Research on Dynamic Modeling and Predictive Control of Portable Autonomous Underwater Vehicle

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Abstract—**In order to accurately control the portable AUV, a dynamic modeling method based on computational fluid dynamics (CFD) and a improved Generalized Predictive Control (GPC) method were presented. First, the whole modeling process was described from two aspects: dynamic model derivation and model parameter identification. Second, the validity of the model and modeling method were tested by comparing the simulation data and experimental data. Finally, based on the mathematical model, the improved GPC method was used to control the portable AUV in the depth plane and heading plane, and the better control performance was obtained.**

Keywords- portable AUV, dynamic modeling, GPC, CFD

I. INTRODUCTION

Due to its low-cost, light-weight and easy to handle, Portable AUV developed by Shenyang Institute of automation, Chinese Academy of Sciences has been widely used, as shown in Figure 1. However, the control performance has a direct impact on its potential applications in many fields, Such as recording underwater video, which needs Portable AUV keep a stable attitude, underwater target tracking require that portable AUV has the feature of fast response to the position changes of goal, otherwise it is easy to lose the target. There are also a variety of sensors used for scientific investigations, which have high control requirements for portable AUV in order to obtain the best observation results.

Figure 1. The shape and structure of Pole-ARV

However, the kinetic parameters of AUV change at different speed, and AUV itself has nonlinear characteristic and the interference of external environment is uncertain, all of these factors make the AUV motion control difficult. The traditional PID or subsection PID control algorithm is widely used in real AUV system. The advantages of this method are less parameter, simple and easy to understand. However, it also has some disadvantages, for example, the parameter adjustment takes a long time; in different operating environments, the control system cannot adapt automatically or even is unstable. With the development of computer technology and the theory of nonlinear system, the nonlinear control method of AUV based on model has made great progress. But these methods often require high precision of model, and there are great calculations and many assumptions, which make them not be applied directly to the real AUV.

It can be seen from the above analysis that the current control method has solved some stability and tracking problems at a given speed, but the potential control capability of AUV has not been fully developed. In order to improve the control performance of AUV, we need to study its motion control deeply and obtain an efficient and practical control method of AUV. In order to complete the above task, this paper firstly studied the structure of AUV model and the parameter identification method, and then we made some improvement on traditional GPC, and applied it to the motion control loop of portable AUV. At the same time, the model contrast results and the final control performance of portable AUV were given in this paper.

II. DYNAMIC MODELLING OF PORTABLE AUV

A. Dynamic model derivation

Selecting the coordinate system as shown in Figure 2, $E-\xi\eta\zeta$ is the inertial coordinate system, $G-xyz$ is the body-fixed coordinate system, G is the center of mass, X, Y, Z are the inertial forces acting at the center of mass; K, M and N are the inertial moments acting at the center of mass. We can assume that the origin of the dynamic coordinate is same as the center of AUV's mass.

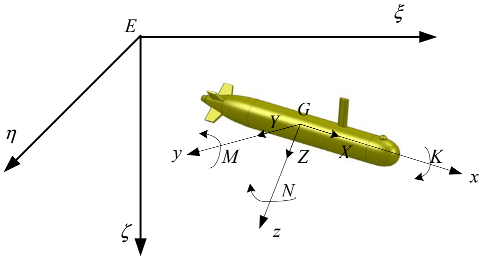

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Figure 2. Definition of coordinate system

The kinetic equations of the portable AUV can be obtained by Newton's law of motion and the theorem of moment of momentum as follows:

$$\begin{cases} m(\dot{u}+qw-rv)=X \\ m(\dot{v}+ru-pw)=Y \\ m(\dot{w}+pv-qu)=Z \\ I_x\dot{p}+(I_z-I_y)qr=K \\ I_y\dot{q}+(I_x-I_z)rp=M \\ I_z\dot{r}+(I_y-I_z)pq=N \end{cases} \tag{1}$$

