



## FUZZY-SLIDING-MODE-BASED ROBUST TRACKING CONTROL OF AUTONOMOUS UNDERWATER VEHICLES

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Key words: sliding mode control, fuzzy logic control, trajectory tracking, underwater vehicles.

## ABSTRACT

Control of an autonomous underwater vehicle (AUV) is difficult due to its nonlinear and coupled characteristics, parameter uncertainties, and unknown disturbances. This paper presents a motion control system based on an adaptive fuzzy sliding mode control (FSMC) method for trajectory tracking of an AUV. The proposed FSMC method is primarily based on a combination of sliding mode control (SMC) strategy with an adaptive fuzzy algorithm to estimate external disturbances and weaken the chattering effect. A waypoint guidance law based on a line-of-sight (LOS) algorithm is applied to the guidance system. Simulation studies confirm a good performance of the proposed controller. The results are compared with those obtained with a sliding mode controller in terms of robustness and accuracy.

## I. INTRODUCTION

In recent years, autonomous underwater vehicles (AUVs) are widely used in exploration, landscape mapping, salvage, and so on. AUVs are highly nonlinear, coupled, and uncertain systems with environmental disturbances and unknown hydrodynamic parameters. In general, the AUV hydrodynamics can be described by nonlinear differential equations. Conventional PID control system is not the most suitable choice for AUVs and cannot guarantee the required performance, thus, robust control of AUVs is challenging in both theory and application.

A considerable amount of literature was published on advanced control algorithms for the AUV control system design

(Roy et al., 2013; Jin, 2016). Lyshevski (2001) designed robust linear and nonlinear tracking control algorithms using tracking errors and state feedback. Valentinis et al. (2015) presented a motion control system for the guidance of an underactuated unmanned underwater vehicle using energy routing. A linear quadratic regulator control design (Suebsaiprom and Lin, 2015) was applied for orientation control and stabilizing control for pitch and roll of a fish robot. Yoerger and Slotine (1985) designed adequate controllers based on the sliding mode control method, which was shown to be highly robust to nonlinearities and imprecise models.

SMC was accepted as an efficient method for the robust control of uncertain systems (Guo et al., 2003). Sabanovic (2011) discussed applications of variable structure systems with sliding modes to different problems in motion control. Sarkar et al. (2016) presented a mathematical framework for a suboptimal energy sliding mode control algorithm for an AUV. Studies showed that SMC is an attractive control system design method for underwater vehicles (Soylu et al., 2008).

Although the chattering problem of SMC can be mitigated by choosing a sufficiently large width of the boundary layer, the tracking precision cannot be guaranteed if the available control bandwidth is limited. Soylyu et al. (2008) proposed a chattering-free sliding mode controller for underwater vehicles by replacing the discontinuous switching term with a continuous adaptive term. Liu et al. (2016) proposed a fully tuned fuzzy-neural-network-based robust adaptive control scheme for trajectory and attitude tracking.

Fuzzy logic control is taken as an intelligent control method capable of dealing with complex and ill-defined systems. The combination of fuzzy logic and variable structure control was applied in control system design in recent years.

An adaptive fuzzy sliding mode controller was proposed for the kinematic variables of an underactuated underwater vehicle (Sebastián and Sotelo, 2007; Bessa et al., 2010). A novel multivariable output feedback terminal sliding mode control approach (Wang et al., 2016) was designed to stabilize the trajectory tracking error in finite time. Seo (2011) defined a new complementary sliding variable to the conventional sliding variable and adopted a novel fuzzy logic system to approximate  $n$ th order nonlinear systems. Nekoukarv and

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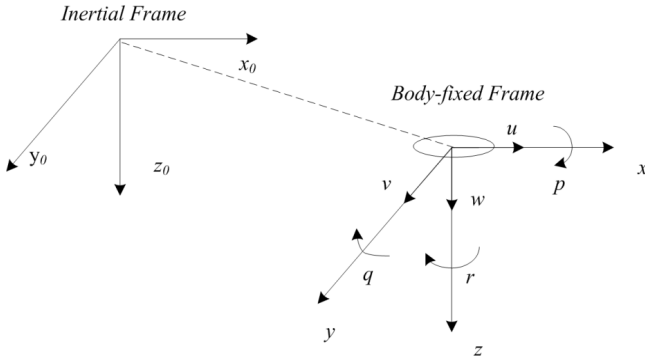


Fig. 1 Reference frames of AUV

Erfanian (2011) presented a new adaptive terminal sliding mode tracking control design for a class of nonlinear systems using a fuzzy logic system. Recently, an adaptive robust control system was proposed by employing fuzzy logic, backstepping and sliding mode control theory for the path following for the problem of an underactuated AUV (Liang et al., 2016 and Liang et al., 2018).

In present work, we discuss problems of robust trajectory control of an AUV to achieve high-quality performance in the presence of model uncertainties and unknown disturbances. The dynamics of an AUV are described as a high-order nonlinear system. The vehicle model used for the control system includes a model of high certainty and a model with unknown disturbances. The controller is designed utilizing the FSMC algorithm. The rest of this work is organized into 5 sections. Section 2 introduces the dynamic equations of the AUV. Section 3 describes the LOS guidance law. The FSMC algorithm and its theoretical derivation of stability are presented in section 4. In section 5, simulation studies and analyses are discussed to confirm the efficacy of the proposed method. Section 6 concludes the work.

## II. AUV DYNAMICS

When analyzing the motion of an AUV in six degrees of freedom (DOF), it is convenient to define an inertial reference frame and a body-fixed reference frame, as shown in Fig.1.

$\boldsymbol{\eta} = [x, y, z, \phi, \psi]^T$  is the position and orientation state vector of an AUV with respect to the inertia frame,  $\mathbf{v} = [u, v, w, p, q, r]^T$  is the velocity state vector with respect to the body-fixed frame. The relation between the position state vector and the velocity state vector is described as equation (1):

$$\boldsymbol{\eta} = \mathbf{J}(\boldsymbol{\eta})\mathbf{v} \quad (1)$$

In this work, a Newton-Euler formula (Fossen, 2011) is used to describe the complex motion of underwater vehicles in 6 DOF using the following vectorial form:

$$\mathbf{M}\dot{\mathbf{v}} + \mathbf{C}(\mathbf{v})\mathbf{v} + \mathbf{D}(\mathbf{v})\mathbf{v} + \mathbf{g}(\boldsymbol{\eta}) = \boldsymbol{\tau} + \mathbf{d} \quad (2)$$

where  $\mathbf{M}$  is the inertia matrix including the added mass effect,  $\mathbf{M} = \mathbf{M}^T > 0$ , and  $\dot{\mathbf{M}} = 0$ .  $\mathbf{J}(\boldsymbol{\eta})$  is the transformation matrix between the inertial frame and the body-fixed frame,  $\mathbf{C}(\mathbf{v})\mathbf{v}$  is centrifugal and Coriolis forces and moments, including the added mass effect,  $\mathbf{C}(\mathbf{v}) = -\mathbf{C}^T(\mathbf{v})$ ,  $\mathbf{D}(\mathbf{v})$  is the drag matrix  $\mathbf{D}(\mathbf{v}) > 0$ ,  $\mathbf{g}$  is the vector of gravity and buoyancy forces and moments,  $\mathbf{d}$  is the vector of forces and moments caused by unknown disturbances, and  $\boldsymbol{\tau}$  is the control forces and moments.

