Path-following control of remotely operated vehicle based on improved hybrid fuzzy PID control

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Abstract: A remotely operated vehicle (ROV) is essentially an underwater mobile robot that is controlled and powered by an operator outside of the robot working environment. The issue of 2D path-following control of ROV was studied. Based on single-input fuzzy controller expressed in analytical form, an improved hybrid fuzzy PID control algorithm was proposed. And its application to the tracking control of path-following approach angle was investigated. The design and parameter tuning of the tracking controller was studied, and the stability of the tracking control system based on the proposed hybrid fuzzy PID control algorithm was analyzed using small gain theorem . At last, simulation studies using the nonlinear dynamic model of ROV were implemented, and the results demonstrate the robustness and adaptability of the hybrid fuzzy PID based path-following control system, and the ROV can follow the predefined path precisely.

Key words: ROV; Improved hybrid fuzzy PID control; Path-following

1. Introduction

A remotely operated vehicle (ROV) is tethered and power-supplied underwater vehicle. The use of this vehicle is rapidly increasing in the deeper and riskier areas that drivers can not reach. ROV has the ability of powerful deep-sea assignments, so it gets more and more application on marine scientific research, resource agent, equipment maintenance, etc [1]. High performance of the ROV control system has very important impact on the research and development of the ROV system.

ROV path-following means that through the rational design of the control input, the robot sails along a given reference path from the initial state in the inertial coordinate system [2]. In the present work, this paper uses improved hybrid fuzzy PID control method. Based on PID control structure, keep its conventional integral and differential items unchanged, using the fuzzy controller to replace the proportional term of conventional PID controller, the simulation demonstrates the robustness and adaptability of the improved hybrid fuzzy PID controller.

2. Hybrid fuzzy P+ID control

The conventional PID control can be described as the follows:

$$O(k) = K_p e(k) + K_I \sum_{i=1}^{k} e(i)T + K_D \dot{e}(k) \tag{1}$$

In the formula, the role of the integral term is mainly decrease the steady-state error of the control system; the role of the differential term is mainly to increase system damping, keep the control response smoothly and improve the stability of the system; While proportional term affect the rapidity of system response, the overshoot, control precision and stability.

This paper makes nonlinear transformation by the error $e(k)$ in proportion term by using fuzzy controller and takes the output $e_f(k)$ of the fuzzy controller as the new error. Keep the structure, parameters, $e(k)$ in the integral term and $\dot{e}(k)$ in the differential term unchanged. To improve the control effect and response capability, we define the sliding error (2) as the input of fuzzy controller.

$$S^*(k) = \frac{S(k)}{G_e} = \frac{\left(\lambda e(k) + (1-\lambda)\dot{e}(k)\right)}{G_e} \tag{2}$$

In the same way, the output of the fuzzy controller can be expressed as:

$$e_f^*(k) = \frac{e_f(k)}{G_u} \tag{3}$$

In the formula, G_u is the normalization factor of $e_r(k)$ .The input $S^*(k)$ and the output $e_f^*(k)$ can be divided into 7 levels: PB, PM, PS, ZO, NS, NM, NB, the fuzzy control rules can be described as the follows:

Rule 1: if $S^*(k)$ is PB, then $e_f^*(k)$ is PB; Rule 2: if $S^*(k)$ is PM, then $e_f^*(k)$ is PM; Rule 3: if $S^*(k)$ is PS, then $e_f^*(k)$ is PS; Rule 4: if $S^*(k)$ is ZO, then $e_f^*(k)$ is ZO; Rule 5: if $S^*(k)$ is NS, then $e_f^*(k)$ is NS; Rule 6: if $S^*(k)$ is NM, then $e_f^*(k)$ is NM; Rule 7: if $S^*(k)$ is NB, then $e_f^*(k)$ is NB;

To analysis and design conveniently, the fuzzy controller input/output relation curve can be approximated by using the Sigmoid function in this paper:

$$e_f^*(k) = \frac{2}{1 + \mathrm{e}^{\left(-K \times S^*(k)\right)}} - 1 \tag{4}$$

In conclusion, the improved hybrid fuzzy PID control algorithm can be described as:

$$O(k) = K_P \times G_u \times e_f^*(k) + K_I \sum_{i=1}^{k} e(i)T + K_D \dot{e}(k) \tag{5}$$

We call it hybrid fuzzy P+ID controller.