Where u, v and w are the velocities of the center of mass; p, q and r are the angular velocity of Portable AUV; The mass of portable AUV is m and the inertia tensors are I_x, I_y and I_z

In general, the hydrodynamic forces acting on AUV are related to shape of AUV, kinematic characteristics and fluid parameters, which are functions of these parameters. If the force produced by propeller is processed separately and the roll of portable AUV is not controlled, the dynamic equation can be simplified to five degrees of freedom. The hydrodynamic forces acting on the portable AUV are shown as follows:

$$\begin{cases} X=X_{\dot{u}}\dot{u}+X_{uu}u^2+X_{vv}v^2+X_{rr}r^2+X_{vr}vr+F_{X_\delta} \\ Y=Y_{\dot{v}}\dot{v}+Y_{\dot{r}}\dot{r}+Y_v v+Y_r r+F_{Y_\delta} \\ Z=Z_0+Z_{\dot{w}}\dot{w}+Z_{\dot{q}}\dot{q}+Z_w w+Z_q q+F_{Z_\delta} \\ M=M_0+M_{\dot{w}}\dot{w}+M_{\dot{q}}\dot{q}+M_w w+M_q q+F_{M_\delta} \\ N=N_{\dot{v}}\dot{v}+N_{\dot{r}}\dot{r}+N_v v+N_r r+F_{N_\delta} \end{cases} \tag{2}$$

Where F_{X_δ}, F_{Y_δ}, F_{Z_δ}, F_{M_δ} and F_{N_δ} are the hydrodynamic forces acting on the rudder and elevator of portable AUV, M_0 and Z_0 are the static force and moment produced by the difference between buoyancy and gravity of portable AUV.

B. *Model parameters identification*

The mass and moment of inertia around the three coordinate axes on the left side of the dynamic equations were obtained via the three-dimensional design software "Solidworks".

For the calculation of acceleration coefficient of portable AUV, we approximated it as a cylinder. Under this assumption, the rotational acceleration $\dot{r}$ around the Z axis did not produce fluid inertial force Y, it means $Y_{\dot{r}}=0$; The accelerated motion along the Y axis was not able to produce the fluid inertia moment N, means $N_{\dot{v}}=0$; Similarly, $Z_{\dot{q}}=M_{\dot{w}}=0$. The other acceleration coefficients were calculated according to the empirical formula of the acceleration motion of the cylinder in water, as shown in equation (3).

$$\begin{cases} X_{\dot{u}}=-0.1m \\ Y_{\dot{v}}=Z_{\dot{w}}=-\pi\rho r^2 L \\ M_{\dot{q}}=N_{\dot{r}}=-{}^{1}\!/_{12}\,\pi\rho r^2 L^3 \end{cases} \tag{3}$$

Where L is the length of the portable AUV, r is its radius.

Computational fluid dynamics (CFD) method was used to get the hydrodynamic velocity coefficients, as shown in figure 3, by using software ANSYS to simulate the rotating arm basin, and using different direction flow to get the forces and moments, we identified the velocity coefficients in dynamic model.

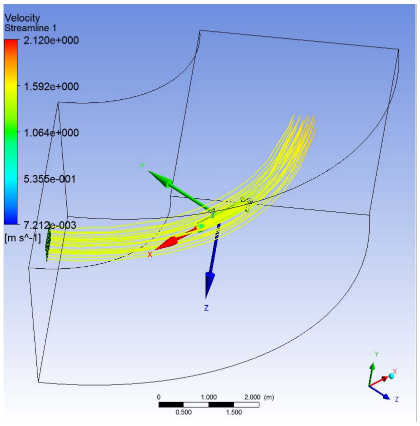

Figure 3. Simulation and calculation of fluid resistance of portable AUV in rotating arm basin

In order to get the hydrodynamic coefficients of the rudder and elevator, the calculation was carried out in CFX by simulating the towing tank, as shown in figure 4.

