# 무인 수중 잠수정을 위한 채터링이 없는 슬라이딩 모드 제어기 설계

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# Design of Chattering Free Sliding Mode Controller for AUV

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**Abstract** - The sliding mode control is acceptable for Autonomous Underwater Vehicle(AUV), since the dynamics of AUV are highly nonlinear and have several parameter uncertainty such as the added mass terms, the hydrodynamic coefficients. The sliding mode control can deal well with nonlinearity of the system and offers a robustness to controller with parameter uncertainty. Since sliding mode control has the defect of chattering problem, only in ideal case the actuator can respond by control law. Therefore we propose the sliding mode control with non-chattering. And computer simulations illustrate the performance of the proposed controller.

## 1. Introduction

In Autonomous Underwater Vehicle(AUV), the control problem is currently main issue. The AUV has the parametric uncertainties and highly nonlinear feature, such as added mass, hydrodynamic coefficients, etc. To control the AUV, many control strategies are adopted[1], [2]. One of them is sliding mode control(SMC) method. The SMC is one of the most used control method in AUV. Since SMC is an effective approach to deal with uncertainties for nonlinear system[3], the SMC is widely used for the nonlinear control scheme[4], [5]. However the SMC has a serious defect, that is the chattering problem. That can drive unmodeled high frequency modes. Chattering also involves high control activity and increase electric power consumption.

In this paper, we proposed the chattering free SMC for the AUV. The proposed method improves the sliding condition in the SMC. Using this chattering free SMC, we design the controller which is applicable to the AUV. In this paper we use the REMUS model[2] for the simulation.

## 2. AUV Model

### 2.1 Dynamic equation of AUV

The 6 DOF(Degree of Freedom) dynamics model[6] of the AUV can be described as follows:

$$M(\nu)\dot{\nu} + C(\nu)\nu + D(\nu)\nu + g(\eta) = \tau, \tag{1}$$

where, $\eta = [\eta_1, \eta_2]^T = [x, y, z, \phi, \theta, \psi]^T$ represents the position vector $\eta_1 = [x, y, z]^T$ and the orientation vector $\eta_2 = [\phi, \theta, \psi]^T$ in earth-fixed frame, and $\nu = [u, v, w, p, q, r]^T$ represents the linear velocities vector $\nu_1 = [u, v, w]^T$ and the angular velocities vector $\nu_2 = [p, q, r]^T$ in body-fixed frame. Here $u$, $v$, $w$, $p$, $q$, $r$ are the surge, sway, heave, roll, pitch, yaw, respectively. Figure 1 represents the AUV and a diagram of the vehicle coordinate system.

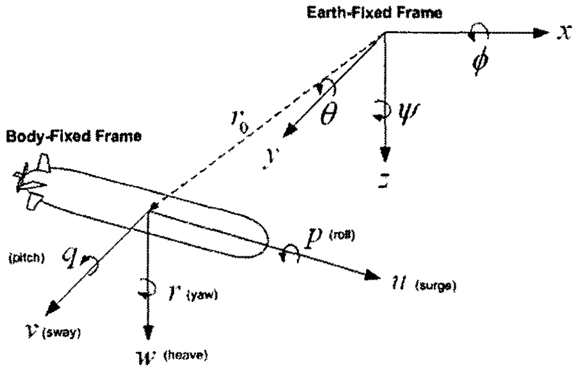
In (1), $M(\nu)$ is the inertia matrix with added mass, $C(\nu)$ is the Coriolis and centripetal matrix with add mass, $D(\nu)$ is damping matrix, $g(\eta)$ is the vector of gravitational force and moments and $\tau$ is the vector of control inputs.

And the kinematics model of the AUV is as follows:

$$\dot{\eta} = \begin{bmatrix} J_1(\eta_2) & 0_{3\times3} \\ 0_{3\times3} & J_2(\eta_2) \end{bmatrix} \nu, \tag{2}$$

where $J_1(\eta)$ is transform matrix which relates linear velocities between body-fixed and earth-fixed frame, and transform matrix $J_2(\eta)$ relates rotational velocities. The matrix $J_1(\eta)$ and $J_2(\eta)$ are as follows:

$$J_1(\eta) = \begin{bmatrix} cos\psi cos\theta & -sin\psi cos\phi + cos\psi sin\theta sin\phi & sin\psi sin\phi + cos\psi sin\phi cos\theta \\ sin\psi cos\theta & cos\psi cos\phi + sin\psi sin\theta sin\phi & -cos\psi sin\phi + sin\psi sin\theta cos\phi \\ -sin\theta & cos\theta sin\phi & cos\theta cos\phi \end{bmatrix},$$



**<Fig. 1> Body-fixed and earth-fixed frames of the AUV**

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

#### 2.1.1 Steering model

If the AUV is restricted to move along the horizontal plane, only the states $[v, r, \psi, u]$ are consider(we assume that the surge velocity $u$ is constant). While the states of representing vertical motion are negligible(*i.e.* $[w, p, q, z, \phi, \theta] = 0$).

In the horizontal(steering) plane, the model equation[7] is as follows:

$$M\dot{X} = A_c X + B_c U, \text{ with } X = [v, r]^T \tag{3}$$

$$\dot{\psi} = r \tag{4}$$

where

$$M = \begin{bmatrix} 65.9791 & -1.9300 \\ -1.9300 & 8.3300 \end{bmatrix}, A_c = \begin{bmatrix} -66.6000 & -44.8293 \\ -4.4700 & -6.8700 \end{bmatrix},$$

$$B_c = \begin{bmatrix} 14.4571 & 0 \\ 0 & -9.8857 \end{bmatrix}, U = \begin{bmatrix} \delta_r \\ \delta_r \end{bmatrix}.$$

A more detailed description of the model refers to [7].