3. Path-following Control of ROV

3.1 *Path-following error*

The research of path-following control mainly includes the definition of path following error and the controller design, at first, we define path-following error of ROV in Serret - Frenet (SF) coordinate system.

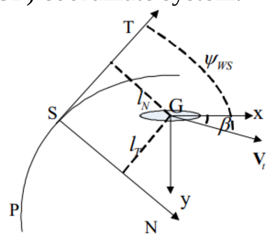

Fig.1. Schematic diagram of path following error

S is the motion reference point in planning horizontal navigation path, we take the G as the carrier of the origin coordinate system. ψ_{ws} is the Euler Angle of rotation.

P is the following path of ROV, the speed coordinate system follows the coordinate system (SF) with the resultant velocity(V_{tc}), so path-following error includes the resultant velocity following error: $e_{V_t} = V_{tc} - V_t$, position following error in the coordinate system(SF): $[l_t, l_n]^T$, and the angle following error ψ_{ws}.

3.2 *Path-following controller*

For the underactuated ROV, the path following position error can not be used for the closed-loop feedback control, so we introduce the approaching angle:

$$\psi_a = -sign(V_t)\psi_l\left(\frac{2.0}{1.0 + e^{-k_N I_N}} - 1.0\right) \quad (6)$$

In the formula, V_t is the actual resultant velocity, so if we design controller to ensure that V_t follows V_{tc}, and the angle error ψ_{ws} follows the approaching angle, we can guarantee path following position and angle error can converge to zero gradually, that when $t \to \infty$, the designed controller can guarantee $V_t \to V_{tc}$ and $\psi_{ws} \to \psi_a$, then $[l_t, l_n]^T \to 0$ and $\psi_{ws} \to 0$.

Due to the approaching angle following control system is a complex nonlinear system, this paper proposes the hybrid fuzzy P+ID control algorithm to design the controller.

3.2.1 *Controller design of approaching angle*

The tracking error of the approaching angle $e_{\psi}(k)$ can be expressed as follows:

$$e_{\psi}(k)=\psi_{a}(k)-\psi_{ws}(k)=\left(\psi_{a}(k)+\psi_{SF}(k)-\beta(k)\right)-\psi(k) \tag{7}$$

We take the $\left(\psi_{a}(k)+C_{SF}(k)-\beta(k)\right)$ as the reference tracking signal ($\psi_{c}(k)$) of the heading angle. The ROV heading angle widely uses discrete form of PID controller:

$$o_{\psi}(k)=K_{p}e_{\psi}(k)+K_{I}\sum_{i=1}^{k}e_{\psi}(i)T-K_{D}r(k) \tag{8}$$

The formula uses the $-r(k)$ instead of $\dot{e}_{\psi}(k)$ to avoid the differential item control output too big when the system started, and the $r(k)$ also has the effect of system damping.

So in this paper, the hybrid fuzzy P+ID controller of heading following is based on (8), we just take nonlinear transformation with the $\dot{e}_{\psi}(k)$ in the proportion by the fuzzy controller, and keep the other items unchanged, just like the follows:

$$o_{\psi}(k)=K_{p}\times Gu\times e_{f\psi}^{*}(k)+K_{I}\sum_{i=1}^{k}e_{\psi}(i)T-K_{D}r(k) \tag{9}$$

3.2.2 *Parameters design and adjust*

In the formula (9), the parameters *Gu* and *Ge* are respectively the input quantization factor and output scaling factor, the higher requirement of tracking precision, the smaller of *Ge* values selection; the greater of *Gu* value, the faster of control response, the higher of the control accuracy, and when $\left|e_{f\psi}^{*}(k)\right|\to 1$, $K_{p}\times Gu$ should be greater or equal to maximum output of the ROV actuator, so we should select $Gu\geq o_{\psi\ \max}/K_{p}$, $o_{\psi\ \max}$ is maximum control output of the actuator.