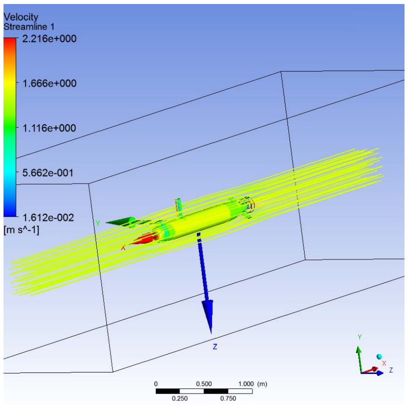

Figure 4. Simulation and calculation of fluid resistance of portable AUV in towing tank at different rudder angle

Through the comparison of several curve fitting results, the hydrodynamic model structure of the rudder and elevator was finally determined, as shown in equation (4).

$$\begin{cases} F_{X_\delta} = X_{uauae} u|u||\delta_e| + X_{uauar} u|u||\delta_r| + X_{uauear} u|u|\delta_e|\delta_r| \\ F_{Y_\delta} = Y_{uaur} u|u|\delta_r + Y_{uauaer} u|u||\delta_e|\delta_r \\ F_{Z_\delta} = Z_{uaue} u|u|\delta_e + Z_{uauear} u|u|\delta_e|\delta_r| \\ T_{M_\delta} = M_{uaue} u|u|\delta_e + M_{uauear} u|u|\delta_e|\delta_r| \\ T_{N_\delta} = N_{uaur} u|u|\delta_r + N_{uauaer} u|u||\delta_e|\delta_r \end{cases} \tag{4}$$

C. Test verification

In order to test the accuracy of the mathematical model, the simulation results of portable AUV was compared with real navigation results in some dynamic process, such as dive, turning heading and spiral dive. The experimental results show that the mathematical model can describe the motion of portable AUV in real environment.

(1) Diving

This case was that Portable AUV dived from the surface to the depth of 80 meters, the real diving curve and simulation diving curve are as shown in figure 5.

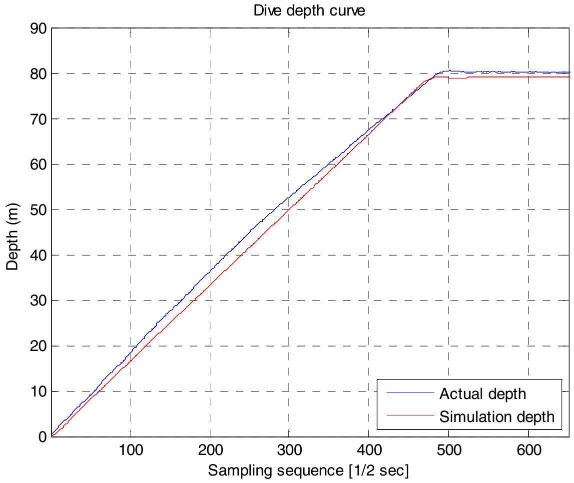

Figure 5. The comparison of portable AUV diving depth in practical navigation and simulation

(2) Turning heading

This case was that portable AUV changed heading from 45 degree to 225 degree when it navigated underwater, the real heading change curve and simulation curve are as shown in figure 6.

(3) Spiral diving

In order to reduce horizontal deviation during dive and make the AUV dive in a small area, we designed a spiral diving task, it could make portable AUV dive along a spiral trajectory. Figure 7 shows the real trajectory and simulation trajectory.