The x-z, y-z and x-y planes of symmetry are considered here.

$$\mathbf{M} = \text{diag}\{m, m, m, I_x, I_y, I_z\} - \text{diag}\{X_u, Y_v, Z_w, K_p, M_q, N_r\}$$

$$\mathbf{C}_A(\mathbf{v}) = \begin{bmatrix} 0 & 0 & 0 & 0 & -Z_w w & Y_v v \\ 0 & 0 & 0 & Z_w w & 0 & -X_u u \\ 0 & 0 & 0 & Y_v v & X_u u & 0 \\ 0 & -Z_w w & Y_v v & 0 & -N_r r & M_q q \\ Z_w w & 0 & -X_u u & N_r r & 0 & -K_p p \\ -Y_v v & X_u u & 0 & -M_q q & K_p p & 0 \end{bmatrix}$$

$$\mathbf{C}_{RB}(\mathbf{v}) = \begin{bmatrix} 0 & 0 & 0 & m(y_g q + z_g r) & -m(x_g q - w) & -m(x_g r + v) \\ 0 & 0 & 0 & -m(y_g p + w) & m(z_g r + x_g p) & -m(y_g r - u) \\ 0 & 0 & 0 & -m(z_g p - v) & -m(z_g q + u) & m(x_g p + y_g q) \\ -m(y_g q + z_g r) & m(y_g p + w) & m(z_g p - v) & 0 & I_z r & -I_y q \\ m(x_g q - w) & -m(z_g r + x_g p) & m(z_g q + u) & -I_z r & 0 & I_x p \\ m(x_g r + v) & m(y_g r - u) & -m(x_g p + y_g q) & I_y q & -I_x p & 0 \end{bmatrix}$$

$$C(v) = C_{RB}(v) + C_A(v)$$

$$g(\eta) = \begin{bmatrix} (W-B)\sin\theta \\ -(W-B)\cos\theta\sin\phi \\ -(W-B)\cos\theta\cos\phi \\ -(y_g W - y_b B)\cos\theta\cos\phi + (z_g W - z_b B)\cos\theta\sin\phi \\ (z_g W - z_b B)\sin\theta + (x_g W - x_b B)\cos\theta\cos\phi \\ -(x_g W - x_b B)\cos\theta\cos\phi - (y_g W - y_b B)\sin\theta \end{bmatrix}$$

In most cases, it is difficult to accurately measure or estimate the hydrodynamic coefficients for all operating conditions. Therefore, the system disturbances can be written as the sum of the estimated  $\hat{d}$  and the unknown  $\tilde{d}$

From equations (1) and (2), we can obtain AUV dynamics in the inertial reference frame

$$M_\eta(\eta)\ddot{\eta} + C_\eta(v, \eta)\dot{\eta} + D_\eta(v, \eta)\dot{\eta} + g_\eta(\eta) = J^{-T}(\eta)(\tau + d) \quad (3)$$

Where

$$M_\eta(\eta) = J^{-T}(\eta)MJ^{-1}(\eta),$$

$$C_\eta(v, \eta) = J^{-T}(\eta)[C(v) + MJ^{-1}(\eta)\dot{J}(\eta)]J^{-1}(\eta),$$

$$g_\eta(\eta) = J^{-1}(\eta)g(\eta)$$

$$D_\eta(v, \eta) = J^{-1}(\eta)D(v)J^{-1}(\eta).$$

### III. LOS GUIDANCE

Guidance represents a basic methodology concerned with the transient motion behavior associated with the achievement of motion control objectives (Fossen, 2011). A guidance law was used here to generate commands to control the true plant so that its trajectory matches that of the vertical plant. As a widely utilized simple and robust method, the LOS was applied to surface ships (Moreira et al., 2007). A uniform semi-global exponential stability (USGES) proof for LOS guidance laws was presented (Fossen, 2014). Consider a path-fixed reference frame with origin in  $p_{nk}$  whose  $x$ -axis has been rotated by a positive angle

$$\alpha_k = a \tan 2(y_{k+1} - y_k, x_{k+1} - x_k) \quad (4)$$

Compute the desired course angle  $\chi_d$  using the look-ahead-based steering law:

$$x_d(e) = x_p + x_r(e) = \alpha_k + \arctan\left(\frac{-e}{\Delta}\right) \quad (5)$$

The control objective  $\chi \rightarrow \chi_d$  is satisfied by transforming

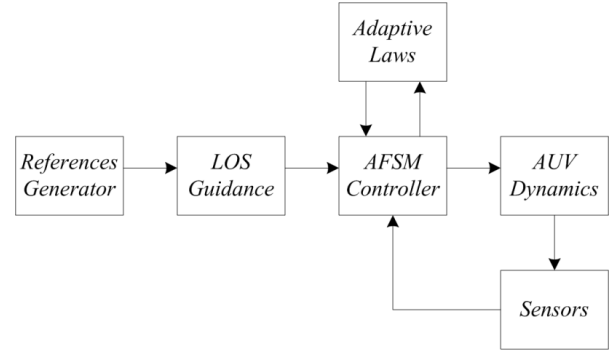


Fig. 2 The FSMC system structure

the course angle command  $\chi_d$  to a heading angle command  $\psi_d = \chi_d - \beta$ . The sideslip angle  $\beta$  can be computed by

$$\beta = \arcsin\left(\frac{v}{U}\right) \quad (6)$$

When moving along a straight-line path defined by two waypoints  $P_k^n = [x_k, y_k, z_k]^T \in \mathbb{R}^3$  and  $P_{k+1}^n = [x_{k+1}, y_{k+1}, z_{k+1}]^T \in \mathbb{R}^3$ .

The next waypoint  $P_{k+1}^n$  can be selected on the basis of whether the vehicle lies within a *sphere* of acceptance with radius  $R_0$  around the waypoint  $P_k^n$ . If the vehicle positions  $(x(t), y(t))$  at time  $t$  satisfy the following equation (7),  $P_{k+1}^n$  should be selected:

$$[x_{k+1} - x(t)]^2 + [y_{k+1} - y(t)]^2 + [z_{k+1} - z(t)]^2 \leq R_{k+1}^2 \quad (7)$$

### IV. THE FSMC SYSTEM

#### 1. Sliding mode controller

The main purpose of this study is to develop a robust trajectory tracking control system for an AUV. The overall structure of the control system is shown in Fig.2. The tracking error should converge to zero, and the current vector  $\eta$  should converge to the desired vector  $\eta_d$ . Let  $e_1 = \eta - \eta_d$  be the tracking error. A sliding surface defined in the state space by the equation  $s = 0$ . The AUV dynamics can be represented separately for each DOF, coupled due to the Coriolis and centripetal terms, as well as the buoyancy and weight. Semi-decoupled single DOF equations can be described as follows:

$$\ddot{x} = m_i^{-1}(\tau_i - c_i(v) - X_{|\dot{x}|} |\dot{x}| \dot{x}_i - g_i(\eta) - d_i(t)) \quad (8)$$

where, for each DOF  $i$ ,  $\dot{x}$ ,  $\tau_i$ ,  $m_i$ ,  $g_i(\eta)$ , and  $d_i$ , are the

components of  $\boldsymbol{\eta}$ ,  $J^{-T}(\boldsymbol{\eta})\boldsymbol{\tau}$ ,  $\mathbf{M}_\eta$ ,  $\mathbf{g}_\eta$ , and  $\mathbf{d}$ .  $X_{|\dot{x}|}$  is the square hydrodynamic drag coefficient.

