APPLICATION OF FUZZY SLIDING MODE CONTROL TO THE MOTION CONTROL OF A REMOTELY OPERATED VEHICLE

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Abstract:
The effectiveness of subsea inspection relied on the capability of an Autonomous Underwater Vehicle or Remotely Operated Underwater Vehicle control system. However, these vessel's dynamics vary considerably with operating condition , are strong coupled , and are expensive and difficult to derive, theoretically or by conventional testing, making the design of conventional control system difficult to achieve . The requirement for having a simple controller which performs satisfactorily in the presence of dynamical uncertainties calls for a design using the sliding mode approach .Whereas the conventional sliding mode controller has the drawback of chattering which affect the practical application of VSC. In recent years, the integration of fuzzy logic and sliding mode to exploit the superior sides of these two control methodologies is an active area in control theory. In this paper, a adaptive fuzzy sliding mode controller for the control of a remotely operated vehicle developed at this institution is presented . In contrast to the existing fuzzy sliding mode control system designs, where the sliding mode control law is directly substituted by a fuzzy controller, in our approach, a fuzzy adaptive reaching law method is adopted for control synthesis . Based on the value of error variable , fuzzy control is incorporated into the VSC to adaptively regulate the parameters of the reaching law of VSC. In order to apply the fuzzy adaptive reaching law method to ROV control system synthesis, a 4 DOF dynamic model is first constructed and then regularized into controllable regular form. Based on the controllable regular form of ROV dynamic model, control synthesis is carried out with the method of fuzzy adaptive reaching law. Pole-setting method is adopted in designing switching function and then by using the strategy of singleton fuzzification, product inference and center-average defuzzification , a fuzzy system is constructed to regulating the parameter of reaching law on line. Simulation experiments are made to illustrate the quality and robustness of the control achieved and to show comparisive results with regard to the conventional sliding mode control. Simulation result shows that it not only retains the robustness of VSC, but also greatly reduces the average chattering of VSC control system..Pool test experiments are made to verify the feasibility of the proposed sliding mode controller in practical application.

Keywords: Sliding mode control; Fuzzy control ; Remotely Operated Vehicle, Chattering.

1. Introduction

Control problems related to ROVs presents several difficulties, due to their non-linear dynamics, the presence of disturbance, and the observation noises. This paper attempts to addressing the problem of motion control of a ROV "GDROV" by combing fuzzy control and slidming-mode control method . In this paper, a fuzzy reaching law control method is presented . The parameters of the reaching law of the sling-mode controller are tuned on-line by a fuzzy inference system constructed by expert experience. After being tuned, the fuzzy sliding-mode controller is used in the motion control of the ROV's system. The results are then compared with those of a conventional sliding mode controller.

This paper has been organized as follows. First a dynamic model of the ROV is derived. A conventional sliding-mode controller is discussed next. The fuzzy sliding mode controller is then discussed in detail in the following section. Experiment on the motion control of the ROV using the proposed methodology and conventional sliding-mode control are discussed in the section that follows.

2. Vehicle Modeling

The three-dimensional equations of motion for underwater vehicles have been described in general terms by Gertler in reference [1], and are conveniently developed using a body fixed coordinate frame and a global reference frame . The body fixed frame has components of motion given by the six velocity components:

$$[u(t), v(t), w(t), p(t), q(t), r(t)]$$

and the velocity vector is represented as

$$x^T(t) = [u(t), v(t), w(t), p(t), q(t), r(t)]$$

the six components of position in the global reference frame are

$$z^T(t) = [X(t), Y(t), Z(t), \phi(t), \theta(t), \psi(t)] \ .$$

Control inputs acting on the vehicle include hydrodynamic forces and thrust forces taken specially for this vehicle. The six components of thrust forces are :

$$F = [F_x, F_y, F_z, K, M, N].$$

The complete three-dimensional equations of motion can be refered to in reference [1]. In this paper ,a simplified four-degree-of freedom vehicle(DOF) model is presented based on the following assumption :

1) The ROV operates at low speed
2) The ROV is almost symmetric with three section planes
3). The origin of the body fixed frame is fixed on the center of gravity of the vehicle
4). The motion in pitch and roll direction are very small and can be neglected .

