Research on Motion Control Algorithms for Underactuated System of Underwater Vehicle

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Keywords: Underwater vehicle; Underactuated system; Motion control; Trajectory tracking

Abstract: Aiming at the unknown model and external disturbance of underwater vehicle, the Serret-Frenet coordinate system is used to describe the path tracking error. Based on adaptive fuzzy backstepping sliding mode control method, the horizontal and vertical path tracking control systems are designed respectively. The path parameters are regarded as an additional control variable, and the path tracking error is gradually reduced by adjusting its change rate. The simulation results show that the designed horizontal and vertical path tracking control system based on adaptive fuzzy inversion sliding mode method has good adaptability and strong robustness.

1. Introduction

Underactuated system refers to a system whose dimension of space is less than that of configuration space, that is, a system whose command input is less than the degree of freedom of the system. Underactuated control underwater vehicle is an autonomous underwater vehicle whose input dimension is less than the degree of freedom of the system [1-3]. In order to perform precise underwater tasks, autonomous underwater vehicles (AUVs) with six degrees of freedom and full freedom movement usually need to be equipped with multiple thrusters. According to the driving characteristics, underwater vehicles are divided into underactuated "overactuated" and fully actuated underwater vehicles [4-5]. As shown in Figure 1, the input-output thrust feedback diagram reflects the relationship between the control system and the output system of a six-degree-of-freedom underwater vehicle.

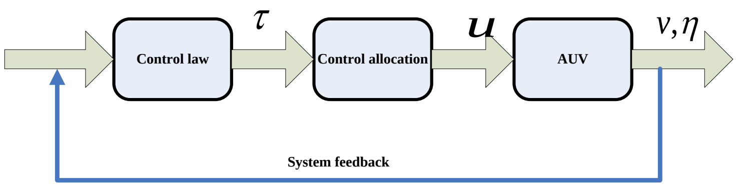


Figure 1. Thrust feedback chart

2. Underwater-Driven AUV Horizontal Motion Control

A stabilization control law is designed by simplifying the three-degree-of-freedom horizontal motion equation and trajectory equation of under-actuated AUV. Based on the global differential homeomorphic coordinate transformation, the mathematical model of underactuated AUV is transformed into a cascaded nonlinear system [6-8]. It is proved that the stabilization problem of the original system can be simplified to that of the cascaded subsystem. The stabilization control law is obtained through the state feedback control research, and the convergence of the control law is proved, and the stabilization simulation experiment is demonstrated [9].

The kinematics equation of the transformation between the inertial coordinate system and the dynamic reference coordinate system of the underwater robot hull is as follows:

$$\tilde{\eta}=R(\varphi)v \tag{1}$$

which is:

$$\begin{cases} \tilde{x} = u\cos\varphi - v\sin\varphi \\ \tilde{y} = u\sin\varphi + v\cos\varphi \\ \tilde{\varphi} = r \end{cases} \tag{2}$$

Where v= $\left[u, v, r\right]^T$ represents the velocity of AUV in the body-following coordinate system. R is the position conversion matrix between the geodetic coordinate system and the hull moving coordinate system.

$$R(\varphi) = \begin{bmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

And satisfied $R^T = R^{-1}$.The coordinate system is shown in Figure 2.

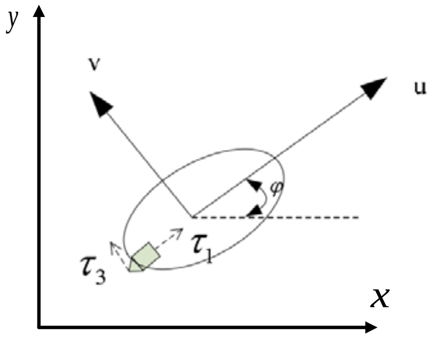


Figure 2. AUV planar motion coordinate system

In the dynamic coordinate system of the hull, the dynamic equation of under-actuated AUV with three degrees of freedom in the horizontal plane can be written.

$$M\tilde{v} + C(v)v + D(v)v + g(\eta) = \tau \tag{4}$$

$\tau = \left[\tau_1, \tau_2, \tau_3\right]^T$ represents the three control inputs of the motion control system, and represents the longitudinal thrust and lateral thrust and the turning moment of AUV respectively. Horizontal motion of underactuated AUV does not have transverse control input.

Aiming at the horizontal motion control model of under-actuated AUV with longitudinal input and head-rocking input, a cascade system is designed based on the trajectory tracking error equation. A new trajectory tracking control method is proposed by using cascade system theory. Firstly, the reference motion equation of virtual AUV is assumed, and the tracking error equation is obtained [10]. The tracking error system is expressed in cascade form by differential co-assignment transformation, and then the stabilization control problem of cascade system is transformed into the stabilization control problem of two subsystems. In the design of under-actuated AUV trajectory tracking control, the main considerations are: (1) to determine the trajectory tracking error model; (2) to design the stabilization of cascade system error model.