The sliding surfaces are defined as equation (9)

$$s_i = \dot{\tilde{x}}_i + \lambda_i \tilde{x}_i \quad (9)$$

Let  $x_{id}$  be the desired values of position vectors. To guarantee the state error  $\tilde{x}_i = x_i - x_{id}$  changes from the approximation phase to the sliding phase, the control law is developed by making  $s_i$  and  $\dot{s}_i$  approach zero. For closed-loop operation under feedback, the system should fulfill

$$\dot{s}_i \rightarrow 0 \text{ as } t \rightarrow \infty \text{ subjected to } s_i \rightarrow 0 \text{ as } t \rightarrow \infty$$

The Lyapunov function is defined as equation (10) to ensure the global asymptotic stability of the system dynamics:

$$V_i = \frac{1}{2} s_i^2 \quad (10)$$

$$\dot{V}_i = \dot{s}_i s_i < 0 \text{ for } t > 0 \quad (11)$$

where,  $\dot{s}_i$  can be defined as:

$$\dot{s}_i = -k_i \text{sgn}(s_i) \quad i = 1, 2, 3 \quad (12)$$

The control law is

$$\begin{aligned} \tau_i = & \hat{c}(\mathbf{v}) + \hat{X}_{|\dot{x}|} |\dot{x}| \dot{x} + \hat{g}_i(\boldsymbol{\eta}) \\ & + \hat{d}_i(t) + \hat{m}_i (\ddot{x}_d - \lambda_i \dot{\tilde{x}}) - k_i \text{sgn}(s) \end{aligned} \quad (13)$$

Assume the parameters  $\hat{c}$ ,  $\hat{X}$ ,  $\hat{g}_i$ ,  $\hat{d}_i$ , and  $\hat{m}_i$  are all bounded. If appropriate  $k_i$  values are selected to overcome uncertainties, so  $\dot{V}_i \leq 0$ , then the asymptotic convergence of the tracking error is assured to approach zero. The closed-loop dynamics will match the desired dynamics.

The discontinuous term leads to a well-known chattering phenomenon. When the system approaches the sliding surface, it will stay if  $\dot{s}_i s_i < 0$ .  $k_i$  is a constant gain parameter that ensures that system dynamics can approach the sliding surface despite the uncertainties of the model and environment. Fossen's (1994) work suggests using modified control laws, which are superior to the boundary layer, to reduce the chattering effect. We adopt a suggested continuous function to replace equation(12):

$$\dot{s}_i = -k_i \tanh(s_i/\phi) \quad i = 1, 2, 3 \quad (14)$$

where  $\phi$  represents the boundary layer thickness.

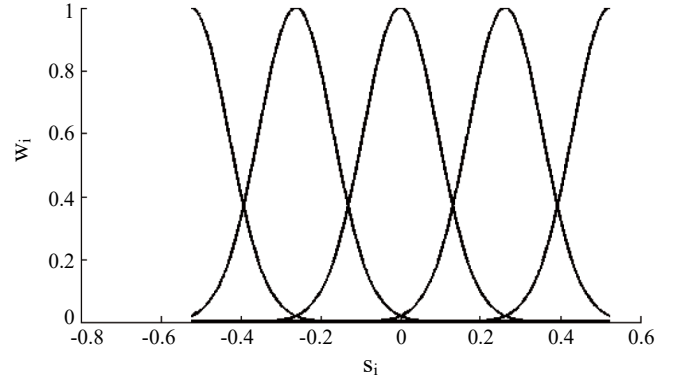


Fig. 3 Fuzzy membership function

## 2. Fuzzy adaptive system

Unknown disturbance terms are often difficult to measure or estimate. Due to the universal approximate ability of fuzzy systems, an adaptive fuzzy algorithm is used here for computing the estimates  $\hat{d}_i$  to obtain a good approximation.

Using the sliding mode function  $s$  as the input of the fuzzy system, five fuzzy sets are designed. The if-then rules of the system are described by equation (15):

$$\text{if } s_i \text{ is } A_{ir} \text{ then } \hat{d}_{ir} = \hat{B}_{ir} \quad (15)$$

$A_{ir}$  is the fuzzy set, and the degree of the membership function is shown in Fig. 3.  $\hat{B}_{ir}$  is the output of each fuzzy rule, and the final output of the fuzzy system is

$$\hat{d}_i(s_i) = \left( \sum_{r=1}^R w_{ir} \cdot \hat{B}_{ir} \right) / \sum_{r=1}^R w_{ir} \quad (16)$$

Equation (16) can be described using vector form

$$\hat{d}_i(s_i) = \mathbf{B}_i^T \boldsymbol{\varepsilon}_i(s_i) \quad (17)$$

where  $\boldsymbol{\varepsilon}_i(s_i) = [\varepsilon_{i1}, \varepsilon_{i2}, \dots, \varepsilon_{iR}]$ ,  $\varepsilon_{ir}(s_i) = w_{ir} / \sum_{r=1}^R w_{ir}$  is fixed, and  $\mathbf{B}_i^T = [B_{i1}, B_{i2}, \dots, B_{iR}]$  is the element that can be adaptively tuned until they reach the optimal values.

The parameter  $\mathbf{B}_i$  adaption algorithm is

$$\dot{\mathbf{B}}_i = -\theta_i \sigma_i \boldsymbol{\varepsilon}_i(s_i) \quad (18)$$

where  $\theta_i$  is a positive constant.

The optimal parameter vector is defined as

$$\mathbf{B}_i^* = \arg \min \left[ \sup |B_i(s_i) - d_i| \right] \quad (19)$$

Tab. 1 Main parameters of the vehicle

DOF	Inertia	Coriolis-centripetal	Squat damping	Buoyancy
Surge	82.5[kg]	$226 \cdot x_v \cdot x_r$ [kg·m/s <sup>2</sup> ]	100[N/(m/s) <sup>2</sup> ]	0
Heave	226[kg]	0[kg·m/s <sup>2</sup> ]	215.25[N/(m/s) <sup>2</sup> ]	0
Yaw	10.84[kg·m <sup>2</sup> ]	$133.5 \cdot x_r \cdot x_v$ [kg·m/s <sup>2</sup> ]	9[N·m/(rad/s) <sup>2</sup> ]	0

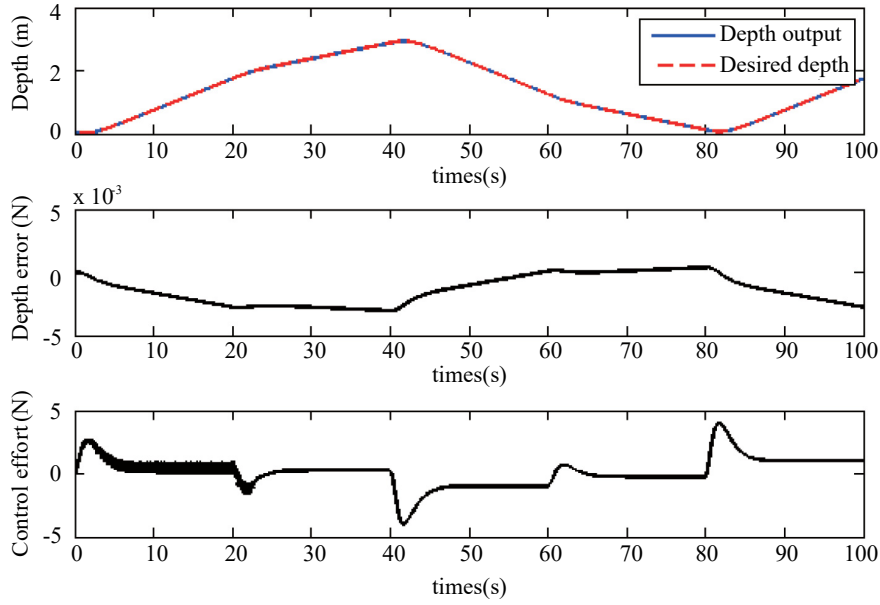


Fig. 4 Depth control using FSMC method

Assuming  $\tilde{\mathbf{B}}_i = \mathbf{B}_i - \mathbf{B}_i^*$ , consider the Lyapunov function:

$$V_i = \frac{1}{2} s_i^2 + \frac{1}{2\gamma} \tilde{\mathbf{B}}_i^T \tilde{\mathbf{B}}_i \quad (20)$$