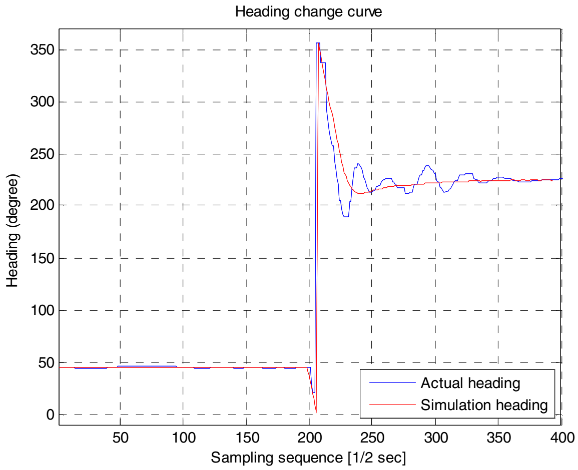

Figure 6. The comparison of portable AUV diving depth in practical navigation and simulation

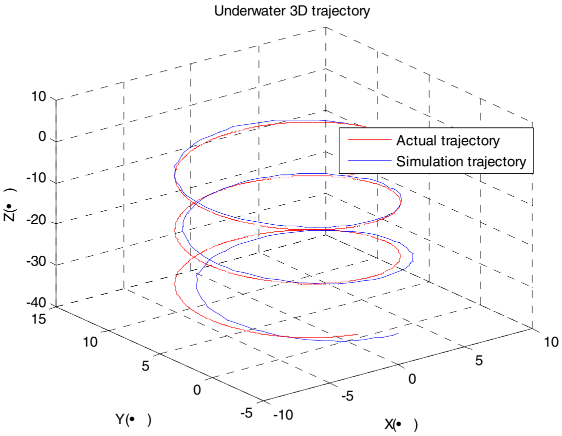

Figure 7. The comparison of portable AUV’ trajectory in practical navigation and simulation

III. CONTROL STRATEGY

In order to accurately control the portable AUV, the improved GPC, which is a kind of MPC (Model Predictive Control), was used in the depth plane and heading plane control.

A. Generalized predictive control

In general, the discrete state-space model is as following:

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k \\ y_k &= Cx_k + Du_k + d_k \end{aligned} \tag{5}$$

Where x is the state variable, y is the output, u is the input, d is the Disturbance, assuming D=0, we can get the predictive equation by recursive computation as follows:

$$\underset{\rightarrow}{y}_{k+1} = Px_k + Ld_k + H\underset{\rightarrow}{u}_k \tag{6}$$

Where,

$$P=\begin{bmatrix}CA\\CA^2\\\vdots\\CA^n\end{bmatrix},\quad H=\begin{bmatrix}CB&0&\cdots&0\\CAB&CB&\cdots&0\\\vdots&\vdots&\ddots&\vdots\\CA^{n-1}B&CA^{n-2}B&\cdots&CB\end{bmatrix},\quad \underset{\rightarrow}{u}_k=\begin{bmatrix}u_{k|k}\\u_{k+1|k}\\\vdots\\u_{k+n-1|k}\end{bmatrix}$$

In this equation, the part of Px_k+Ld_k are known, $H\underset{\rightarrow}{u}_k$ can be decided by choosing the input.

In order to compute the input to make the output follow the desired trajectory, the system optimization function is chosen as follows:

$$J=(R_t-\hat{Y}_t)^T(R_t-\hat{Y}_t)+u_t^T\lambda u_t \tag{7}$$

Where R_t is the expected trajectory, $\hat{Y}_t$ is the predicted output, λ is the weight factors.

Because the performance index is quadratic (and always positive), so a unique minimum can be located by setting the first derivative to zero, finally the result is calculated as equation (8).

$$u_t=(H^TH+\lambda I)^{-1}H^T(R_t-\hat{Y}_t^1) \tag{8}$$

Where H is the predictive matrix, $\hat{Y}_t^1$ is the part of the output vector which is known. Then the first value of vector u is used to control the plant.

B. Improved GPC

Due to external disturbances and uncertainties of model parameters, the predictive results are often biased. Moreover, the calculation of traditional GPC is great because the dimension of the predictive matrix is bigger. Aim at these problems, we make some improvement for the traditional GPC.