3. Vertical Path Tracking Control of Underwater Vehicle

Driven by the control system, the underwater vehicle travels from any initial position to a pre-designed trajectory described by time-independent curve parameters and travels along the path at the desired speed. Considering the cost and weight reduction, most underwater robots have no thrusters in both horizontal and vertical directions, only the longitudinal velocity and bow/pitch angular velocity are directly controllable, which is a typical under-actuated non-linear system. This makes the path tracking control of underwater robots a very challenging problem. The design of adaptive fuzzy backstepping sliding mode path tracking controller for vertical plane is as follows:

Step 1: design of speed adaptive fuzzy backstepping sliding mode controller

The longitudinal speed controller is:

$$X = \frac{1}{b_1(v,t)}\left(-f_1(v,t) - d(S_1,t) - (h_1 + \beta_1)S_1\right) \tag{5}$$

There are 125 fuzzy rules for approximating $f_1(x,t)$ and $b_1(x,t)$ respectively, and 3 fuzzy rules for approaching $d_1(t)$. The corresponding adaptive control law is:

$$\chi_{f1} = \gamma_{f1} S_1 \Omega_{f1}(v); \quad \chi_{b1} = \gamma_{b1} S_1 \Omega_{b1}(v) X; \quad \chi_{d1} = \gamma_{d1} S_1 \Omega_{d1}(S_1) \tag{6}$$

In order to converge the longitudinal velocity tracking error of the underwater vehicle, the value of H1 can be selected to make | Q_1 | > 0, so as to ensure that the longitudinal velocity can converge to the desired longitudinal velocity, when $Q_1 = h_1$.

Step 2: Design of adaptive fuzzy backstepping sliding mode controller for pitch angle:

$$\alpha_{d1} = \arctan\left(\frac{w}{u}\right) \tag{7}$$

$$\begin{cases} \tau_e = -U_P - r_P n_e + U_d \cos\Theta \\ n_e = r_P \tau_e - U_d \sin\Theta \end{cases} \tag{8}$$

From the path tracking error model, it can be seen that the tangential tracking τ_e can be controlled by selecting appropriate Up, but the normal tracking error ne must be controlled by Θ. Taking Θ as the virtual control input of n_e and choosing the stabilization function as:

$$\Theta_d = \arctan(k_n, n_e), \Theta \in \left(-\frac{\pi}{2}, \frac{\pi}{2}\right) \tag{9}$$

There are 125 fuzzy rules for approximating $f_3(x,t)$ and $b_3(x,t)$ respectively, and 3 fuzzy rules for approaching $d_3(t)$. The corresponding adaptive control law is:

$$\chi_{f3} = \gamma_{f3} S_2 \Omega_{f3}(v); \quad \chi_{b3} = \gamma_{b3} S_2 \Omega_{b3}(v) X; \quad \chi_{d3} = \gamma_{d3} S_2 \Omega_{d3}(S_2) \tag{10}$$

In order to converge the heading tracking error of the underwater vehicle, the value of h_2, c_1 and k_1 can be selected to make | Q_2 | > 0, so that the heading angle can converge to the desired heading angle. Here:

$$Q_2 = \begin{pmatrix} k_1 + h_2 c_1^2 & h_2 c_1 - \frac{1}{2} \\ h_2 c_1 - \frac{1}{2} & h_2 \end{pmatrix} \tag{11}$$

4. Simulation Experiment and Result Analysis

In order to verify the effectiveness of the designed vertical path tracking controller, the simulation of WL-3 micro underwater vehicle is carried out by using MATLAB/SIMULINK. The nominal model is used as the controlled object.

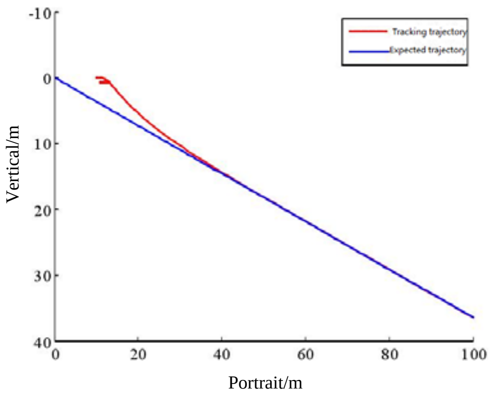
Table 1 Vertical path tracking control parameters

Control parameters	value	Control parameters	value	Control parameters	value Control parameters
h_1	1	h_2	0.4	γ_{f1}	0.6
β_1	0.2	β_2	0.2	γ_{b1}	0.3
ρ_1	0.6	ρ_2	$\pi/3$	γ_{d1}	0.2
σ_1	0.26	σ_2	$\pi/25$	γ_{f3}	$\pi/13$
c_1	0.6	K_t	6	γ_{b3}	$\pi/26$
k_1	1	K_n	2	γ_{d3}	$\pi/13$

Assuming that the micro underwater vehicle is disturbed by the external interference of [5N 5N 5N/m], using the control parameters as shown in Table 6.2, the straight line and sinusoidal curve are selected as the tracking tracks respectively.

