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STABILITY CONTROL OF PROPELLER AUTONOMOUS UNDERWATER VEHICLE BASED ON COMBINED SECTIONS METHOD

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ABSTRACT

Learning from the motion principle of quadrotor, a symmetric propeller AUV, which has small size and low velocity is designed. Compared with the AUV equipped with rudders, it has better maneuverability and manipulation at low velocity. According to the Newton-Euler method, the 6 DOF kinematic model and dynamic model of the propeller AUV are established. A stability controller that consists of 3 different PID controllers is designed. It makes the depth and attitude angle as trigger conditions, and the relevant controller is chosen in different moving process. The simulation experiments simulate ideal motion state and disturbed motion state, and experiments results show that the stability controller based on combined sections method can make the best of mature technology of PID, and meet the control requirements in different stages. It has a higher respond speed and accuracy, improving the stability of the propeller AUV under the disturbance of complex ocean currents.

Keywords: propeller AUV; dynamic model; stability control; simulation

INTRODUCTION

Ocean space is an important competition field of military and economic in the world, and many countries are vigorously developing deep sea exploration technology. As an intercrossed subject of ocean engineering and robot technology, autonomous underwater vehicles (AUVs) have been widely employed in oceanic survey applications, including oceanographic mapping and detection, underwater resources exploration, undersea wreckage salvage, and so on [1-4].

Considering the requirements of machining and reducing the fluid resistance, most of traditional AUVs are revolving body or bionics shape, such as drop type, torpedo type and low-resistance layer fluid type, and they change the velocity and direction by fin, rudder and various propulsions installed at the tail. In this paper, learning from the motion principle of quadrotor, a symmetric propeller AUV is designed. Compared with the shapes of traditional AUV, it has better maneuverability and manipulation at low velocity. By adjusting the rotate speed of four propellers fixed on the rigid cross structure, it can dive, hover, rise, go forward and backward or turn around, which has better maneuverability and flexibility. Based on the combined sections method, a stability controller is designed as well, improving the stability of the propeller AUV under the disturbance of complex ocean currents.

THE PROPELLER AUV MODEL

As shown in Fig.1(a) and 1(b), the propeller AUV has four propellers of which the rotating plane is coplanar. The propellers, fixing at four vertexes, are driven by four independent motors. Motors at diagonal position rotate in the same direction, and motors at adjacent position rotate in the opposite direction. The motion principle is approximately described as follows: each propeller provides lift that is vertical to the fuselage. Without considering interference of other external forces, if propellers' rotating speed or the motors have the same output power, AUV is in the condition of rising, diving or hovering. If the output power is different, the force balance and torque balance will be broken, and then cause changes in attitude and motion direction of the AUV.

(a) Three-dimension graph of model *(b) Real model uninstalled control system*

Fig. 1. Structure of propeller AUV

As shown in Fig.2, OXYZ represents the earth-fixed coordinate and oxyz represents AUV body-fixed coordinate. 6 DOF kinematic modes and attitude parameters are defined in the coordinate system as shown in Table 1.

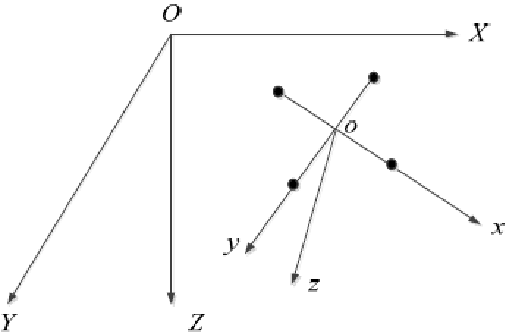

Fig. 2. Earth-fixed coordinate and body-fixed coordinate

According to the parameters in the Table 1, define vectors as follows: $\eta_1 = (x, y, z)^T$, $\eta_2 = (\phi, \theta, \psi)^T$, $\eta = (\eta_1, \eta_2)^T$, $\tau_1 = (F_x, F_y, F_z)^T$, $\tau_2 = (M_x, M_y, M_z)^T$, $\tau = (\tau_1, \tau_2)^T$, $V = (u, v, w)^T$, $\omega = (p, q, r)^T$, $v = (V, \omega)^T$, and the center of gravity position is $r_G = (x_G, y_G, z_G)^T$.