So, The simplified four-DOF model neglecting the coupling effect can be described as follows:

$$(m - X_{\dot{u}})\dot{u} = X_{uu}u^2 + F_x \qquad (1)$$

$$(m - Y_{\dot{v}})\dot{v} = Y_v v + Y_{v|v|} v\,|\,v\,| + F_y \qquad (2)$$

$$(m - Z_{\dot{w}})\dot{w} = Z_w w + Z_{w|w|} w\,|\,w\,| + F_z \qquad (3)$$

$$(I_z - N_{\dot{r}})\dot{r} = N_r r + N_{r|r|} r\,|\,r\,| + N \qquad (4)$$

The simplified equations can be expressed in matrix-multiply form as :

$$\dot{X} = E^{-1}(F_{vis} + F) \qquad (5)$$

where:

$$\mathrm{E} = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 & 0 \\ 0 & m - Y_{\dot{v}} & 0 & 0 \\ 0 & 0 & m - Z_{\dot{w}} & 0 \\ 0 & 0 & 0 & I_z - N_{\dot{r}} \end{bmatrix}$$

$$X = [u, v, w, r]^T$$

$$F_{vis} = \begin{bmatrix} X_{uu}u^2 \\ Y_v v + Y_{v|v|} v\,|\,v\,| \\ Z_w + Z_{w|w|} w\,|\,w\,| \\ N_r r + N_{r|r|} r\,|\,r\,| \end{bmatrix}$$

$$F=\begin{bmatrix}F_x\\F_y\\F_z\\N\end{bmatrix}$$

$X_{\dot{u}}, Y_{\dot{v}}, Z_{\dot{w}}, N_{\dot{r}}, X_{uu}, Y_v, Y_{v|v|}, Z_w, Z_{w|w|}, N_r, N_{r|r|}$

are the hydrodynamic coefficients of the ROV and have been identified through least-square estimation method . The estimation experiment also testified that the simplified model can approximate the real ROV model very well .

3. Sliding mode control

In order to express the motion equations in state space, a state variable

$$\boldsymbol{x}=[\boldsymbol{x}_1^T,\boldsymbol{x}_2^T,\boldsymbol{x}_3^T,\boldsymbol{x}_4^T] \qquad [6]$$

is defined ,where

$$\begin{cases} x_1=\begin{bmatrix}x\\u\end{bmatrix}=\begin{bmatrix}x_{11}\\x_{12}\end{bmatrix}=\begin{bmatrix}x_{11}\\\dot{x}_{11}\end{bmatrix}\\ x_2=\begin{bmatrix}y\\v\end{bmatrix}=\begin{bmatrix}x_{21}\\x_{22}\end{bmatrix}=\begin{bmatrix}x_{21}\\\dot{x}_{21}\end{bmatrix}\\ x_3=\begin{bmatrix}z\\w\end{bmatrix}=\begin{bmatrix}x_{31}\\x_{32}\end{bmatrix}=\begin{bmatrix}x_{31}\\\dot{x}_{31}\end{bmatrix}\\ x_4=\begin{bmatrix}\psi\\r\end{bmatrix}=\begin{bmatrix}x_{41}\\x_{42}\end{bmatrix}=\begin{bmatrix}x_{41}\\\dot{x}_{41}\end{bmatrix}\end{cases} \qquad [7]$$

Define desired state variable

$$x_d=[x_{1d}^T,x_{2d}^T,x_{3d}^T,x_{4d}^T] \qquad [8]$$

where:

$$\begin{cases} x_{1d}=\begin{bmatrix}x_d\\u_d\end{bmatrix}=\begin{bmatrix}x_{11d}\\x_{12d}\end{bmatrix}=\begin{bmatrix}x_{11d}\\\dot{x}_{11d}\end{bmatrix}\\ x_{2d}=\begin{bmatrix}y_d\\v_d\end{bmatrix}=\begin{bmatrix}x_{21d}\\x_{22d}\end{bmatrix}=\begin{bmatrix}x_{21d}\\\dot{x}_{21d}\end{bmatrix}\\ x_{3d}=\begin{bmatrix}z_d\\w_d\end{bmatrix}=\begin{bmatrix}x_{31d}\\x_{32d}\end{bmatrix}=\begin{bmatrix}x_{31d}\\\dot{x}_{31d}\end{bmatrix}\\ x_{4d}=\begin{bmatrix}\psi_d\\r_d\end{bmatrix}=\begin{bmatrix}x_{41d}\\x_{42d}\end{bmatrix}=\begin{bmatrix}x_{41d}\\\dot{x}_{41d}\end{bmatrix}\end{cases} \qquad [9]$$