K is the parameter of adjusting the nonlinear characteristics of fuzzy controller, on the one hand, the selection of *K* should make $\left|e_{f\psi}^{*}\right|\to 1$ when $\left|SE_{\psi}^{*}\right|\to 1$,on the other hand, the value of *K* should not be too big to avoid control system is too sensitive to high frequency dynamics features, Therefore, we generally choose *K* about 4~8.

λ is the weighted coefficient to adjust error and error change rate of $SE_{\psi}(k)$, when the system response is slow, we can increase the value of λ, and when the system overshoot is large , we can reduce the value of λ .

In conclusion, we put forward the parameter design and adjust method is : Based on original heading angle of the PID controller. Firstly, we select the values of *K* and *Ge* according to the characteristics of ROV system and tracking accuracy requirements, then we set λ to 1, by increasing the *Gu* until getting satisfactory control response speed and overshoot, finally by reducing λ to reduce the overshoot and get the final satisfactory control performance.

4. Analysis of Simulation Results

In the simulation, when the speed of ROV is 1.5m/s, we get a group of motion controller parameters in horizontal plane: The forward speed controller parameter is $k_u = 5$, the heading angle parameter of PID controller is $K_p = 2.0$, $K_I = 1.0$ and $K_D = 2.2$. On this basis, the additional parameters of hybrid fuzzy P+ID controller are: *K*=5, $\lambda = 0.9$, $Ge = 10\pi / 180$ and $Gu = 0.35$. We design the parameters of approaching angle are: $\psi_l = \pi / 2, k_N = 0.3$.

In the simulation, firstly we make the ROV follow circular path with 1.5m/s. The simulation time is 100 s, the simulation cycle and ROV control cycle is 0.1 s, ROV starts from stationary state and the heading angel is 0 degree, and we add the interference force that changing with time. Then we move on to PID control simulation and hybrid fuzzy P+ID control simulation respectively. The results are shown in the figure 2~figure 5. In these figures, the solid line is the result of hybrid fuzzy P+ID controller, the dotted line is the result of PID controller.

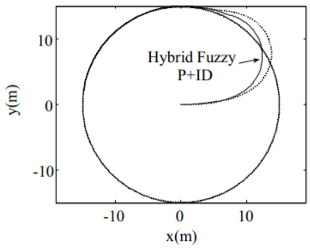

Fig.2. Path-following trajectory of ROV

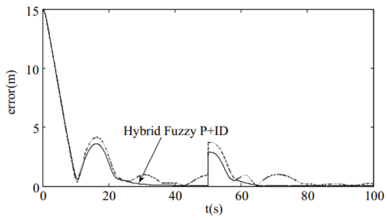

Fig. 3. Path-following position error

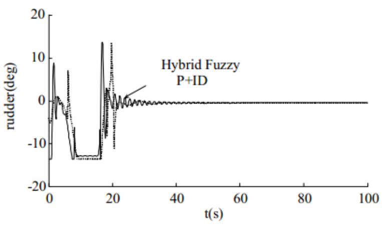

Fig.4 Heading angle

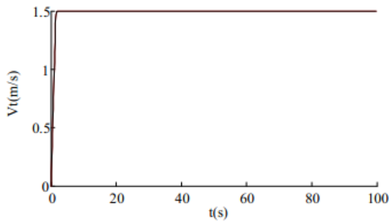

Fig.5 Resultant velocity of ROV

From the result of simulation, we can see that the parameters are adjusted at 1.5m/s, but under the condition of disturbance, the PID path following control performance is poor, and hybrid fuzzy P+ID have better robustness and adaptability, it still can realize ROV path-following accurately.

5. Conclusions

This paper proposes the hybrid fuzzy P + ID control algorithm, we describe it with analytical form and apply it to the path-following control system of ROV, on the basis of PID control of heading angle, we just need to design and adjust the additional parameters of fuzzy controller, and if the parameters designing can meet the stability conditions, the stability of tracking system can be guaranteed at the same time, the results of simulation also show the hybrid fuzzy P+ID controller proposed by this paper have good performance.

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