文章编号：1002-0446(2009)-s1-0022-04

Adaptive Sliding Mode Control of an Autonomous Underwater Vehicle

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Abstract: This paper presents an adaptive sliding mode controller for an autonomous under water vehicle (AUV) in the presence of parameter uncertainties and external disturbance. The controller makes the system stable in the presence of system uncertainties and external disturbances. It is a discrete time sliding mode controller. The proposed algorithm has a time varying sliding surface which is obtained by parameter estimation method. A smooth saturation function for maintaining the stable condition of the system is used to reduce the control chatter and transient performance of system. The presented algorithms are applied to the problem of depth control of an AUV. Resulting performances are tested by simulation.

Keywords: AUV (autonomous underwater vehicle); discrete-time; sliding mode control; adaptive control

1 Introduction

The control performance of the autonomous underwater vehicle (AUV) is affected by several elements such as uncertainty in the model knowledge, presence of hydrodynamic effects, coupling effects between horizon and vertical planes, system nonlinearity, and so on. An adaptive sliding mode control approach is proposed. First, a direct sliding mode control scheme is introduced. This controller is further incorporated into the adaptive control strategy. This approach combines the advantages of traditional adaptive control with sliding control without knowing the accurate dynamic model of the system. The introduced controller compensates the structured and unstructured uncertainty of the vehicle and the environment. It does not require an accurate model of the vehicle dynamics, and ensures robust performance in the presence of disturbances and dynamic uncertainty.

Traditional sliding mode control algorithms are always designed in continuous mode, but control algorithms always run in discrete time implementation that may lead the system to chatter along the desired sliding mode and even to instability. Therefore, the discrete-time sliding mode method is needed to counter this problem. An adaptive parameter identifier is used to estimate the discrete model.

The control system architecture is shown in fig.1.

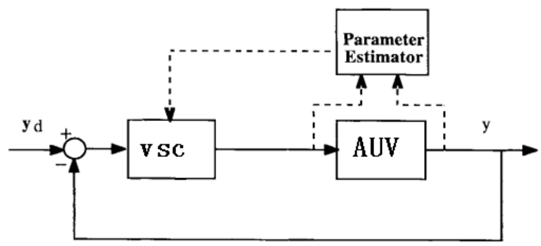

Fig.1 Control system architecture

2 Dynamic model

It is supposed that the vehicle is operating around a desired forward speed. Without regards to the nonlinear components, the equations of motion can be reduced to the following simple forms:

According to Newton theory:

$$\begin{aligned} m(\dot{w}-u_0 q) &= Z \\ I_y \dot{q} &= M \end{aligned} \tag{1}$$

The heave force Z and moment M can be described as follows:

$$Z = Z_{\dot{w}}\dot{w} + Z_{\dot{q}}\dot{q} + Z_w w + Z_q q + Z_\delta \delta \tag{2}$$

$$\begin{aligned} M &= M_{\dot{w}}\dot{w} + M_{\dot{q}}\dot{q} + M_w w + Mq - \\ &\quad mg(z_G - z_B)\sin\theta + M_\delta \delta_s \\ &\approx M_{\dot{w}}\dot{w} + M_{\dot{q}}\dot{q} + M_w w + M_q q - \\ &\quad W\overline{BG_z}\theta + M_\delta \delta \end{aligned} \tag{3}$$

At the stable point we have $\theta_0 = q_0 = \phi_0 = 0$, so:

收稿日期：2009-07-31

$$\begin{aligned} \dot{\theta} &= q \\ \dot{z} &= -\theta u_0 + w \end{aligned} \tag{4}$$

The heave speed w is very slow, so the dynamics can be written as:

$$\begin{bmatrix} \dot{q} \\ \dot{\theta} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} \frac{M}{I_y - M_{\dot{q}}} & -\frac{\overline{BG_z w}}{I_y - M_{\dot{q}}} & 0 \\ 1 & 0 & 0 \\ 0 & -u_0 & 0 \end{bmatrix} \begin{bmatrix} q \\ \theta \\ z \end{bmatrix} + \begin{bmatrix} \frac{M_\delta}{I_y - M_q} \\ 0 \\ 0 \end{bmatrix} \delta_s \tag{5}$$