KINEMATIC MODEL

Based on the conclusions of Refs [5], the kinematic model of AUV is given directly as:

$$\begin{cases} \dot{\eta}_1 = J_1(\eta_2)V \\ \dot{\eta}_2 = J_2(\eta_2)\omega \end{cases} \tag{1}$$

Where, $J_1(\eta_2)$, $J_2(\eta_2)$ represent the transformation matrixes of linear velocity and angular velocity from the body-fixed coordinate to the earth-fixed coordinate, and the concrete expressions are given as follows:

Table 1 Motion modes and attitude parameters of propeller AUV

Degree of freedom	Motion modes	Force/torque (in the body-fixed coordinate)	Linear velocity/ angular velocity (in the body-fixed coordinate)	Location/Euler angles (in the earth-fixed coordinate)
1	Back/forward (movement along the x-axis)	F_x	u	x
2	Sway (movement along the y-axis)	F_y	v	y
3	Lift/dive (movement along the z-axis)	F_z	w	z
4	Roll (rotation along the x-axis)	M_x	p	φ
5	Pitch (rotation along the y-axis)	M_y	q	θ
6	Yaw (rotation along the z-axis)	M_z	r	ψ

$$J_1(\eta_2)=\begin{bmatrix}\cos\theta\cos\psi & -\sin\psi\cos\phi+\cos\psi\sin\theta\sin\phi & \sin\psi\sin\phi+\cos\psi\cos\phi\sin\theta\\ \sin\psi\cos\theta & \cos\psi\cos\phi+\sin\phi\sin\theta\sin\psi & -\cos\psi\sin\phi+\sin\theta\sin\psi\cos\phi\\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi\end{bmatrix} \tag{2}$$

$$J_2(\eta_2)=\begin{bmatrix}1 & \sin\phi\tan\theta & \cos\phi\tan\theta\\ 0 & \cos\phi & -\sin\phi\\ 0 & \sin\phi\sec\theta & \sec\theta\cos\phi\end{bmatrix} \tag{3}$$

DYNAMIC MODEL

Based on the theorem of momentum and theorem of angular momentum, the dynamic formulas in body-fixed coordinate are summarized as follows:

$$\begin{aligned}
&m[\dot{u}-vr+wq-x_G(q^2+r^2)+y_G(pq-\dot{r})+z_G(pr+\dot{q})]=F_x\\
&m[\dot{v}-wq+ur+x_G(qp+\dot{r})-y_G(p^2+r^2)+z_G(qr-\dot{p})]=F_y\\
&m[\dot{w}-uq+vp+x_G(rp-\dot{q})+y_G(rq+\dot{p})+z_G(p^2+q^2)]=F_z\\
&I_x\dot{p}+(I_z-I_y)qr+m[y_G(\dot{w}+vp-uq)-z_G(\dot{v}+ur-wq)]=M_x\\
&I_y\dot{q}+(I_x-I_z)rp+m[z_G(\dot{u}+wq-vr)-x_G(\dot{w}+vp-uq)]=M_y\\
&I_z\dot{r}+(I_y-I_x)pq+m[x_G(\dot{v}+ur-wp)-y_G(\dot{u}+wq-vr)]=M_z
\end{aligned} \tag{4}$$

While AUV is moving underwater, it is mainly influenced by hydrodynamic forces and control forces, as shown in Eq.(5).

$$\tau=\tau_{AM}+f_v+M_R+f_p \tag{5}$$

Where, τ_{AM} is fluid inertia force, f_v is fluid viscous force, M_R is restoring force, and the concrete expressions are given in Refs [6]. The hydrodynamic parameters of propeller AUV are obtained by CFD method and hydrodynamic experiments. f_p is the pull force produced by the propellers, and in body-fixed coordinate.

$$f_p=(0,0,-\sum_{i=1}^{4}F_i,0,0,Q) \tag{6}$$

Where, F_i is the pull force produced by the propeller *i*, and Q is pull torque.

