Fuzzy Adaptive Sliding Mode Controller for Path Following of an Autonomous Underwater Vehicle

Wei Zhang, Zhicheng Liang, Yi Guo, Detao Meng, Jiajia Zhou
College of Automation
Harbin Engineering University
Harbin, China
lzc567@126.com

Yunfeng Han
College of underwater acoustic engineering
Harbin Engineering University
Harbin, China

***Abstract*—In order to reduce chattering while promoting control precision in a sliding mode control (SMC) method, a new control scheme for path following system of an under-actuated autonomous underwater vehicle (AUV) in the horizontal plane via fuzzy adaptive sliding mode control (FASMC) method was presented. A novel reaching law based on exponential reaching law and sigmoid function was proposed for sliding mode controllers of the path following system. The fuzzy adaptive controllers of boundary layers were designed based on the following errors of the AUV and the angles between the sliding surface and state vector. Compared to the SMC method, the chattering was reduced effectively and following precision was improved at the same time when the FASMC method was used. Other than that, the FASMC method maintained the robustness to the uncertainties of the mathematical models of the AUV. The results were illustrated with numerical simulations.**

Keywords—under-actuated AUV; path following; fuzzy adaptive sliding mode; reaching law; boundary layer

I. INTRODUCTION

In recent years, under-actuated autonomous underwater vehicles (AUVs) have been widely used in mine hunting, deep sea survey, safe guarding of ports and so on because of theirs inexpensive cost and simple structure [1, 2]. Thus, a higher control precision of path following system of the AUVs is expected. Path following problem of the AUVs does not consider time constraints [3]. It means that the errors of path following does not change over time, just according to the current status and the desired status of AUVs to calculate the errors, which makes the anti-interference performance of the AUVs can be improved when encountered significant external disturbance. Due to the good robustness, this path following scheme is more suitable for AUVs under the complex sea current disturbance, although real-time performance of the scheme is bad.

The popular methods for path following system of AUVs include PID control, back-stepping technology, sliding mode control and so on. A PID control method can be found in [4], fuzzy PID motion controllers are designed for 3D path following system, and the shortcoming of PID control method is that poor anti-interference performance. A back-stepping technology is adopted in [5], limited robustness to parameter uncertainties is demonstrated. Both of the methods mentioned above were based on the accurate mathematical models of AUVs to guarantee robustness of path following system. However, the high accuracy mathematical model means that design of controllers is more complex. The sliding mode control (SMC) method, which has good robustness to uncertainties [6], can be applied to overcome these shortcomings. The SMC methods based on a variety of novel reaching laws can be found in [7−10]. A double power reaching law is proposed to improve the convergence rate of SMC method in [7]. In [8], an exponential reaching law is combined with status variable to reduce the chattering in SMC, that is, the switch gain will be reduced adaptively when the state variable is near to the sliding surface. In [9], a variable coefficient is introduced for changing the absolute value of the sliding function adaptively in the power reaching law. In [10], the hyperbolic tangent function is added into the exponential reaching law, and the upper bounds of the control inputs are guaranteed. Some fuzzy adaptive laws are often combined with the SMC method to improve the control performance. A fuzzy adaptive sliding mode control (FASMC) method can be found in [11]. Two fuzzy adaptive controllers are designed for switch gain and boundary layer respectively. In [12], two fuzzy adaptive controllers were designed for slope of the linear sliding surface and switching control term respectively. In all these works mentioned above, the unsmooth saturation function and the discontinuous sign function are considered. These works do not take into account of the sigmoid function. Due to the continuity and smoothness of the sigmoid function, a better performance of chattering reduction in SMC method can be achieved [13].

Inspired by the above-mentioned works, a new FASMC method based on a novel reaching law was proposed for path following system of an AUV in [3] in the horizontal plane. The path following system can be decoupled as three subsystems: the surge velocity control subsystem, position control subsystem and yaw angle control subsystem. The main works of this paper can be summarized as: First, the novel reaching law included the sigmoid function that was proposed based on the conventional exponential reaching law. Then the SMC laws for the three subsystems were designed by using the reaching law. At last, the fuzzy adaptive laws of boundary layers were designed based on the following errors and the angles between the sliding surface and state vector [14]. The

978-0-933957-43-5 ©2015 MTS

results were shown by numerical simulations.

II. Mathematical Model

Because of the robustness of the SMC method, the high accuracy mathematical model of the AUV is unnecessary. Thus, the mathematical model can be simplified according to the following assumptions [3]:

Assumption 1: The AUV can be seen as a symmetrical object.

Assumption 2: Ignore the elements which are not in the main diagonal of the inertia matrix and damping matrix.

