}$$

Assuming that the ship is subjected to a small disturbance, and the longitudinal velocity is constant, so X, Y and N can be decoupled separately considered. Formula (13) can be divided into

$$(m + m_x)\Delta\dot{u} = X_u\Delta u \tag{14}$$

$$\left\{\begin{array}{l} (m + m_y)\dot{v} + (m + m_x)u_0 r = Y_{Hv}v + Y_{Hr}r + X_p\delta \\ (I_{zz} + J_{zz})\dot{r} = N_{Hv}v + N_{Hr}r + x_{\delta s}X_p\delta \end{array}\right. \tag{15}$$

Make $Y_{Hv} = Y_v$, $Y_{Hr} = Y_r$, $X_p = Y_\delta$, $N_{Hv} = N_v$, $N_{Hr} = N_r$, and $x_{\delta s}X_p = N_\delta$. Formula (15) can be simplified as

$$\left\{\begin{array}{l} (m + m_y)\dot{v} = Y_v v + (Y_r - (m + m_x)u_0 r) + Y_\delta\delta \\ (I_{zz} + J_{zz})\dot{r} = N_v v + N_r r + N_\delta\delta \end{array}\right. \tag{16}$$

In order to simplify the problem, assuming that the initial state is uniform motion, and all the motion variables have zero initial value, then $\Delta u(0) = 0$, $v(0) = 0$, $r(0) = 0$, $\dot{v}(0) = 0$, $\dot{r}(0) = 0$, $\delta(0) = 0$, and $\dot{\delta}(0) = 0$. After Laplace transformation, Formula (16) is changed to (17).

$$\left\{\begin{array}{l} (m + m_y)sv(s) = Y_v v(s) + (Y_r - (m + m_x)u_0)r(s) + Y_\delta\delta(s) \\ (I_{zz} + J_{zz})sr(s) = N_v v(s) + N_r r(s) + N_\delta\delta(s) \end{array}\right. \tag{17}$$

Then the transfer function of propulsion angle δ and yawing angular velocity r can be got.

$$H(s) = \frac{r(s)}{\delta(s)} = \frac{K(1 + T_3 s)}{(1 + T_1 s)(1 + T_2 s)} \tag{18}$$

$$T_1T_2 = \frac{(m + m_y)(I_{zz} + J_{zz})}{Y_v N_r - N_v\left\{Y_r - (m + m_x)u_0\right\}} \quad T_1 + T_2 = \frac{-(m + m_y)N_r - (I_{zz} + J_{zz})Y_v}{Y_v N_r - N_v\left\{Y_r - (m + m_x)u_0\right\}}$$

$$K = \frac{N_v Y_\delta - N_\delta Y_v}{Y_v N_r - N_v\left\{Y_r - (m + m_x)u_0\right\}} \quad T_3 = \frac{(m + m_y)N_\delta}{N_v Y_\delta - N_\delta Y_v}$$

There is a certain inertia in the motion of the unmanned vehicle, and the energy of the propulsion mechanism's is limited, so the movement of the unmanned vehicle has the characteristics of low frequency. Therefore, Formula (18) can be reduced to a one order model at low frequency.

$$H(s) = \frac{r(s)}{\delta(s)} \approx \frac{K}{Ts+1} \tag{19}$$

where $T = T_1 + T_2 - T_3$. The transfer function of the course angle and the propulsion angle is

$$\frac{\psi(s)}{\delta(s)} = \frac{K}{Ts^2+s} \tag{20}$$

Two order yawing response equation can also approximate to a first-order yawing response equation.

$$T\dot{r} + r = K\delta \tag{21}$$

This is the famous Nomoto model. Thus it can be seen, for the podded propulsor USV, the propulsion system is different from the general propeller rudder propulsion system. However, theoretically, it is still in line with the model of Nomoto.

2.3. **Servo system model.** Due to the interaction between the propulsor and the water flow in the actual navigation, there is a very obvious oscillation in the propulsion angle. Therefore, according to the actual situation, based on the experimental process of the acquisition of the real ship data, the servo response model is processed as a two order less damping model.

$$\ddot{\delta} + 2\zeta\omega_n\dot{\delta} + \omega_n^2\delta = K\omega_n^2\delta_r \tag{22}$$

where ω_n is the natural frequency, ζ is the damping ratio, K is the coefficient of proportional, and δ_r is target propulsion angle.

3. USV Model Identification and Verification.

3.1. **Data acquisition.** In order to ensure the accuracy of the experimental data, turning test with 5 degrees and z type test with 15 degrees and 15 degrees are carried out in a relatively stable condition. Part of the data are listed in this paper, as shown in Tables 1 and 2.