According to the research object and specific issues, some reasonable assumptions are made during the computation process:

(1) AUV is rigid body.

(2) The body has two symmetry planes of upper and lower, left and right. The origin of the body-fixed coordinate is buoyant center, which is coincident with the center of gravity, and that means $r_G=(0,0,0)^T$.

(3) If AUV moves slightly near the equilibrium position, it is assumed that the relationship between the fluid damping force and motion parameters is linear approximately. Thus, $\sin\theta=\theta$, $\cos\theta=1$.

Based on the analysis above, the transfer functions of depth, pitch angle and roll angle are calculated using MATLAB as follow:

$$G_z(s)=\frac{9.1640s^2-134.5019s-902.4235}{s^4+18.0997s^3+121.1859s^2+390.2967s+268.4251} \tag{7}$$

$$G_\theta(s)=\frac{-11.378s-35.0461}{s^4+18.0997s^3+121.1859s^2+390.2967s+268.4251} \tag{8}$$

$$G_\phi(s)=\frac{-11.378s-35.0461}{s^4+18.0997s^3+121.1859s^2+390.2967s+268.4251} \tag{9}$$

THE STABILITY CONTROLLER

DESIGN OF A STABILITY CONTROLLER

Due to the presence of external disturbance, whatever the AUV is going forward or backward, even in hover, vertical rise or dive state, it requires a certain pitch angle to maintain the predetermined trajectory. If turning around, it also requires a certain roll angle. According to the AUV model, several attitude angles can't be confirmed in some special situations, the singularity will appear [7]. For example, when θ=±90°, the roll angle φ is uncertain. Due to the effects of unknown ocean currents in real environment, the attitude angles are easily to change. And the AUV will be instable and even out of control. Various kinds of research have studied the motion control methods, such as self-adaptive control [8-9], neural network control [10-11], and fuzzy logic control [12-13] etc., which make the AUV robust and more resistant to interference. However, most of these new methods are only applied in simulation or experiments, and rarely for engineering and commercial application. It is pointed out in Refs [14] that, when the model is decoupled linearly, each subsystem can be controlled independently using linear control theory. PID controller has advantages of simple algorithm and high reliability. Learning from the idea of combined sections method in Refs.[15], the stability controller of propeller AUV is composed of several PID controllers, and each of them is corresponding to a certain motion state. PID controllers switch each other by triggering critical state value.

As shown in Fig.3, AB represents that propeller AUV dives vertically from water surface to predetermined depth, and DE represents contrary process to AB. During both AB and DE, because the influence of surface wave is obvious, the controller must have a better robustness. In stable motion process BC, attitude angles need to keep within a certain range, and avoid jittering. In case large current interference appears at point C, the augmentation controller should be started to prevent the AUV to be out of control, which is caused by the attitude angles exceeding the critical values. Likewise, the AUV may overturn owing to unforeseen circumstances in diving and rising stages, and it should be taken into consideration when design the controllers.