An under-actuated AUV with one propeller in the longitudinal and two (vertical and horizontal) rudders in the rear is studied. The simplified kinematics and dynamics models in a horizontal plane can be expressed as [3]:

$$\begin{cases} \dot{x} = U\cos(\psi+\beta) \\ \dot{y} = U\sin(\psi+\beta) \\ \dot{\psi} = r \end{cases}, \tag{1}$$

and

$$\begin{cases} \dot{u} = \dfrac{m_{11}}{m_{22}}vr - \dfrac{d_{11}}{m_{22}}u + \dfrac{1}{m_{22}}F_X \\ \dot{v} = \dfrac{m_{22}}{m_{11}}ur - \dfrac{d_{22}}{m_{11}}v \\ \dot{r} = \dfrac{m_{22}-m_{11}}{m_{33}}uv - \dfrac{d_{33}}{m_{33}}r + \dfrac{1}{m_{33}}T, \end{cases} \tag{2}$$

where x and y represent the position of the AUV, u and v are surge and sway velocity respectively, ψ and r denote yaw angle and yaw angular velocity respectively, $U=(u^2+v^2)^{1/2}$ is resultant velocity, $\beta = \arctan(v/u)$ denotes sideslip angle, F_X and T denote the main thrust and control torque produced by the propeller and vertical rudder respectively, m_{11}, m_{22}, m_{33}, d_{11}, d_{22} and d_{33} are constant coefficients for the specific AUV, $m_{11}=m-Y_{\dot{v}}$, $m_{22}=m-X_{\dot{u}}$, $m_{33}=J_Z-N_{\dot{r}}$, $d_{11}=-X_u$, $d_{22}=-Y_v$, $d_{33}=-N_r$, m and J_Z represent the mass and moment of inertia of the AUV respectively, $Y_{\dot{v}}$, $X_{\dot{u}}$, $N_{\dot{r}}$, X_u, Y_v and N_r are hydrodynamic coefficients.

The causes of the AUV turning action in a horizontal plane, specifically, are due to the hydrodynamic torque generated by the sideslip angle β (β caused by the angle of vertical rudder). Moreover, we can see that the generation of β is accompanied by the generation of v. Thus, the sideslip angle β and sway velocity v are bounded because the output of vertical rudder angle is limited. In general, the value of v is much smaller than the value of u, that is, $|v| \ll |u|$. Then the following relationship can be obtained [15]:

$$|U| = \sqrt{v^2+u^2} \approx |u|. \tag{3}$$

Therefore, based on the relationship (3), the following reasonable assumptions can be obtained [15]:

Assumption 3: It can be considered that the resultant velocity U is equal to the surge velocity u.

Assumption 4: $\exists u_{\max}$ and $u_{\min}$ such that $u_d \in [u_{\min}, u_{\max}]$, where u_d is desired surge velocity, $u_{\max} > u_{\min} > 0$.

Based on (1), assumption 1 and assumption 2, Serret-Frenet frame is introduced for the establishment of the errors differential equation model which can be written as [16]:

$$\begin{cases} \dot{x}_e = -\dot{s} + k_s\dot{s}y_e + u\cos\psi_e \\ \dot{y}_e = -k_s\dot{s}x_e + u\sin\psi_e \\ \dot{\psi}_e = r + \dot{\beta} - \psi_d \end{cases}, \tag{4}$$

where s and k_s are arc length and curvature of the desired path in the horizontal plane respectively, $x_e=x-x_d$ and $y_e=y-y_d$ denote the position errors of the AUV, $\psi_e=\psi+\beta-\psi_d$ denote the error of the yaw angle, ψ_d is desired yaw angle.

III. Controller Design

In this section, a new control scheme for path following system of the AUV was proposed. An idea of decoupling was selected for the path following controllers, namely, select the tangential velocity $\dot{s}$ as a virtual control input [16], then the position following error x_e can be converge to zero by designing a SMC law of $\dot{s}$, as also ψ_e can be converge to zero by designing a SMC law of T for the yaw angle control subsystem, then the position following error y_e converges to zero naturally. Therefore, the design of the path following system for the AUV can be decoupled as:

- Design the surge velocity control law F_X based on the first equation of (2), which makes $u \to u_d$.
- Design the position control law $\dot{s}$ based on the first equation of (4), which makes $x_e \to 0$.
- Design the yaw angle control law T based on the last equation of (4) and the last equation of (3), which makes $\psi_e \to W$.

The purpose of this plan is to allow the AUV to follow a desired path with a certain speed. The approaching angle $W = -\arctan(uy_e)$ denotes the desired angle of ψ_e, which can be used to adjust the transient behavior of the convergence process of the yaw angle's error ψ_e [3].