The derivative of V is

$$\begin{aligned} \dot{V}_i &= \dot{s}_i s_i + \frac{1}{\gamma} \tilde{\mathbf{B}}_i^T \dot{\tilde{\mathbf{B}}}_i \\ &= (\ddot{x} - \ddot{x}_d + \lambda \dot{\tilde{x}}) s_i + \frac{1}{\gamma} \tilde{\mathbf{B}}_i^T \dot{\tilde{\mathbf{B}}}_i \end{aligned} \quad (21)$$

The control law and adaption law are replaced; then, we can obtain the following equation:

$$\begin{aligned} \dot{V} &= \begin{pmatrix} m_i^{-1} \left( \tau_i - c_i(\mathbf{v}) - X_{|\dot{x}|} |\dot{x}| \dot{x}_i \right) \\ -g_i(\eta) - d_i(t) \\ -\ddot{x}_d + \lambda \dot{\tilde{x}} \end{pmatrix} s_i + \frac{1}{\gamma} \tilde{\mathbf{B}}_i^T \dot{\tilde{\mathbf{B}}}_i \\ &= \begin{pmatrix} \hat{c}(\mathbf{v}) + \hat{X}_{|\dot{x}|} |\dot{x}| \dot{x} + \hat{g}_i(\eta) + \hat{d}_i(t) \\ + \hat{m}_i (\ddot{x}_d - \lambda \dot{\tilde{x}}) - k_i \tanh(s_i / \phi_i) - c_i(\mathbf{v}) \\ -X_{|\dot{x}|} |\dot{x}| \dot{x}_i - g_i(\eta) - d_i(t) \end{pmatrix} m_i^{-1} s_i \\ &\quad + \frac{1}{\gamma} \tilde{\mathbf{B}}_i^T \dot{\tilde{\mathbf{B}}}_i \end{aligned} \quad (22)$$

Let  $\xi = \hat{d}_i^* - d$  and  $\gamma = (s_i \mathbf{M}^{-1})^{-1} \theta$ , then

$$\begin{aligned} \dot{V} &\leq -m_i^{-1} s_i [k_i \tanh(s_i / \phi_i) - c_i + \hat{c} - X + \hat{X} + \hat{g}_i - g \\ &\quad - d_i + \hat{d}_i - \xi + \hat{m}_i (\ddot{x}_d - \lambda \dot{\tilde{x}})] + \frac{1}{\gamma} \tilde{\mathbf{B}}_i^T \dot{\tilde{\mathbf{B}}}_i \\ &= -m_i^{-1} s_i [k_i \tanh(s_i / \phi_i) - c_i + \hat{c} - X + \hat{X} + \hat{g}_i - g \\ &\quad - \tilde{\mathbf{B}}_i^T \boldsymbol{\varepsilon}_i(s_i) - \xi + \hat{m}_i (\ddot{x}_d - \lambda \dot{\tilde{x}})] + \frac{1}{\gamma} \tilde{\mathbf{B}}_i^T \dot{\tilde{\mathbf{B}}}_i \\ &= -m_i^{-1} s_i [k_i \tanh(s_i / \phi_i) - (c_i - \hat{c} + X - \hat{X} + \hat{g}_i - g + \xi) \\ &\quad + \hat{m}_i (\ddot{x}_d - \lambda \dot{\tilde{x}})] + \tilde{\mathbf{B}}_i^T \boldsymbol{\varepsilon}_i(s_i) \left( m_i^{-1} s_i - \frac{1}{\gamma} \theta_i s_i \right) \end{aligned} \quad (23)$$

Suppose  $\gamma = m_i \theta_i$  and the parameters  $\hat{c}$ ,  $\hat{X}$ ,  $\hat{g}_i$ ,  $\hat{d}_i$ , and  $\hat{m}_i$  are all bounded. If appropriate  $k_i$  values are selected to overcome all uncertainties, so  $\dot{V}_i \leq 0$ , then the tracking errors and their first derivatives converge to zero in finite time. The closed-loop dynamics are stable.

## V. SIMULATION STUDIES AND ANALYSIS

The proposed control system was implemented in MATLAB/Simulink platform to confirm its effectiveness. The AUV