Then the motion equations can be regularized into the following controllable regular form composed of four subsystems :

$$\begin{cases} \dot{\mathbf{x}}_1=\begin{bmatrix}0 & 1\\ \hline & 0\end{bmatrix}\mathbf{x}_1+\begin{bmatrix}0\\\alpha_1^0(\mathbf{x})\end{bmatrix}+\begin{bmatrix}0\\1\end{bmatrix}u_1\\ \dot{\mathbf{x}}_2=\begin{bmatrix}0 & 1\\ \hline & 0\end{bmatrix}\mathbf{x}_2+\begin{bmatrix}0\\\alpha_2^0(\mathbf{x})\end{bmatrix}+\begin{bmatrix}0\\1\end{bmatrix}u_2\\ \dot{\mathbf{x}}_3=\begin{bmatrix}0 & 1\\ \hline & 0\end{bmatrix}\mathbf{x}_3+\begin{bmatrix}0\\\alpha_3^0(\mathbf{x})\end{bmatrix}+\begin{bmatrix}0\\1\end{bmatrix}u_3\\ \dot{\mathbf{x}}_4=\begin{bmatrix}0 & 1\\ \hline & 0\end{bmatrix}\mathbf{x}_4+\begin{bmatrix}0\\\alpha_4^0(\mathbf{x})\end{bmatrix}+\begin{bmatrix}0\\1\end{bmatrix}u_4\end{cases} \qquad [10]$$

where:

$$u=\begin{bmatrix}u_1 & u_2 & u_3 & u_4\end{bmatrix}^T=\mathrm{E}^{-1}F \qquad [11]$$

$$\begin{aligned}\alpha(x)&=\begin{bmatrix}\alpha_1^0(x) & \alpha_2^0(x) & \alpha_3^0(x) & \alpha_4^0(x)\end{bmatrix}^T\\&=E^{-1}F_{vis}\end{aligned} \qquad [12]$$

So,We obtain $F=Eu$ [13]

Define the state error vector

$$\mathbf{e}(t)=\mathbf{x}(t)-\mathbf{x}_d(t)\,. \qquad [14]$$

For the ith subsystem x_i,

$$\mathbf{e}_i(t)=\mathbf{x}_i(t)-\mathbf{x}_{id}(t)$$

$$\dot{e}_i = \begin{bmatrix} \dot{e}_{i1} \\ \dot{e}_{i2} \end{bmatrix} = \begin{bmatrix} \dot{x}_{i1} - \dot{x}_{i1d} \\ \dot{x}_{i2} - \dot{x}_{i2d} \end{bmatrix}$$
$$= \begin{bmatrix} x_{i2} - x_{i2d} \\ \dot{x}_{i2} - \dot{x}_{i2d} \end{bmatrix} = \begin{bmatrix} e_{i2} \\ \dot{x}_{i2} - \dot{x}_{i2d} \end{bmatrix} \quad [15]$$

Substituting equation (10) into equation (15),we got the controllable regular form:

$$\dot{e}_i = \left[\begin{array}{c|c} 0 & 1 \\ \hline \multicolumn{2}{c}{0} \end{array}\right] e_i + \begin{bmatrix} 0 \\ \alpha_i^0(x) - \dot{x}_{i2d} \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u_i \quad [16]$$

Define the switching function :

$$S = [s_1 \ \ s_2 \ \ s_3 \ \ s_4]^T = [C_1e_1 \ \ C_2e_2 \ \ C_3e_3 \ \ C_4e_4]^T \quad [17]$$