First we adopted the incremental inputs to describe the predictive equation, it would make the predictive equation be independent of the work point, and make the predictive error caused by the linearization of AUV model at a given point disappear. It is shown as follows:

$$\Delta\hat{u}(k+i\,|\,k)=\hat{u}(k+i\,|\,k)-\hat{u}(k+i-1\,|\,k) \tag{9}$$

Meanwhile, we assumed that the input variable only vary on the time k, $k+1$, $\cdots$, $k+H_u-1$ and it would no longer change after that time, this would greatly reduce the amount of computation, as shown in follows.

$$\hat{u}(k+1\,|\,k)=\hat{u}(k+H_u-i\,|\,k) \tag{10}$$

Where $H_u\le i\le H_p-1$. Then the predictive equation can be written as follows:

$$\begin{bmatrix}\hat{x}(k+1\,|\,k)\\\vdots\\\hat{x}(k+H_u\,|\,k)\\\hat{x}(k+H_u+1\,|\,k)\\\vdots\\\hat{x}(k+H_p\,|\,k)\end{bmatrix}=\begin{bmatrix}A\\\vdots\\A^{H_u}\\A^{H_u+1}\\\vdots\\A^{H_p}\end{bmatrix}x(k)+\begin{bmatrix}B\\\vdots\\\sum_{i=0}^{H_u-1}A^iB\\\sum_{i=0}^{H_u}A^iB\\\vdots\\\sum_{i=0}^{H_p-1}A^iB\end{bmatrix}u(k-1)+\begin{bmatrix}B&\cdots&0\\AB+B&\cdots&0\\\cdots&\cdots&\cdots\\\sum_{i=0}^{H_u-1}A^iB&\cdots&B\\\sum_{i=0}^{H_u}A^iB&\cdots&AB+B\\\cdots&\cdots&\cdots\\\sum_{i=0}^{H_p-1}A^iB&\cdots&\sum_{i=0}^{H_p-H_u}A^iB\end{bmatrix}\begin{bmatrix}\Delta\hat{u}(k\,|\,k)\\\vdots\\\Delta\hat{u}(k+H_u-1\,|\,k)\end{bmatrix} \tag{11}$$

Depending on the equation of $y(k)=Cx(k)$, the predictive equation of output can be written as follows.

$$\begin{bmatrix}\hat{y}(k+1\,|\,k)\\\hat{y}(k+2\,|\,k)\\\vdots\\\hat{y}(k+H_p\,|\,k)\end{bmatrix}=\begin{bmatrix}c&0&\cdots&0\\0&c&\cdots&0\\\cdots&\cdots&\cdots&\cdots\\0&0&\cdots&c\end{bmatrix}\begin{bmatrix}\hat{x}(k+1\,|\,k)\\\hat{x}(k+2\,|\,k)\\\vdots\\\hat{x}(k+H_p\,|\,k)\end{bmatrix} \tag{12}$$

So the optimal incremental control input value can be computed as follows:

$$\Delta u(k)=(H_I{}^TH_I+\lambda I)^{-1}H_I{}^T(R_k-\hat{Y}_k^1) \tag{13}$$

Where H_I is the predictive matrix of improved predictive equation.

C. Control of portable AUV

The improved GPC was used to the AUV control in simulation platform, and the model built in the above section had been applied in the GPC. The system control loop diagram is shown in figure 8.

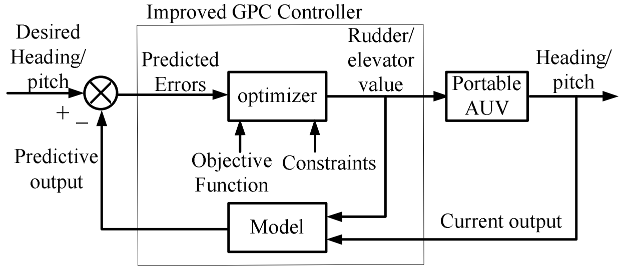

Figure 8. The system control loop diagram

Figure 9 shows the depth control results by using improving GPC. Figure 10 shows the heading control results by using improving GPC.