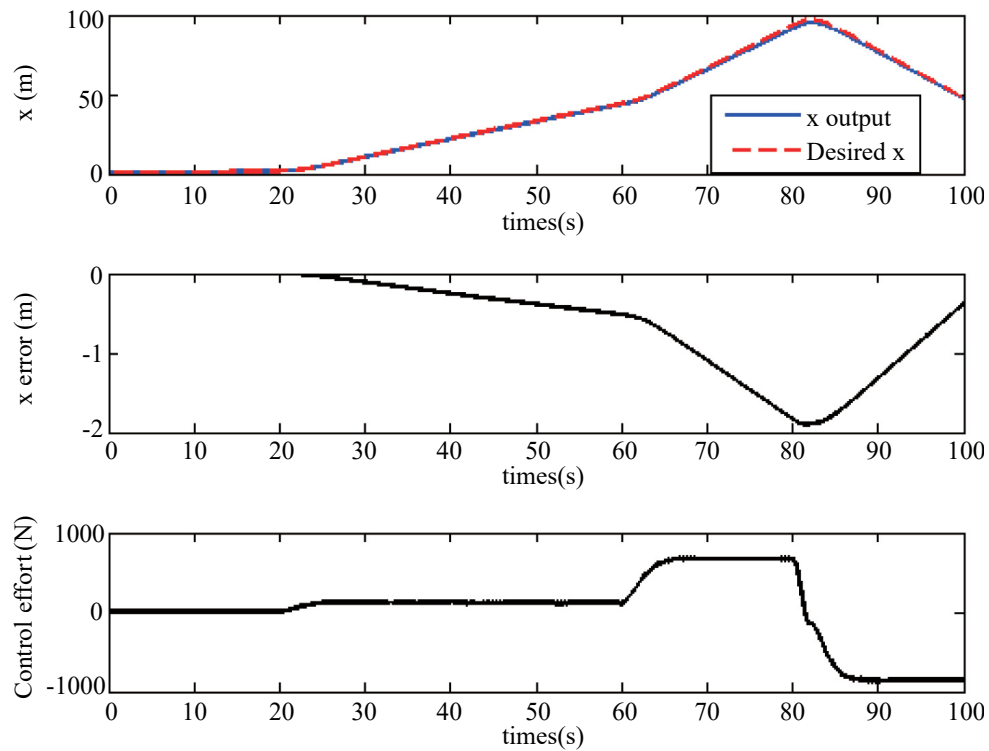


Fig. 5 Surge control using FSMC method

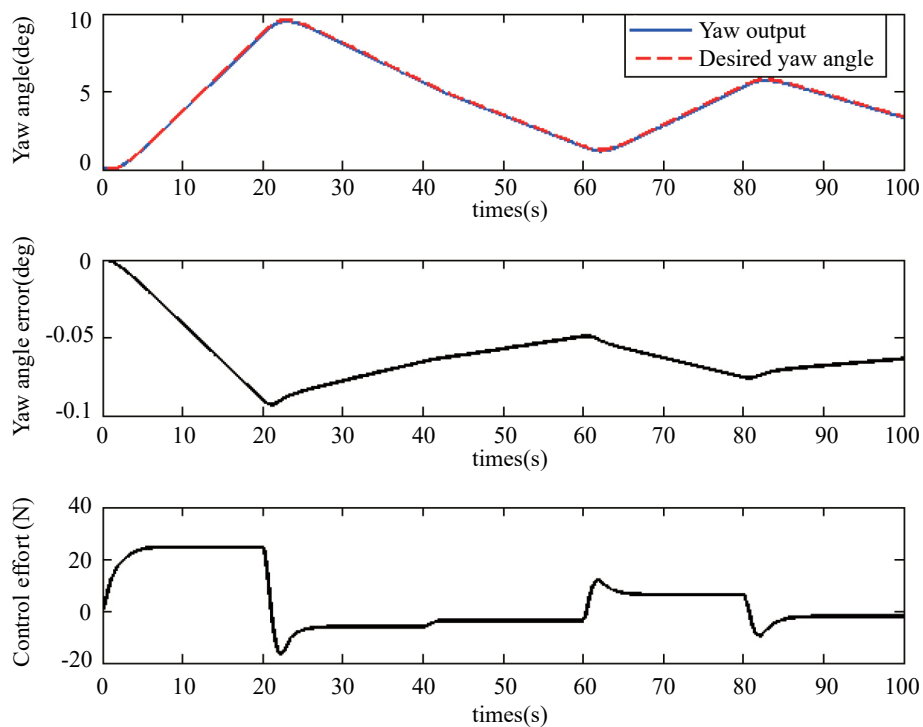


Fig. 6 Yaw control using FSMC method

parameters adopted here are from reference of Sebastián and Sotelo(2007), as shown in Tab.1. We consider two different models: a certain model with known coefficients and a model

with uncertain disturbances.

According to the established system, we need to set all the corresponding parameters to the right values. The simulation



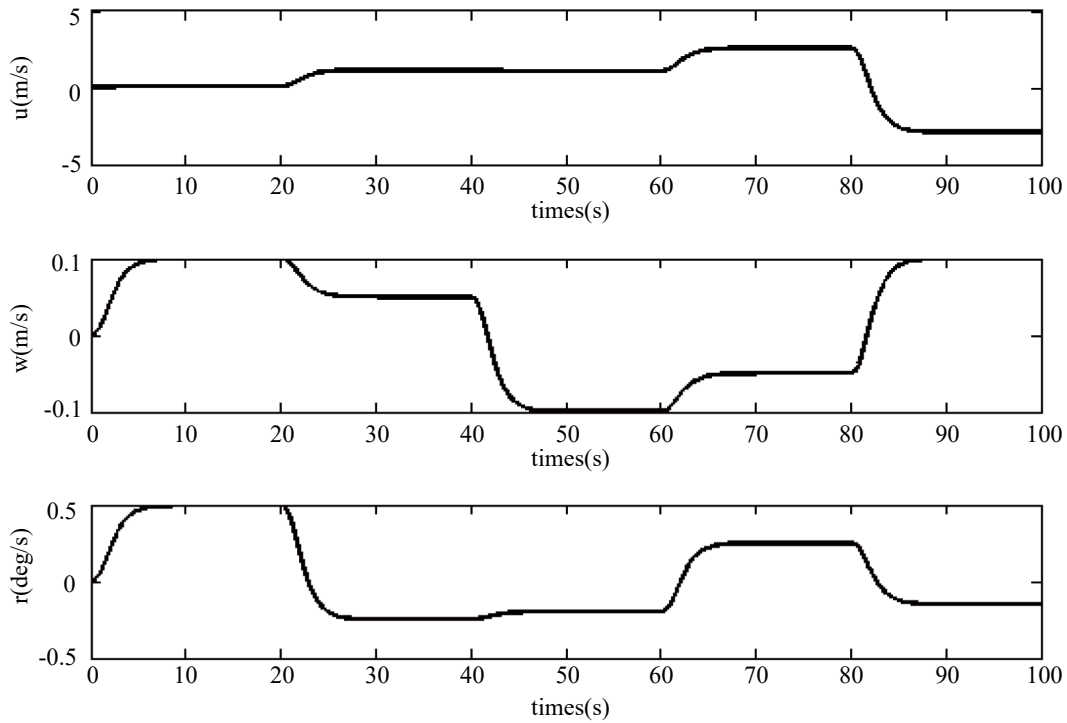


Fig. 7 Speed output using FSMC method

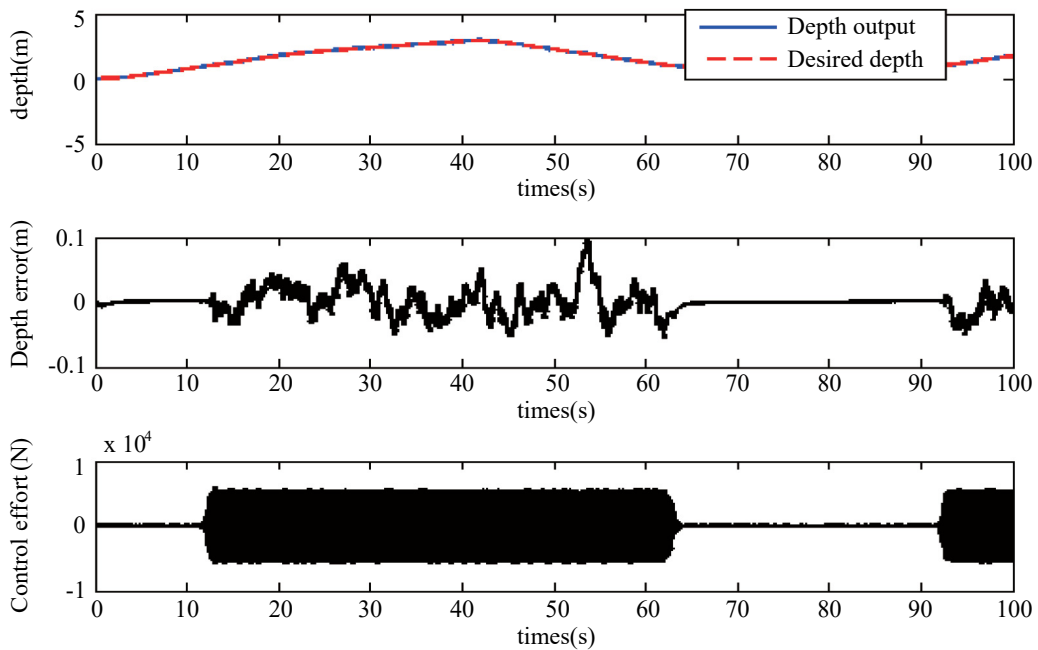


Fig. 8 Depth control using SMC with disturbances

results presented here only refer to surge, heave and yaw. The fixed-step Runge-Kutta algorithm with a step interval of 0.1 s was selected. The desired vertical plane paths consist of a total of six (x, z) waypoints: (0, 0), (2, 2), (25, 3), (47, 1), (100, 0), (40, 2).