The parametric equation Ω for a straight line path is

$$\begin{cases} \xi_p = s \\ \varsigma_P = \tan 20^\circ s \end{cases} \tag{12}$$



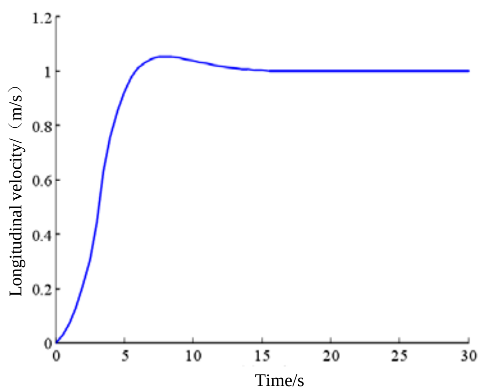
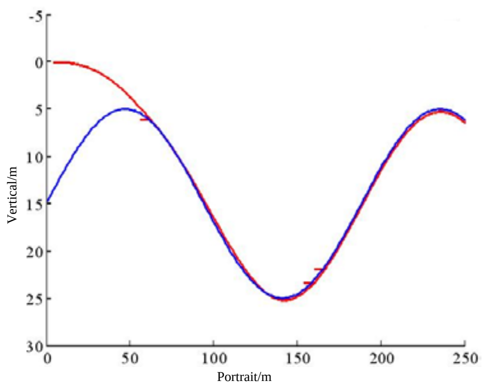


Figure 3. Linear path tracking

Figure 4. Longitudinal vcelocity control curve

The parametric equation AAA for sinusoidal path is:

$$\begin{cases} \xi_p = s \\ \varsigma_P = 10\cos\left(\dfrac{s}{30} + \dfrac{\pi}{2}\right) + 15 \end{cases} \tag{13}$$



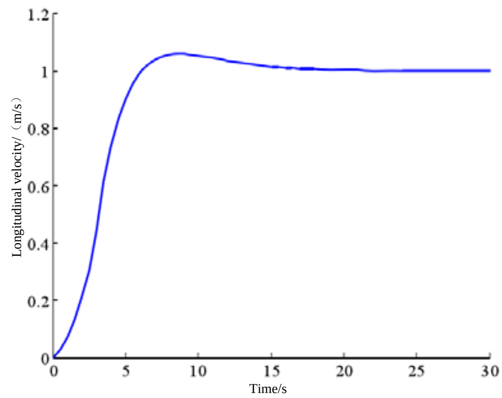


Figure 5. Sinusoidal curve path tracking

Figure 6. Longitudinal velocity control curve

The simulation results (Figure 3-6) show that the designed vertical path controller can quickly converge the longitudinal velocity of the underwater vehicle to the desired value when the model of the underwater vehicle is unknown and disturbed by the outside world. The vertical path tracking control of the underactuated underwater vehicle is realized, and the path tracking error is guaranteed to converge gradually to zero. It should be pointed out that in the process of tracking straight line and sinusoidal curve, the maximum pitch angle of the underwater vehicle is 23.7 degrees and 19.2 degrees, respectively, which fully meets the requirement that the pitch angle should not exceed 30 degrees. For different tracking trajectories, the same control parameters can be used, which reflects the good adaptability and robustness of the controller.

5. Conclusion

Although underactuated control technology has made some achievements in theoretical research and practical application: important progress has been made in the research of underactuated robot's non-linear reachability, non-linear controllability and structural controllability, but the related research is still in the stage of theoretical development, and many aspects need to be improved and perfected. In addition, due to the non-holonomic constraints of under-actuated system, the under-actuated AUV can not track any spatial track curve. Therefore, for the tracking problem of under-actuated AUV space target track, the design method of motion controller needs to be studied in depth. Therefore, it is an inevitable trend for the research of under-actuated autonomous underwater vehicle to continuously put forward new control methods and develop control strategies suitable for under-actuated autonomous underwater vehicle (AUV) combined with various control technologies to achieve system motion planning and trajectory tracking.

Acknowledgements

This work is supported by the scientific research project of institutions of higher learning of Hainan province(No.: hnky2018-67); Science and technology cooperation project of the institute of Sanya(No.: 2016YD29); Youth project of Hainan natural science foundation(No.: 619QN242).

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