For the ith subsystem,

$$\dot{e}_{i1} = e_{i2} \ , \ \dot{e}_{i2} = (\alpha_i^0(\mathbf{x}) - \dot{x}_{i2d}) + u_i \quad [18]$$

$$s_i = C_{i1}e_{i1} + C_{i2}e_{i2} = C_{i1}e_{i1} + e_{i2} \quad [19]$$

Take the exponential reaching law :

$$\dot{s}_i = C_{i1}\dot{e}_{i1} + \dot{e}_{i2} = -\varepsilon \operatorname{sgn}(s_i) - ks_i$$
$$\varepsilon > 0, k > 0 \quad [20]$$

Making necessary substitution ,w obtain

$$u_i = -[\alpha_i^0() - \dot{x}_{i2d}] + [-\varepsilon \operatorname{sgn}(s_i) - ks_i] - C_{i1}e_{i2} \quad [21]$$

After getting u_i, we can obtain the need thrust force by the relation of $\mathbf{F} = \mathbf{Eu}$.

4. Fuzzy sliding mode control

A method to increase the robustness and disturbance rejection ability is to adapt the gain k_i in the sliding surface equation. A intuitive idea on how to adjust the gain without much equation work is to use the fuzzy set theory and fuzzy inference principles. The fuzzy gain adapter will have 2 inputs and 1 output. The inputs of the fuzzy adapter are the error e and the time derivative of the error $\dot{e}$ and the output is the gain k_i for $i = 1,2,3,4$ corresponding to surge, sway, heave and yaw direction .The normalized e and $\dot{e}$ space is the interval [-1,1], and the normalized space for the gain k_i is the interval [0,1]. The input variables are processed through a saturation function with a linear region of slope conveniently chosen. The output variable is scaled using a scale factor of appropriate magnitude . Figure 1 shows the structure of the fuzzy adapter:

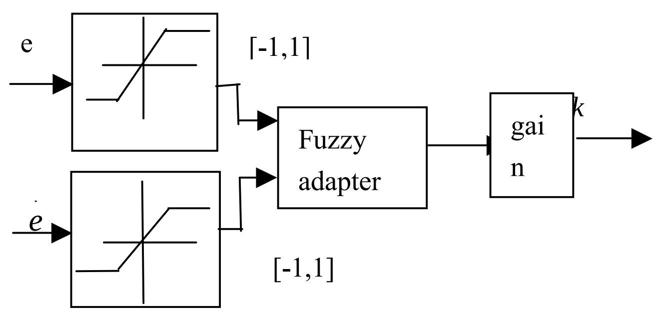

Fig 1 Online fuzzy adjustment of k_i

The Mamdani type fuzzy gain adapter has five fuzzy sets ranging from ‘Negative Big’ to ‘Positive Big’ defined for the normalized e and $\dot{e}$ variables whereas 3 fuzzy sets named ‘Small’, ‘Medium’ and ‘Big’ have been assigned to output variable k_i .The membership of the normalized e and $\dot{e}$ variables and output variable k_i are shown in figure 2 and figure 3 . The rule set for the

Mamdani fuzzy inference is set in table 1.

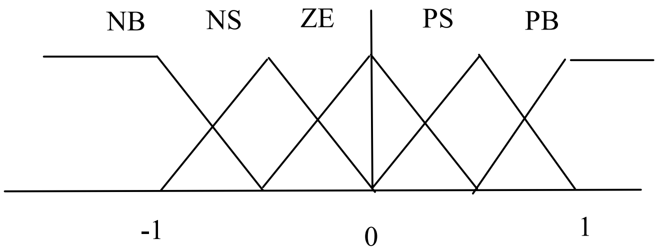

Fig.2 Memberships of e e and $\dot{e}$

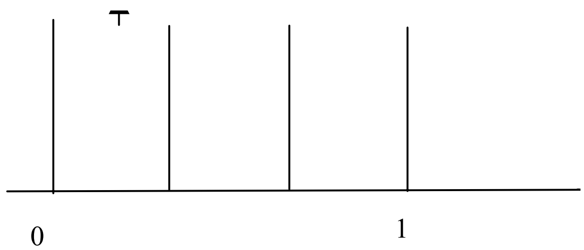

Fig 3 Memberships of k_i

$\dot{e}/e$	NB	NS	ZE	PS	PB
NB	L	L	L	M	S
NS	L	L	M	S	M
ZE	L	M	S	M	L
PS	M	S	M	L	L
PB	S	M	L	L	L

Table 1 Rule Table for Fuzzy Inference

In order to construct the needed fuzzy inference system ,the strategy of singleton fuzzification, product inference and center-average defuzzification had been selected .