## 3. Chattering Free SMC for AUV

### 3.1 Chattering free SMC

Let us consider that the nonlinear system is defined as

$$x^{(n)} = f(\mathbb{X}) + b(x)u(t) \tag{5}$$

where $\mathbb{X} = [x, \dot{x}, \cdots, x^{(n-1)}]^T$ and $u(t)$ is the control input.

And the sliding surface for sliding control is define as

$$s(\mathbb{X}, t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} \tilde{x} \tag{6}$$

where $\tilde{x}$ is the tracking error and $\lambda$ is a strictly positive constant. Let us choose the following Lyapunov function

$$V = \frac{1}{2}s^2 \tag{7}$$

To make the time derivative of (7) the negative definite, a control input must be satisfied such as the following inequality:

$$\dot{V} = s\dot{s} \le -\eta s^2 \tag{8}$$

**Theorem 1**: Control input $u$ ,which is satisfied stability and chattering free, is as follows

$$u = \hat{u} - b^{-1}ks = b^{-1}(\dot{x}_d - \hat{f} - \lambda\dot{\tilde{x}}) - b^{-1}ks$$

where $k = \frac{F}{s} + \eta,\ |f - \hat{f}| < F$.

### 3.2 Steering plane controller for the REMUS

Using the process described in section 3.1, firstly we determine a sliding surface. The sliding surface is as follows:

$$s = S\widetilde{Y} = \alpha(v - v_d) + \beta(r - r_d) + \gamma(\psi - \psi_d) \tag{9}$$

where $S = [\alpha, \beta, \gamma]$, the error vector is $\widetilde{Y} = Y - Y_d$. Then the control input is as follows:

$$U = U_{eq} - ks = -B^{-1}AX - ks$$

## 4. Simulations

In order to make the simulation as realistic as possible, we assume some physical limitation on the actuator. The range of rudder is $[-35^\circ, 35^\circ]$, $u = 1.543 m/s$ and $k = 30$. The simulations are carried out in MATLAB.

Figs. 2 and 3 represent simulation results with general SMC. In this case control input(stern input) is oscillated with high frequency. This signal is impossible physically and derive undesirable events. However, in Figs. 4 and 5, the control input has non-chattering signal. Also the control performance is similar to prior simulation results.

## 5. Conclusion

Generally the AUV has the high nonlinearity feature and the parametric uncertainties. To deal with these characteristic, the SMC is used for the control of AUV, frequently. But the general SMC is difficult to apply to the AUV, because of the chattering problem. Therefore we proposed the chattering free SMC for the AUV. And the proposed control strategy was applied to the REMUS steering model. The simulation results show that chattering problem didn't appear in the proposed algorithm. Also the control performance is similar to general SMC. Consequently, we can conclude that the chattering free SMC reduce the chattering problem and improve the control effort in compared with general SMC.

## [Reference]

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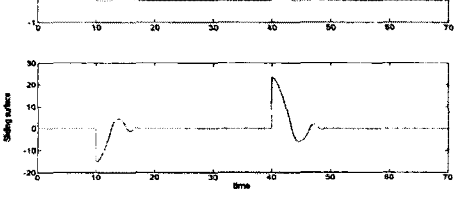
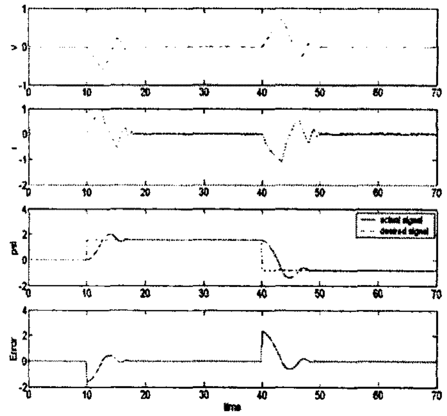
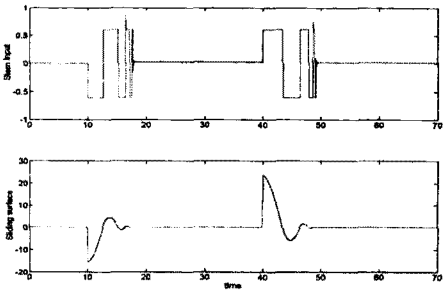


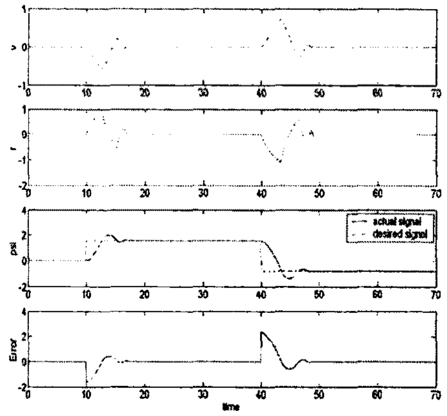
<Fig. 2> Steering control of the REMUS with general SMC(control input, sliding surface)



<Fig. 3> Steering control of the REMUS with general SMC(state $v, r, \psi$ and control error)



<Fig. 4> Steering control of the REMUS with chattering free SMC(control input, sliding surface)



<Fig. 5> Steering control of the REMUS with chattering free SMC(state $v, r, \psi$ and control error)