Table 1. Turning test data

No.	Time	Angle	Speed	Course
1	0.0	4.9	9.12	0.36
2	0.5	4.9	9.21	0.36
3	1.0	4.9	9.11	0.36
4	1.5	5.0	9.06	6.40
...	...	...	...	...
217	108.0	5.0	8.91	357.35
218	108.5	5.1	9.10	359.49

Table 2. Z test data

No.	Time	Angle	Speed	Course
1	0.0	−12.4	9.01	235.04
2	0.5	−16.9	9.01	224.64
3	1.0	−17.4	9.05	220.78
4	1.5	−12.6	9.11	218.36
...	...	...	...	...
29	14.0	13.3	8.69	232.33
30	14.5	13.3	8.69	237.52

3.2. **Parameter identification.** Firstly, the Nomoto model is identified by z type experimental data. The identification curves are shown in Figure 3.

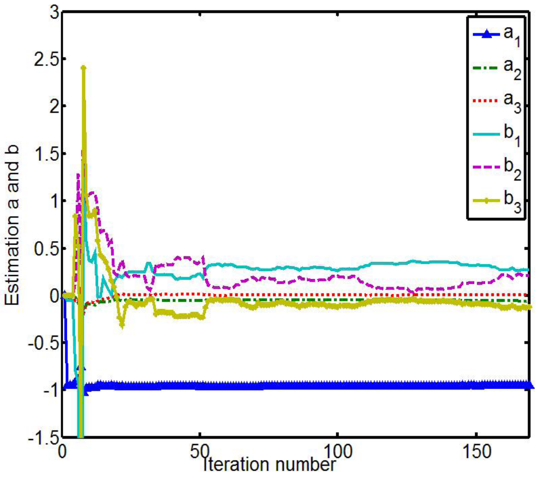

FIGURE 3. Nomoto identification

$a_1 \sim a_3$ and $b_1 \sim b_3$ are the coefficients of discrete transfer function. The transfer function is shown in (23).

$$\frac{0.2743z^2 + 0.2122z - 0.118}{z^3 - 0.9537z^2 - 0.5476z + 0.007182} \tag{23}$$

Discrete transfer function is transformed into a continuous transfer function (24).

$$\frac{1.65s^3 - 10.63s^2 + 88.19s + 225.9}{s^4 + 14.26s^3 + 106.8s^2 + 322s - 0.7904} \tag{24}$$

From Formula (24) it can be seen that the coefficients of higher order terms and the low order terms have a greater difference in the level. So we can omit the higher order items.

$$\frac{225.9}{106.8s^2 + 332s} \tag{25}$$

Compared with Formula (20) it can be obtained that $K = 0.707$ and $T = 0.332$.

Z test experimental data are used to identify the servo response system, and the convergence curves are shown in Figure 4.

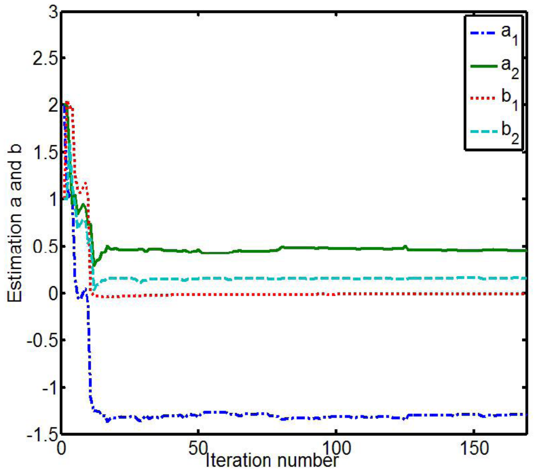

FIGURE 4. Servo system identification

a_1, a_2 and b_1, b_2 are the coefficients of discrete transfer function. The transfer function is shown in Formula (26).

$$\frac{-0.2724z + 0.8464}{z^2 + 1.553z + 0.9169} \tag{26}$$

Formula (26) is transformed into a continuous transfer function.

$$\frac{\delta}{\delta_r} = \frac{0.923 * 0.985^2}{s^2 + 2 * 0.811 * 0.985 + 0.985^2} \tag{27}$$

The average value of natural frequency $\omega_n = 0.958$, the average value of damping ratio $\zeta = 0.811$, and the average value of the amplification factor $K = 0.923$.

4. Identification Result Verification.

4.1. Turning experiment verification.

Under the same state as the actual experiment (speed and propulsion angle), the identified model is used to carry out turning simulation experiment. The simulation result is shown in Figure 5 and the motion trajectory of the real ship is shown in Figure 6.

From Figures 5 and 6 we can obtain that the turning radius of simulation is 85.7621 m and the turning radius of real ship is 84.9716 m. The error is 0.7905 m and it is the range of confidence. Because of the interference of wind and waves, the drift phenomenon has been produced in the real ship turning experiment.