A. Design Controllers by Reaching Law

In [3], the classic SMC laws without singular values based on the sigmoid function and the conventional exponential reaching law can be designed as:

$$\begin{cases} F_X = -m_{22}\left[k_1\Phi(\lambda_1,s_1)+\varepsilon_1 s_1\right] - m_{11}vr + d_{11}u \\ \dot{s} = u\cos\psi_e + \varepsilon_2 s_2 + k_2\Phi(\lambda_2,s_2) \\ T = -m_{33}\left[\dfrac{1}{c}\left(\dot{e}_\psi + \varepsilon_3 s_3 + k_3\Phi(\lambda_3,s_3)\right) + \ddot{\beta} - \ddot{\psi}_d - \ddot{W}\right] - \\ \quad (m_{22}-m_{11})uv + d_{33}r \end{cases}, \tag{5}$$

where k_1, k_2 and k_3 are switch gains, ε_1, ε_2 and ε_3 are coefficients of the exponential term in the exponential reaching laws, $s_1 = u - u_d$, $s_2 = x_e$ and $s_3 = e_\psi + \dot{e}_\psi$ are sliding surface functions, the error $e_\psi=\psi_e - W$, λ_1, λ_2 and λ_3

are reciprocal of the boundary layer thicknesses [14], the Sigmoid function $\Phi(\cdot)$ which is used to reduce the chattering.

In SMC method, the steady-state error is proportional to the thickness of boundary layer and inversely to the switching gain. However, the chattering is proportional to the switching gain and inversely to the thickness of boundary layer [14]. Obviously, the process of reducing chattering and improving control precision is contradictory. Therefore, the switching gain and the thickness of boundary layer should be time-varying so that a better balance between the steady-state error and the chattering can be reached. Based on the above analysis, the novel reaching law with time-varying switching gain in this paper can be expressed as:

$$\dot{s}=-k\frac{1}{|s|^{a}}\Phi(\lambda,s)-\varepsilon s|s|^{b}, \tag{6}$$

where, $k>0$ is switch gain, $\varepsilon>0$ is coefficient of the exponential term, λ and s denote the thickness of boundary layer and sliding surface function respectively, $a>0$ and $b>0$ are design parameters.

By the observation of (6), $1/|s|^{a}$ and $|s|^{b}$ were added into the conventional exponential reaching law. Meanwhile, the sigmoid function was used instead of the sign function. When the state point of control system is far away from the sliding surface, the error of the control system is large. That is, the switch gain k will become smaller with the increase of the value of $|s|^{a}$, which makes the chattering decrease, even though the convergence rate of the error is reduced at the same time. This strategy is allowed to be used in some control systems which have lower requirement for fast, such as motion control systems of underwater vehicles. Moreover, the value of $|s|^{b}$ will be increased with the increase of the error. This can improve the convergence rate to a certain extent. Conversely, when the state point converge to the sliding surface, the switch gain k will be larger with the decrease of the value of $|s|^{a}$, which makes the error decrease. However, the chattering will be increased in the meantime. Thus, the design parameter a is important for chattering reduction. Furthermore, the value of $|s|^{b}$ will be decreased with the decrease of the error. This will slow down the convergence rate when the state point is near to the sliding surface.

Based on the novel reaching law (6), the control laws (5) of the path following system can be rewritten as:

$$\begin{cases} F_X=-m_{22}\left[\dfrac{k_1}{|s_1|^{a_1}}\Phi(\lambda_1,s_1)+\varepsilon_1|s_1|^{b_1}s_1\right]-m_{11}vr+d_{11}u \\ \dot{s}=u\cos\psi_e+\varepsilon_2|s_2|^{b_2}s_2+\dfrac{k_2}{|s_2|^{a_2}}\Phi(\lambda_2,s_2) \\ T=-m_{33}\cdot\left[\dfrac{1}{c}\left(\dot{e}_\psi+\varepsilon_3|s_3|^{b_3}s_3+\dfrac{k_3}{|s_3|^{a_3}}\Phi(\lambda_3,s_3)\right)+\right. \\ \qquad \left.\ddot{\beta}-\ddot{\psi}_d-\ddot{W}\right]-(m_{22}-m_{11})uv+d_{33}r \end{cases}, \tag{7}$$

where, the design parameters a_1, a_2, a_3, b_1, b_2 and b_3 are positive numbers.