The dynamic model for control in the vertical plane yields the general form of state equation in discrete time:

$$\boldsymbol{x}(k+1) = \boldsymbol{A}\boldsymbol{x}(k) + \boldsymbol{B}u(k) + d \tag{6}$$

where

$$\boldsymbol{A} = \begin{bmatrix} -a_1 & -a_2 & 0 \\ 1 & 0 & 0 \\ 0 & -u_0 & 0 \end{bmatrix} \tag{7}$$

$$\boldsymbol{B} = \begin{bmatrix} b \\ 0 \\ 0 \end{bmatrix} \tag{8}$$

$$\boldsymbol{x} = [q, \theta, z]^{\mathrm{T}} \tag{9}$$

u is the elevator angle, and d represents the system disturbance vector. A control law can be designed using this simplified equation.

From the state space equation (6) we can deduce the input and output model of pitch angle θ:

$$\begin{aligned} y(k+2) &= -a_1 y(k+1) - a_2 y(k) + bu(k) + d \\ y &= \theta \end{aligned} \tag{10}$$

The coefficients, a_1, a_2 and b verify according to the vehicle speed. Due to the difficulty of modeling the system disturbances d and handling the coupling effects, a robust controller is needed to control the vehicle in the presence of system uncertainties.

3 Sliding mode controller design

The discrete-time sliding mode control is briefly described in this section. A single-input multiple-output discrete system is described by:

$$\boldsymbol{x}(k+1) = \boldsymbol{A}(k)\boldsymbol{x}(k) + \boldsymbol{B}(k)u(k) \tag{11}$$

Where $\boldsymbol{x}(k)$ is a n dimensional state vector and $u(k)$ is a scalar control input. It is assumed that the matrix $\boldsymbol{B}(k)$ is a known constant $\boldsymbol{B}$ and the system matrix $\boldsymbol{A}(k)$ is modeled as a system model $\boldsymbol{A}_0$ with uncertainties $\Delta \boldsymbol{A}$ at time step k.

If the system uncertainty satisfies the matching condition $\Delta \boldsymbol{A}$ is reduced to:

$$\Delta \boldsymbol{A} = \boldsymbol{B}\boldsymbol{d}^{\mathrm{T}}(k) \tag{12}$$

Where $\boldsymbol{d}(k) = [d_{k1}, d_{k2}, ..., d_{kn}]$. It is assumed that the uncertainties are bounded and the maximum bound of each component is known. Define a vector

$$\boldsymbol{D}^{\mathrm{T}} = [D_1, D_2, ..., D_n] \tag{13}$$

Where each D_i is a positive constant satisfying the following condition:

$$D_i > |d_{ki}| \quad k=1,2,\ldots,n \tag{14}$$

If the desired trajectory $r(k)$ is given at each time step, the error vector will be obtained as

$$e(k) = x(k) - r(k) \tag{15}$$

The switching hyperplane $s(k)$ is defined as

$$s(k) = \boldsymbol{G}^{\mathrm{T}} e(k) \tag{16}$$

Where the $\boldsymbol{G}^{\mathrm{T}}$ is designed such that the system is stable on the hyperplane $s(k) = 0$.

It is supposed that the control input is composed of equivalent control and switching control. The switching inputs are exclusively available in the outside of an equivalent control region, which is a sector near the switching hyperplane.

By applying the condition

$$s(k+1) = s(k) \tag{17}$$

which is analogous to the sliding mode condition $\dot{s} = 0$ in the conventional sliding mode controller, the equivalent control reduces to

$$u_e(k) = \alpha^{-1}\boldsymbol{G}^{\mathrm{T}}\Delta r(k+1) - \alpha^{-1}\boldsymbol{G}^{\mathrm{T}}(\boldsymbol{A}_0 - \boldsymbol{I})x(k) \tag{18}$$

Where

$$\alpha = \boldsymbol{G}^{\mathrm{T}}\boldsymbol{B} \quad \text{and} \quad \Delta r(k+1) = r(k+1) - r(k) \tag{19}$$

A switching control law for the system to track a reference trajectory and to keep the state on the hyperplane in the presence of the uncertainties is suggested as follows:

$$\begin{aligned} u(k) &= \alpha^{-1}\boldsymbol{G}^{\mathrm{T}}\Delta r(k+1) - \alpha^{-1}\boldsymbol{G}^{\mathrm{T}}(A_0 - I)\boldsymbol{x}(k) + k\,\mathrm{sgn}(s(k)) \\ k &> \boldsymbol{D}^{\mathrm{T}}|\boldsymbol{x}| \end{aligned} \tag{20}$$

where the first two terms on the right side is the equivalent control, and the last term is the switching control for robustness improvement.