Five membership functions are used in the estimation of  $\hat{d}_i$ . The membership functions adopted here have a Gaussian form. For each membership function, the center is set to  $[-1, -0.52, 0, 0.52, 1]$ , and the deviation is  $\frac{\pi}{12}$ .

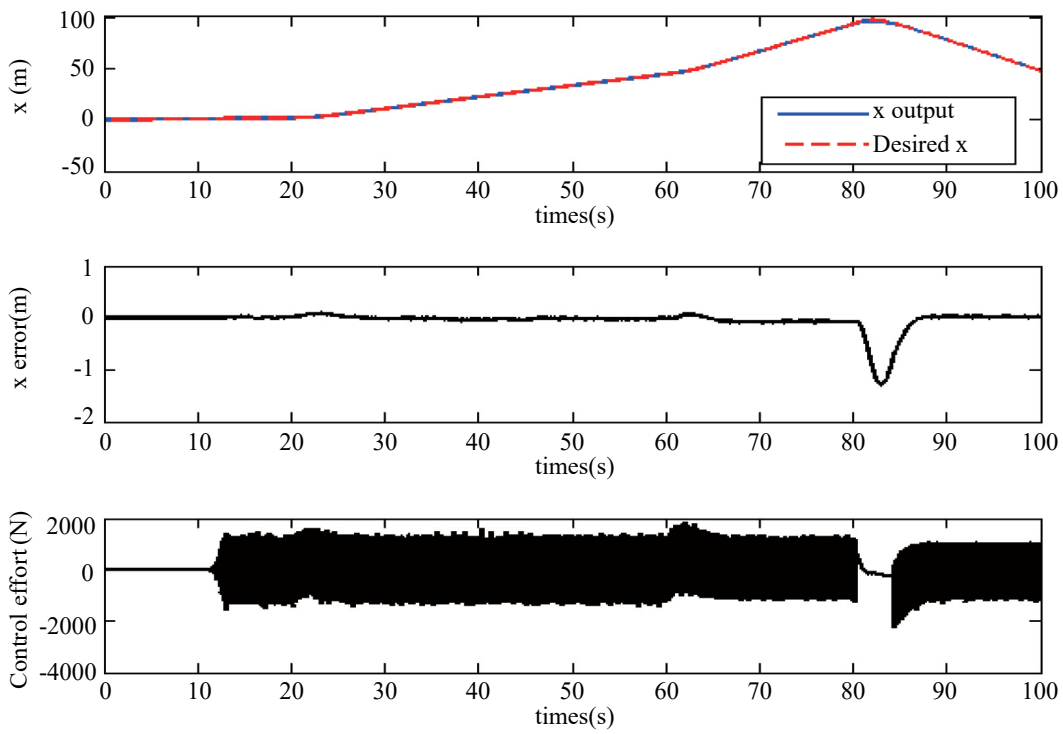


Fig. 9 Surge control using SMC with disturbances

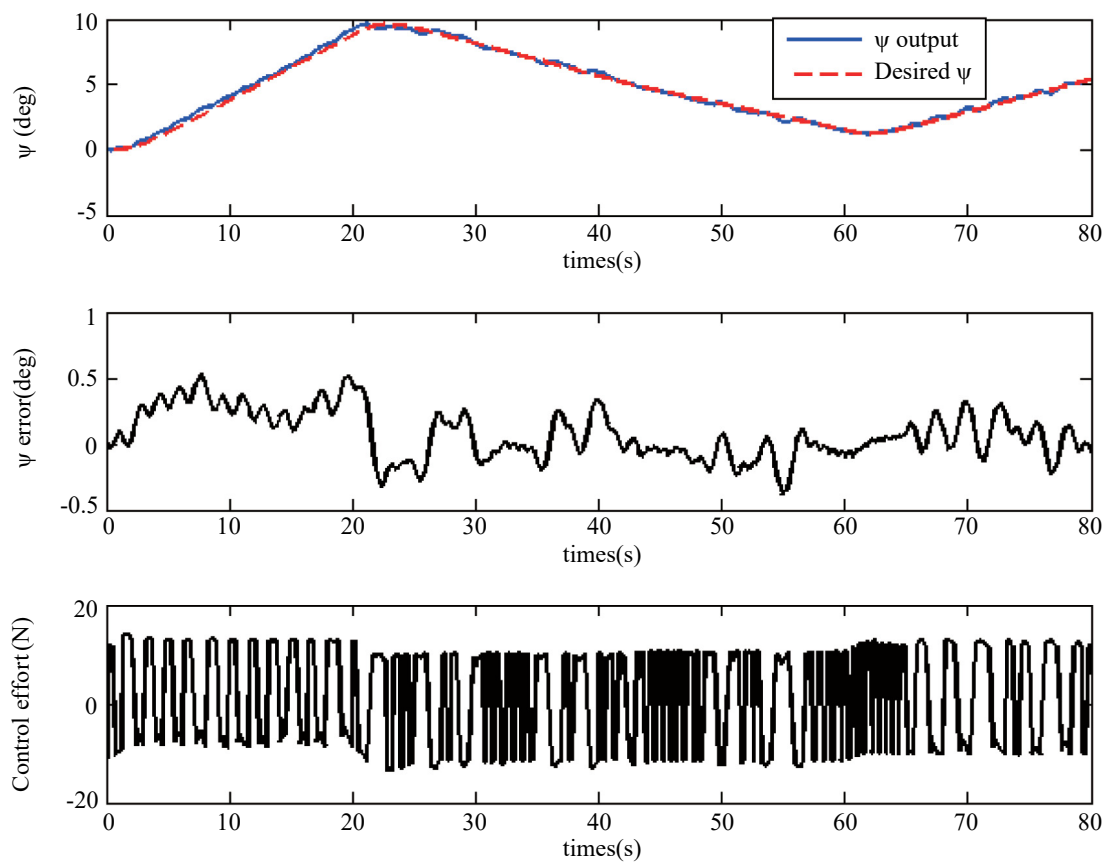


Fig. 10 Yaw control using SMC with disturbances

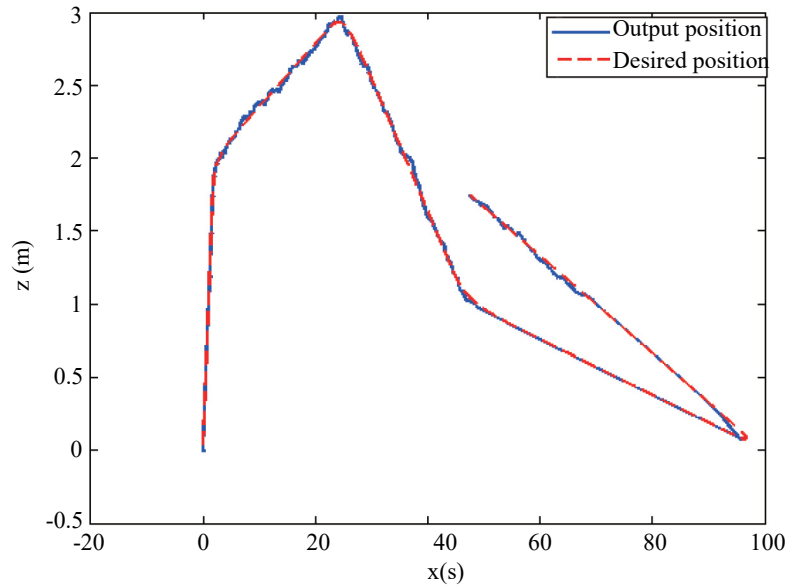


Fig.11 Vertical plane trajectory by SMC with disturbances

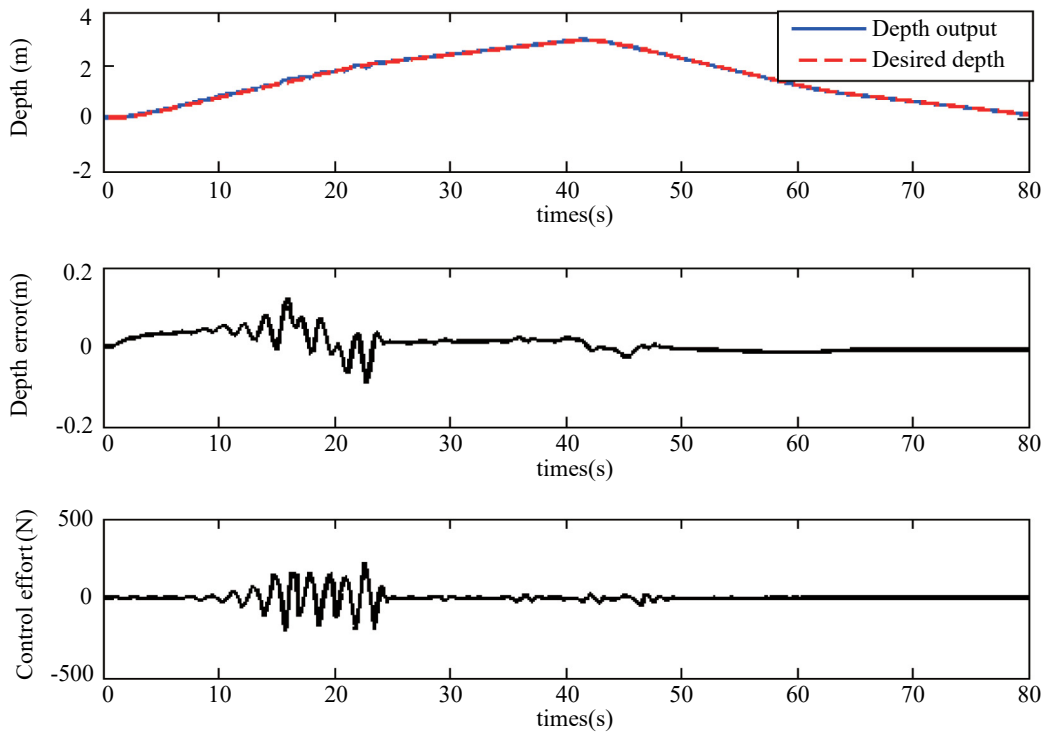


Fig.12 Depth control using FSMC with disturbances

Figs. 4-7 show the performance of a certain vehicle model without disturbances for the desired path, which consists of six points using the proposed method. From the simulation results, we can see the heave, surge and yaw trajectory, tracking error and control effort. The trajectory of the vehicle fits the desired route well. It can be concluded that the methodology can be applied with success to minimize the error between the actual and the desired path of the vehicle.

Case studies are presented to allow comparison of the trajectories based on the SMC method and the FSMC method. Figs. 8–11 present the performance of an uncertain model with unknown disturbances for the same desired path using the SMC. In this case, we considered the following disturbances:  $d_z(t) = 3\sin(0.1t - \pi/4)$ ,  $d_x(t) = 10\sin(0.1t - \pi/4)$  and  $d_\psi(t) = 0.2\sin(0.1t - \pi/4)$ .