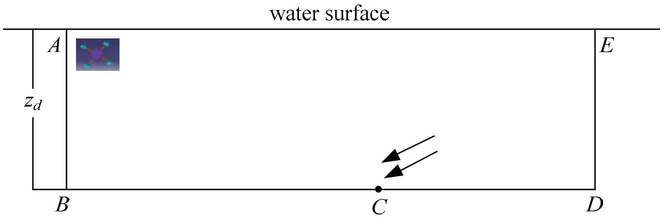

Fig.3 Motion process of AUV in a whole cycle

The stability controller consists of three parts, which are diving/rising controller Ctr1, smooth controller Ctr2 and augmentation controller Ctr3. The diving depth Z, pitch angle θ and roll angle φ are selected as switch triggering variables. Since the roll direction and pitch direction are symmetrical, take Z and θ as examples to introduce the whole process. Starting Ctr1, the propeller AUV begins to dive to a predetermined depth Zd (Zd=10m), with pitch angle θ<5°. After reaching Zd, the Ctr2 is started, then adjust the moving velocity according to the actual situation, and make 5°<θ<30°, therefore, the AUV will be in a stable state. During the rising process, adjust and keep θ<5°, and Ctr1 is restarted. Whichever stage the AUV is in, if it is disturbed strongly, and make θ>30°,Ctr3 will be started to resume its safe moving attitude. The switch mode of controllers is shown in Fig.4.

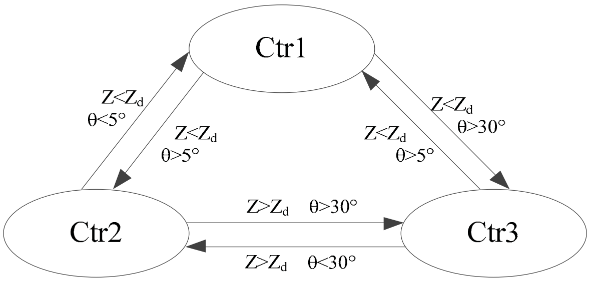

Fig.4 Switch mode of controllers

THE STABILITY OF CONTROLLER

Based on the Ziegler-Nichols method, the parameters of Ctr1, Ctr2, and Ctr3 after setting are given in Table 2.

Table 2 PID parameters

ID NO.	K_p	K_i	K_d
Ctr1	0.045	0.045	0.30
Ctr2	0.015	0.015	0.20
Ctr3	0.030	0.010	0.35

When Ctr1 works, $K_p = 0.045, K_I = 0.045, K_D = 0.30$.

The transfer function of PID controller is: $G_{c1} = K_p + \frac{K_I}{s} + K_D s$, so the system state equation can be get as follow.

$$\begin{cases} \dot{x} = Ax + bu \\ y = Cx \end{cases} \tag{10}$$

Where,

$$A = \begin{bmatrix} -8 & -5.6569 & 0 & 0 \\ 5.6569 & 0 & 0 & 0 \\ -22.6772 & -23.0649 & -10.0997 & -2.8963 \\ 0 & 0 & 2.8963 & 0 \end{bmatrix},$$

$$b = \begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 0 & 0 & 3.1641 \end{bmatrix} \tag{11}$$

According to the Lyapunov-stability theory and $AP + PA^T = -Q$, set

$$Q = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{12}$$

The matrix *P* can be obtained:

$$P = \begin{bmatrix} 0.1250 & -0.0884 & 0.0252 & 0.1535 \\ -0.0884 & 0.2500 & -0.2998 & -0.2042 \\ 0.0252 & -0.2998 & 0.7272 & -0.1726 \\ 0.1535 & -0.2042 & -0.1726 & 1.7535 \end{bmatrix} \tag{13}$$

After calculation, the 4 order principle minors of *P* are 0.1250, 0.0234, 0.0070 and 0.0078 respectively, and all are greater than zero, which means that *P* is positive definite matrix, so the system is stable. Similarly, when Ctr2 or Ctr3 works, the system is stable as well. The system can be proved approximately global stable due to the very short switching time among these three controllers.

THE SIMULATION RESULTS AND ANALYSIS

THE SIMULATION CONDITIONS

As shown in Fig.5, the simulation model of pitch channel is established under the circumstance of MATLAB/SIMULINK. It mainly consists of 5 parts: stateflow module, PID module, transfer function module, switch module and display module. Stateflow module, which involves 3 states of diving/rising state, smooth moving state and augmentation moving state, is used to set AUV's motion states and realize transition. PID module accomplishes attitude control and depth control of the AUV, so as to achieve the predetermined results. Transfer function module describes the AUV's dynamic model. Switch module selects different PID controllers according to the output signal of the state stream. Display module shows the motion state and change trend. *z* and *x* are depth and pitch angle respectively.