Proof:

The sliding mode existing condition can be stated as follows:

$$s(k)\Delta s(k+1) < 0 \tag{21}$$

$$\begin{aligned}\Delta s(k+1) &= s(k+1) - s(k) \\ &= \boldsymbol{G}^{\mathrm{T}}\Delta \boldsymbol{A}\boldsymbol{x}(k) + \boldsymbol{G}^{\mathrm{T}}\boldsymbol{B}\boldsymbol{K}\,\mathrm{sgn}(s(k)) \\ &= \boldsymbol{G}^{\mathrm{T}}\boldsymbol{B}\boldsymbol{d}(k)\boldsymbol{x}(k) + \boldsymbol{G}^{\mathrm{T}}\boldsymbol{B}\boldsymbol{K}\,\mathrm{sgn}(s(k)) \\ &\le \boldsymbol{G}^{\mathrm{T}}\boldsymbol{B}(\boldsymbol{D}^{\mathrm{T}}\boldsymbol{x}(k) + \boldsymbol{K}\,\mathrm{sgn}(s(k)))\end{aligned} \tag{22}$$

When $k > \boldsymbol{D}^{\mathrm{T}}|\boldsymbol{x}|$, we have

$$s(k)\Delta s(k+1) < 0 \tag{23}$$

The upper limit of each switching gain guarantees the stability of the discrete-time quasi-sliding mode control.

A saturation function is used to reduce the control chatter and transient performance of the system.

$$\mathrm{sat}(s/\varDelta) = \begin{cases} 1, & s > \varDelta \\ ks, & |s| < \varDelta \qquad k = 1/\varDelta \\ -1, & s < \varDelta \end{cases} \tag{24}$$

4 Self-tuning sliding mode control

The algorithm designed above assumes that the coefficients a_1, a_2 and b are known before and change slowly. This condition is not always satisfied. When coefficients uncertainties are present in the plant, the performances of the sliding mode control system may chatter badly and even becomes unstable.

The performances of the system can be improved by updating the control law parameters through on-line estimation.

We use least squire method in this paper with dead zone modification.

$$\hat{\boldsymbol{\theta}}_k = [a_1, a_2, b] \tag{25}$$

$$\hat{\boldsymbol{\theta}}_{k+1} = \hat{\boldsymbol{\theta}}_k + \boldsymbol{K}_k \alpha(k)(y_{k+1} - \boldsymbol{q}_{k+1}\boldsymbol{\theta}_k) \tag{26}$$

$$\boldsymbol{K}_k = \boldsymbol{P}_k \boldsymbol{q}_{k+1}^{\mathrm{T}}(\rho + \boldsymbol{q}_{k+1}\boldsymbol{P}_k\boldsymbol{q}_{k+1}^{\mathrm{T}})^{-1} \tag{27}$$

$$\boldsymbol{P}_{k+1} = (\boldsymbol{I} - \boldsymbol{K}_k q_{k+1})\boldsymbol{P}_k / \rho \tag{28}$$

$$\alpha(k) = \begin{cases} 1, & |y_{k+1} - q_{k+1}\theta_k| > g \\ 0, & |y_{k+1} - q_{k+1}\theta_k| < g \end{cases} \tag{29}$$

Dead zone parameter g can be chosen according to the level of sensor noise.

The parameters of vertical dynamic model (10) can be updated using $\hat{\boldsymbol{\theta}}_k$.

5 Simulation

Simulation has been made to verify the effectiveness of the controller presented above. The disturbances are caused by the variation of forward speed, sensor noise, coupling forces, and the current. The switching gains and the disturbances are chosen as $\boldsymbol{G}^{\mathrm{T}} = [1, 0.15, 0.0001]$ and $\boldsymbol{D}^{\mathrm{T}} = [1,1,1]$. The estimator parameter are selected as ρ=0.99, $\alpha(k)$=1. The switching gain K is 0.15.