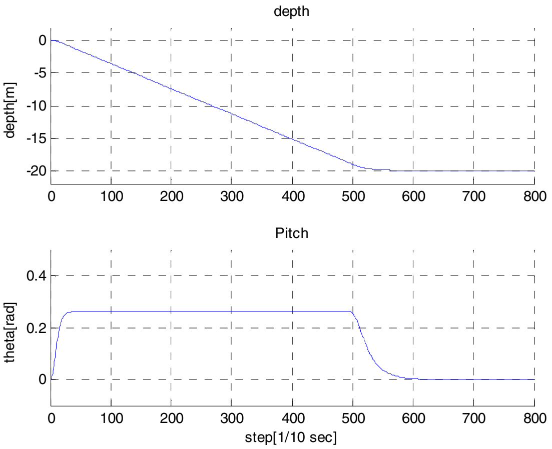

Figure 9. The depth control by using improving GPC

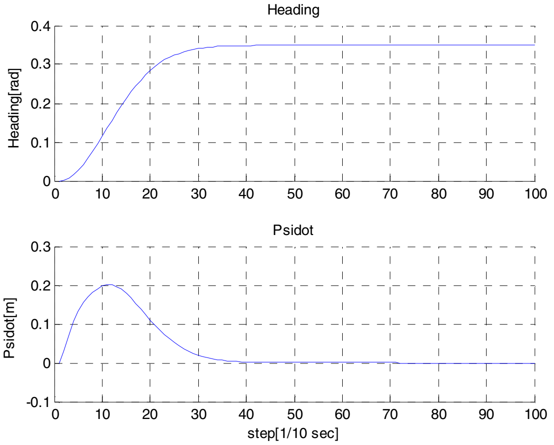

Figure 10. The heading control by using improving GPC

IV. CONCLUSION

This paper introduces a CFD dynamic modeling method and improved model predictive control algorithm for portable AUV. The model was validated by comparing the simulation data and the field test data, the result shown that the model had good stability, and could accurately describe the dynamic characteristics of the portable AUV. Based on the established model, the improved GPC algorithm was applied to the motion control loop of portable AUV, and the better control performance was obtained, which solved the problem that it was difficult to adjust control parameters in traditional control method, such as PID control. Because of its low-cost, light-weight and easy to handle, portable AUV has a broad market prospect in the underwater survey and inspection operations, this study of dynamic modeling and predictive control will play a greater role in future research and application of portable AUV.

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REFERENCES

[1] Junbao Zeng, Shuo Li, Yiping Li, Xiaohui Wang, Shuxue Yan, Performance of the Portable Autonomous Observation System, Proceedings of the OCEANS 2014 MTS/IEEE Conference, April 7-10, 2014, Taipei.

[2] Timothy Prestero, Verification of a Six-Degree of Freedom Simulation Model for the REMUS Autonomous Underwater Vehicle, MScE Thesis, Massachusetts institute of technology, September 2001.

[3] Tang S, Ura T, Nakatani T, Thornton B, and Jiang T, Estimation of the hydrodynamic coefficients of the complex-shaped autonomous underwater vehicle tuna-sand[J]. Journal of Marine Science and Technology, 2009, 14(3): 373–386

[4] Wang CF, Zhang FM, Schaefer D. Dynamic Modeling of an Autonomous Underwater Vehicle: the Ecomapper[J]. Journal of Marine Science and Technology, 2015, 20(2): 199-212.

[5] Jixin Qian, Jun Zhao, Zuhua Xu, Predictive control [M], Beijing: Chemical Industry Press, 2007

[6] Dalei Song, Experimental Research on Estimation and Control for Fly-robot with Rotor Wings, Phd Thesis, Graduate School of Chinese Academy of Sciences, November 2011

[7] J. Witt, S. Boonto, H. Werner.Approximate model predictive control of a 3-DOF helicopter. IEEE Conference on Decision and Control, New Orleans, 2007, USA: 4501-4506

[8] J. A. Rossiter, Model-based predictive control [M], CRC press, 2005