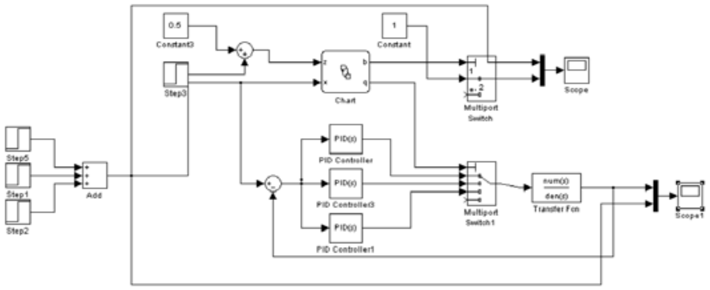

Fig.5 Control simulation model for pitch channel

ANALYSIS OF SIMULATION RESULTS

Simulation process (1): the AUV dives vertically first and then moves horizontally under the ideal or small interference conditions, as shown in Fig.6. During the period of t < 10s, the AUV is diving vertically and its depth is less than 10 m. With two periods of 0-5 s and 5-10 s, the input signals of pitch angle are 1° and 4° respectively, and both of them are less than the setting critical value of the diving/rising state. In this process, the diving state is relatively stable, which shows that Ctr1 can meet the control requirements. When t = 10 s, since the diving depth exceeds 10 m, which is the predetermined depth, the AUV stops diving and begins to move horizontally or approximate horizontally. The input signal of pitch angle is 9°, and smooth controller works. After about 5 s, the AUV reaches a stable moving state. Because of the different controller parameters and real circumstances, the rise time of step response of smooth moving stage is about 2.5 s, while in diving stage it is less than 1s. At the same time, overshoot when it reaches steady state of the diving stage are smaller than that of the smooth moving stage. When diving or rising vertically, the AUV must keep an approximately horizontal attitude with a small pitch angle (θ <5°), which requires better rapidity and higher accuracy. However, when moving horizontally or approximately horizontally, the AUV will adjust its pitch angle in a larger scope (5°< θ <30°) to meet the requirements of changing the moving velocity.

Simulation process (2): the AUV is moving horizontally, and when t = 15 s, it encounters strong currents, which cause that the instantaneous pitch angle is greater than 30°, as shown in Fig.7. The stability controller generates augmentation stimulus, meanwhile, augmentation controller will be started so that it can adjust the attitude angle quickly to avoid being out of control.

As shown in Fig.8, the control error of Ctr1 is less than 2°, which of Ctr2 is less than 5°. In almost all actual cases, the attitude angles change continuously. But the simulation input in this paper is a step signal under ideal conditions, which is more rigorous. So the stability controller can meet the control requirements.