Figs.2,3 show the step responses of the vehicle with the adaptive sliding mode controller in the presence of system uncertainty and environment disturbance. The desired depth is 10 meters. The total simulation time is 50 seconds, and at the 25th second a parameter variation of 25% with respect to the nominal value has been applied to all the parameters appearing in the model (30) and a 0.5 meter sudden variation to depth is simulated.

Fig.2 depicts the desired depth and real depth response. Solid line denotes the desired value and dashed line denotes the real value.

Fig.3 depicts the theta angle response. Solid line denotes the desired value and dashed line denotes the real value.

Fig.4 shows the elevator input.

Fig.5 shows the parameter tracking error.

The figures show that the controller generates stable control signals, which are robust to uncertainty of system parameters and environment disturbance.

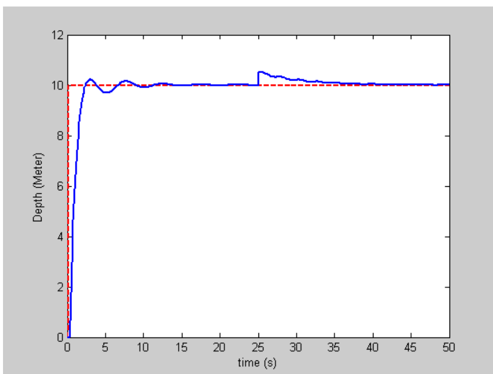

Fig.2 Vehicle depth response

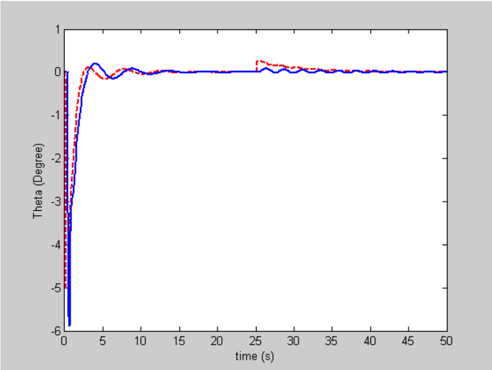

Fig.3　Vehicle theta angle response

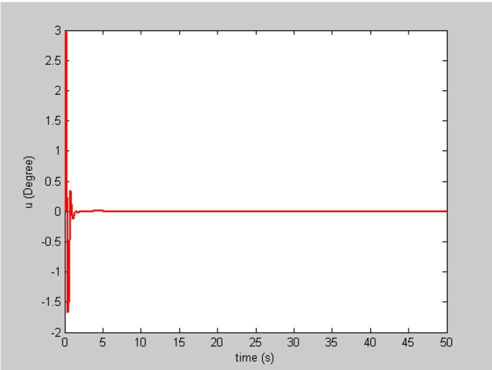

Fig.4　Vehicle elevator input

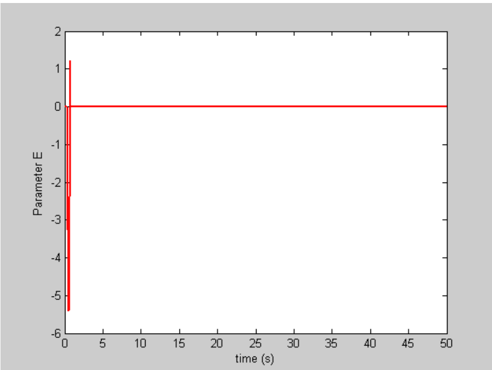

Fig.5　Parameter estimating error

6　Conclusion

The adaptive parameter identifier estimates the input-output model, and the sliding mode controller compensates external disturbances. No state feedback is needed, but only output measurements are fed to the controller. The robustness of the algorithm is ensured both by the sliding mode mechanism and by the adaptive characteristics of the control law. The controller provides robust performance of coordinated control in the presence of uncertainties about the dynamics and the hydrodynamic disturbances.

Extensive computer simulations are performed to verify the feasibility and efficiency of the proposed control algorithm. The results show the estimated parameters are converged and the robustness and accuracy are obtained.

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