For each DOF, we can see the trajectory, tracking error and

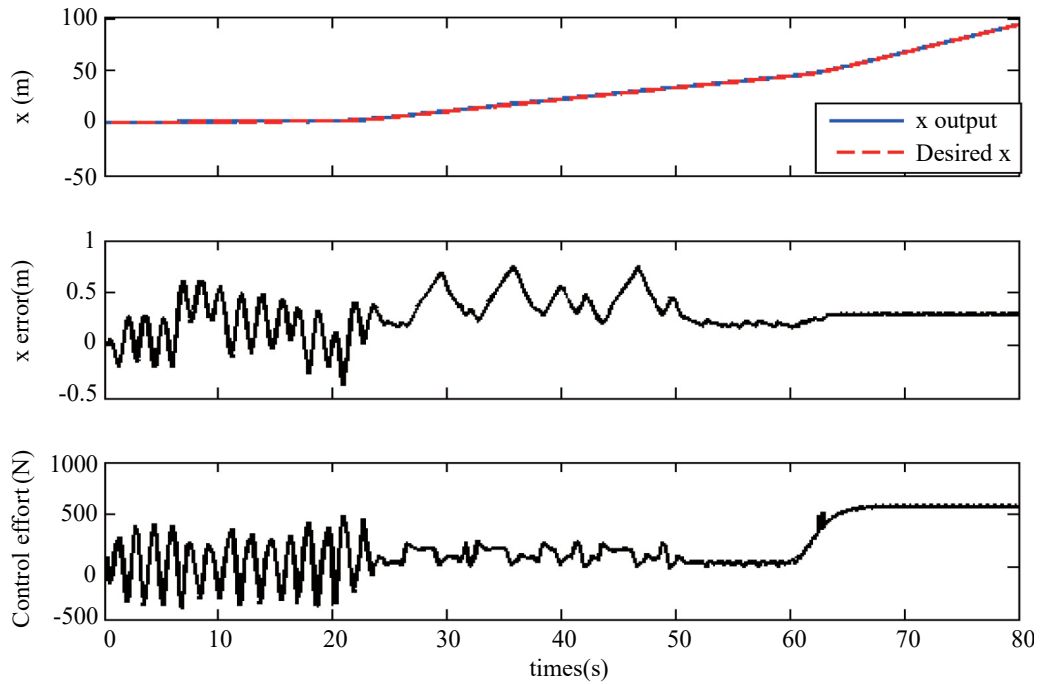


Fig.13 Surge output using FSMC with disturbances

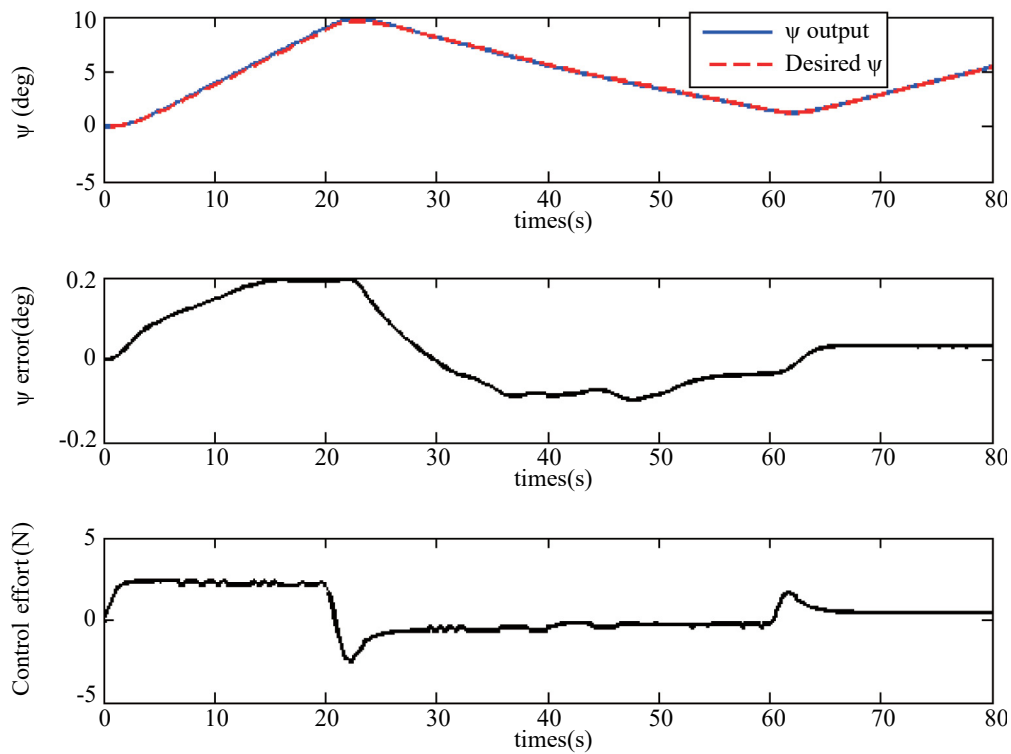


Fig.14 Yaw control using FSMC with disturbances

control efforts based on the SMC method in Figs. 8-10. The results show that there are distinct control efforts in surge, heave and yaw. Fig.11 shows the vertical plane trajectory using the SMC method. It is clear that the disturbances in-

fluence the trajectory from the simulation results. Obtaining a minimal track error causes large chattering in control efforts.

Figs. 12-15 show the influence of the same disturbances on the behavior of the FSMC controller. Based on the FSMC

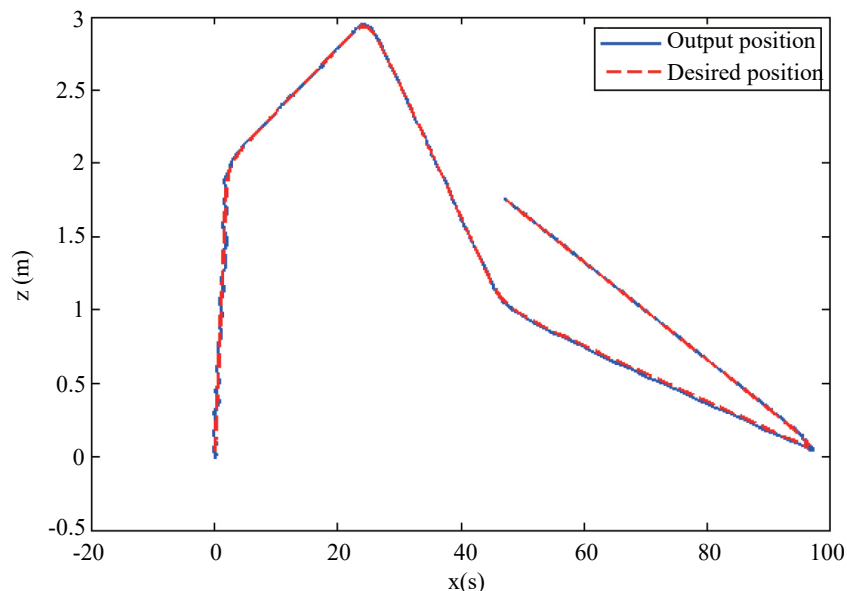


Fig.15 Vertical plane trajectory by FSMC with disturbances

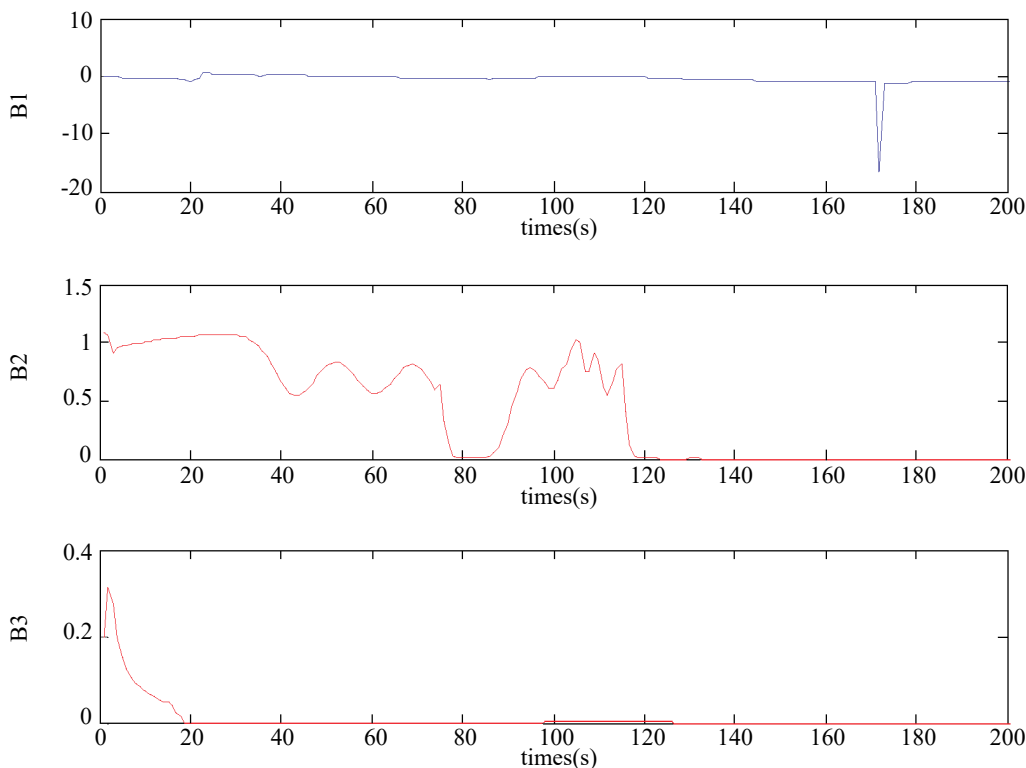


Fig. 16 The parameters  $B_i$  of fuzzy adaption system refer to surge, heave and yaw

method, we can see the AUV trajectory, tracking error and control effort for each DOF, i.e., heave, surge and yaw, respectively, in Figs. 12-14. Obviously, the introduction of disturbances affects the control performance. Fig.15 shows the vertical plane trajectory using the FSMC method. The error does exist between the vehicle trajectory and the desired

path. Although differences exist, path planning can be accomplished with all disturbances.

The parameters  $B_i$  of the fuzzy adaption system, which are adjusted to ensure that the controller can adapt on-line to changing characteristics, are shown for surge, heave and yaw in Fig.16. The circumstances are different when comparing the

SMC (Fig. 11) with the FSMC (Fig.15). However, the control effort and track error of the SMC system are larger than those of the FSMC control system. We can clearly see that the disturbances had a negative effect on the proposed scheme. However, the disturbance will not cause radical changes. Disturbances are not a big problem with the proposed controller.

From the simulation results, we can see that the proposed adaptive FSMC system is robust in producing good control performance.

## VI. CONCLUSIONS

The presence of nonlinearities and uncertainties makes estimating vehicle motion and disturbance challenging. This paper presents a nonlinear control system to address the AUV trajectory tracking problem. The vehicle model used for the control system includes a model of high certainty and a model with unknown disturbances. An adaptive FSMC method was implemented using an adaptive fuzzy system to estimate the unknown disturbances. Using LOS guidance law, a vertical plane path that consists of six waypoints was simulated to demonstrate the effectiveness of the proposed strategy. According to reported simulation results, the proposed method has the ability to achieve robust performance with a reference trajectory. Future work will involve experimentally validating the proposed control scheme.

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