5. Simulation and results

In order to verify the validity of the proposed method , simulation experiments are carried out . Figure 4 shows the comparison of error curves of the ROV's northbound motion with Fuzzy sliding mode control(FSLC)and conventional sliding mode control(SLC) .

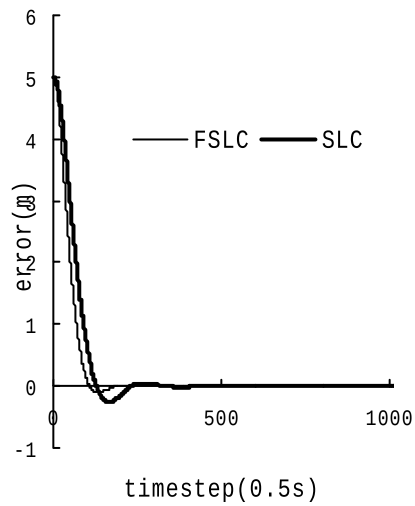

Fig.4 The error curves of northbound motion with two different controllers

From Figure 4, We can see that fuzzy sliding mode control can obtain faster response and smaller overshoot compared with conventional sliding mode control.

In figure 5 , the yaw curve of pool test is shown. We can see that the fuzzy sliding mode controller can achieve good performance in pool test.

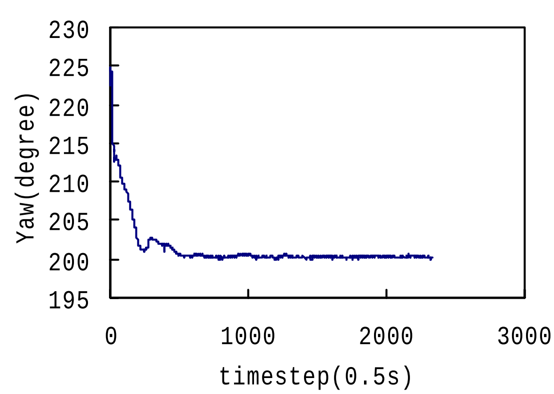

Fig.5 The yaw curve of pool test

6. Conclusion

In this paper , a fuzzy sliding mode control algorithm has been presented. Its main feature is that it combines the fuzzy gain adapter with a sliding mode controller . At the same time ,its implementation is simple enough without much equation work. Also, it is shown that the controller presented had better performance than that of a conventional sliding mode controller.

Reference

[1]. M.Gertler and G.R. Hagen, "Standard equations of motion for submarine simulations," Naval Ship Research and Development, NSRD Rep.2510,1967

[2]. Roberto Cristi , Fotis A. Papoulias and Anthony J. Healey ."Adaptive Sliding Mode Control of Autonomous Underwater Vehicles in the Dive Plane . IEEE Journal of Ocean Engineering ,Vol. 15 NO.3, pp 152-160 July 1990

[3]. Anthony J. Healey and David Lienard . "Multivariable Sliding Mode Control for Autonomous Diving and Steering of Unmanned Underwater Vehicles". IEEE Journal of Ocean Engineering ,Vol. 18 NO.3, pp 327-339 July 1993

[4]. J.P.V.S. Cunha, R.R.Costa,L.Hsu, "Design of a high performance variable structure control of ROV's," IEEE Journal of Ocean Engineering, Vol. 20, No.1,pp 42-55,1995

[5]. K. David, Vadim I.Utkin and Umit Ozguner. A Control Engineer's Guide to Sliding Mode Control IEEE Transactions on Control Sytems Technology, Vol.7 No.3 pp328-342 MAY 1999

[6]. R. Palm, "Robust control by fuzzy sliding mode", Automatica Vol.30 No.9, pp. 1429-1437

[7]. WenJun Chang, JianCheng Liu, Huanan Yu. "A Mathematical Model for Motion Control and Simulation of Underwater Vehicle Ship Engineering 2002 .3 pp58-60

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