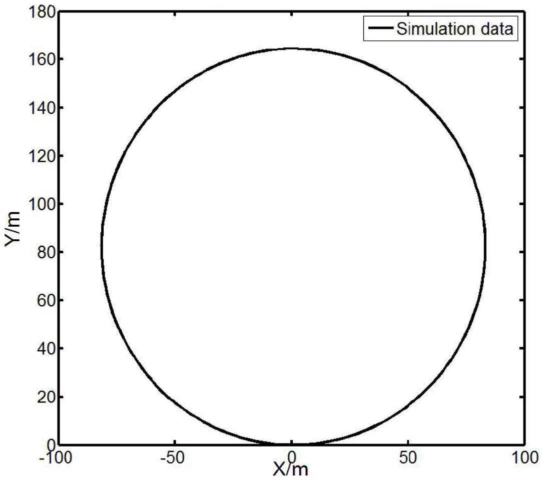

Figure 5. Simulation turning experiment

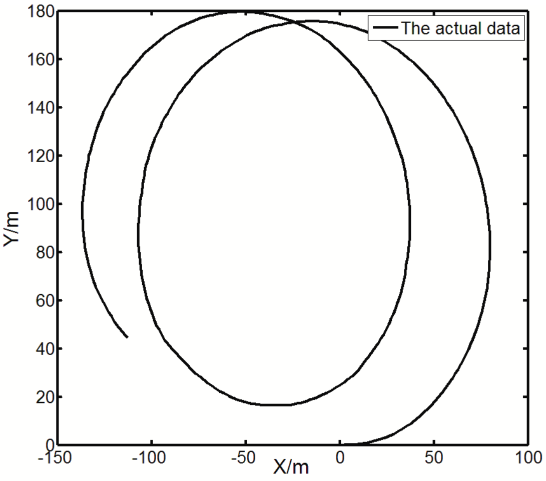

Figure 6. Real turning experiment

4.2. **Z type experimental verification.** In the case of considering the real ship experiment, the identified model is used to carry out z type simulation experiment with 15 degrees and 15 degrees. The comparison results are shown in Figures 7 and 8.

It can be seen from Figures 7 and 8 that the propulsion angle period of simulation is 11.3 seconds and actually is 12.9 seconds. From the above conclusions, it is easy to prove that the two order less damping model is in line with the actual servo system, and the identification results are credible. At this point, the entire fourth chapters can be concluded that the whole identification results are reliable.

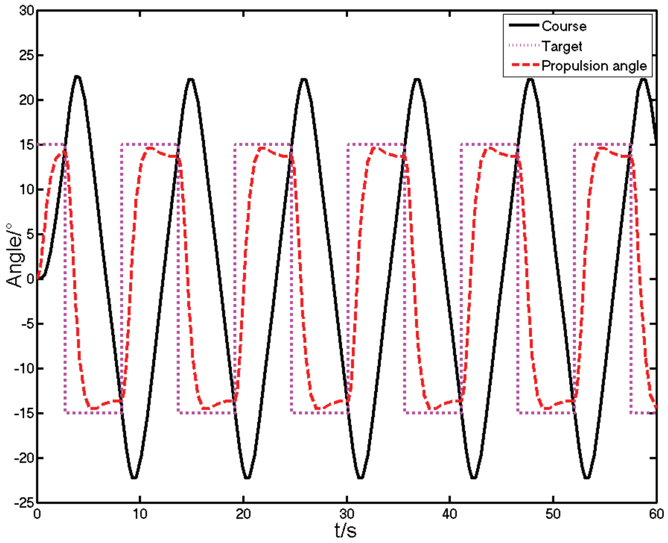

Figure 7. Simulation z type experiment

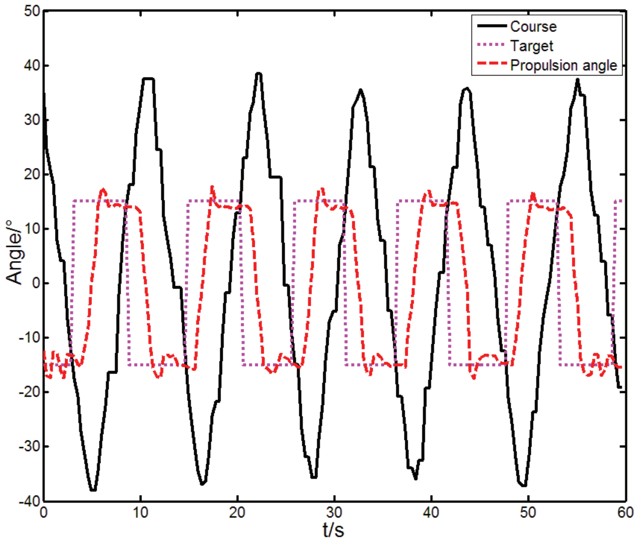

Figure 8. Real z type experiment

5. **Conclusions.** Based on podded propulsion unmanned surface vehicle, this article carries on the analysis and identification of the model. Firstly, USV and its propulsion system are introduced, and under the reasonable assumptions, the response model of USV is proved that it is consistent with the classical Nomoto model. Meanwhile, recursive least square is used to identify Nomoto model and propulsor servo model. Finally, in order to prove the correctness of the model derivation and identification results, in the

simulation, the turning experiment and the z type experiment are carried out, in which the simulation results are compared with the actual data. The final results show that the error of identification results and experimental results are in a credible range, which proves the correctness of this paper. In the next research plan, multi modal model under different conditions will be identified.

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