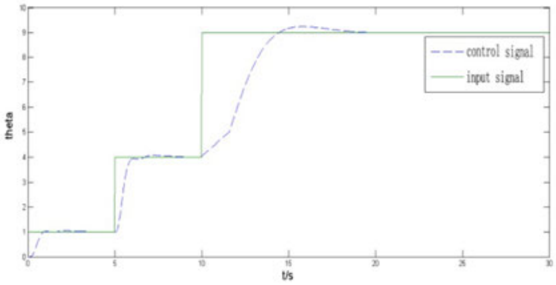

Fig.6 Control process of pitch angle

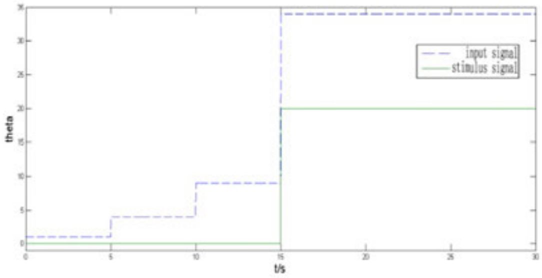

Fig.7 Stability stimulus

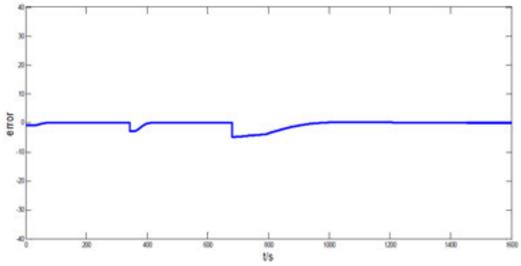

Fig 8 Error curve

CONCLUSIONS

1. Learning from the motion principle of quadrotor, a symmetric propeller AUV, which has small size and low velocity, is designed. Compared with the AUV equipped with rudders, it can dive, hover, rise, go forward and backward or turn around by adjusting the rotate speed of four propellers fixed on the rigid cross structure, which has better maneuverability and flexibility. The linear models of depth, pitch angle and roll angle are obtained.
2. Based on the thoughts of combined sections method, a stability controller is designed. It is composed of 3 PID controllers, which switch each other by triggering critical state value, and each of them is corresponding to a certain motion stage, improving the stability of the propeller AUV under the disturbance of complex ocean currents. The simulation results demonstrate the effectiveness of the stability controller.

REFERENCE

1. Forrest A L, Laval B, Doble M J, et al. AUV measurements of under ice thermal structure[C]//Proceedings of MTS/IEEE OCEANS 2008. Quebec City: IEEE Press, 2008:1-10.

2. Jun B H, Park J Y, Lee F Y, et al. Development of the AUV 'ISiMI' and a free running test in an ocean engineering basin [J]. Ocean Engineering, 2009, 36(1): 2-14.

3. PETRCH J, WOOLSEY C A, STILWELL D J. Planar flow model identification for improved navigation of small AUVs [J]. Ocean Engineering, 2009, 36(1): 119-131.

4. JIANG Jun, SONG Baowei, PAN Guang, et al. Study on design of shape and hydrodynamic layout for ultra-low-speed AUV [J]. TORPEDO TECHNOLOGY, 2011, 19(5): 321-324.

5. JIA Heming. Study of spatial target tracking nonlinear control of underactuated UUV based on backstepping [D]. Harbin: Harbin Engineering University, 2012.

6. DU Bing. Dynamic behavior and control strategy of a landing AUV [D]. Tianjin: Tianjin University, 2012.

7. YAN Weisheng. Torpedo sailing mechanics[M]. Xi'an: Northwestern Polytechnical University Press, 2005

8. Do K D, Pan J. Robust and adaptive path following for underactuated autonomous underwater vehicles. Proceedings of the American Control Conference, Denver, CO, USA, 2003,3:1994-1999

9. Roberts A, Tayebi A. Adaptive position tracking of VTOL UAVs [J]. IEEE Transactions on Robotics, 2011, 27(1):129-142

10. Sarath B S, Kumar C S, Faruqi M A. A neural network online controller for autonomous underwater vehicle. Industrial Technology,2006:2320-2324

11. CONG Shuang, SONG Ruixiang, Qian Zhen, et al. Improved B-spline fuzzy neural networks [J]. Control Theory and applications, 2001, 18(2): 277-280.

12. ZHAO Jing. AUV fuzzy neutral network hybrid learning algorithm control [D]. Harbin: Harbin Engineering University, 2007.

13. ZHANG Bo. Research on fuzzy PID controller [J]. Journal of Software Guide, 2010, 9(1):22-25.

14. SUN Wei. Research on low cost flight control and application of UAV [D]. Nanjing: Nanjing University of Aeronautics and Astronautics. College of Aerospace Engineering, 2011

15. LI Guodong, SONG Zili, WU Hua, et al. Design of stability augmentation hybrid controller for a quadrotor unmanned air vehicle [J]. JOURNAL OF HARBIN INSTITUTE OF TECHNOLOGY, 2013,45(5):86-90.

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