B. Fuzzy Adaptive Control Scheme for Boundary Layers

The design of the boundary layer thickness in SMC method is mainly rely on the expert knowledge. Therefore, fuzzy adaptive method is suitable for the design of boundary layer thickness because of the good imitation of expert knowledge [17]. In the surge velocity control subsystem and position control subsystem, the inputs for the fuzzy adaptive laws of λ_1 and λ_2 are surge velocity error $|s_1|$ and position error $|x_e|$, respectively. Whereas, the input for the fuzzy adaptive law of λ_3 is the absolute value of the angle which between the sliding surface and state vector in the yaw angle control subsystem. The Takagi-Sugeno (T-S) fuzzy model is used for the adaptive laws of λ_1, λ_2 and λ_3 to simplify the design [17]. The inputs can be decomposed into three fuzzy sets include Zero (Z), Medium (M) and Big (B). The decision making logic is based on the expert knowledge, that is, when the inputs are large, the output should be small, so that the larger boundary layer thickness can be obtained to reduce the chattering. Conversely, when the inputs are small, the outputs should be large so that the smaller boundary layer thickness can be obtained to improve following accuracy.

First, design the fuzzy adaptive output $\tilde{\lambda}_1$. In order to simplify the design process and the fuzzy reasoning process, thus reducing the calculation time and improving the real-time performance of the controllers, T-S fuzzy model with constant function was considered. The membership function of input error $|s_1|$ was shown in Fig. 1. The expert knowledge can be described as the following rules:

- Rule 1: If $|s_1|$ is Z then $\tilde{\lambda}_1=4.75$.
- Rule 2: If $|s_1|$ is M then $\tilde{\lambda}_1=2.5$.
- Rule 3: If $|s_1|$ is B then $\tilde{\lambda}_1=0.05$.

Second, design the fuzzy adaptive output $\tilde{\lambda}_2$. The membership function of input error $|x_e|$ was shown in Fig. 2, and then the expert knowledge for the position control subsystem can be described as the following if-then rules:

- Rule 1: If $|x_e|$ is Z then $\tilde{\lambda}_2=1.6$.
- Rule 2: If $|x_e|$ is M then $\tilde{\lambda}_2=0.8$.
- Rule 3: If $|x_e|$ is B then $\tilde{\lambda}_2=0.1$.

It should be noted that, the fuzzy adaptive output $\tilde{\lambda}_1$, $\tilde{\lambda}_2$ and $\tilde{\lambda}_3$ are reciprocal of the boundary layer thicknesses. In other words, a large fuzzy adaptive output corresponds to a small boundary layer thickness; conversely, a small fuzzy adaptive output means a large boundary layer thickness (the positive integer 1 is a special case).

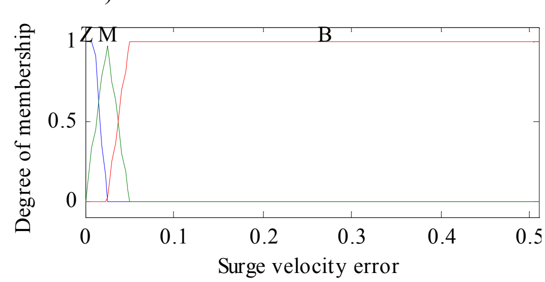

Fig. 1. Membership functions for input $|s_1|$.

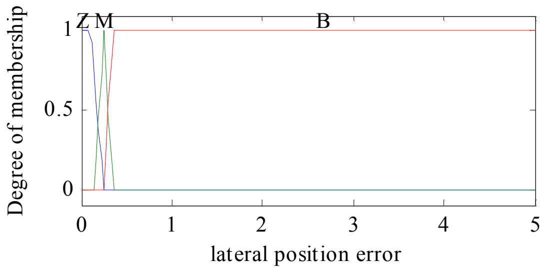

Fig. 2. Membership functions for input $|x_e|$.

The division of the input spaces in Fig. 1 and Fig. 2 is based on the surge velocity steady-state error and the position following steady-state error, respectively, that is, the input spaces are divided into Z, M and B by the values of these errors which are obtained by using the SMC control laws in (5), and maintain at least 50 percent of the completeness in the membership functions. Therefore, this division manner allows the control subsystems to get better following precision.

Third, design the fuzzy adaptive output $\tilde{\lambda}_3$. The approaching angle θ between the sliding surface and state vector $\overrightarrow{OA}$ is introduced into the design of the boundary layer thickness of the last control law in (7), see Fig. 3. This angle can better describe the convergence process of the state point A. Thus, the boundary layer thickness can be adjusted by this angle according to the convergence process. This control strategy has achieved good control effect for a simple second-order system which can be found in [14]. In this paper, we extend this strategy to the yaw angle control subsystem by using the angle as a fuzzy input variable, so as to get good following precision and less chattering. The membership function of input angle θ was shown in Fig. 4. The expert knowledge for the yaw angle control subsystem can be described as the following if-then rules:

- Rule 1: If θ is S then $\tilde{\lambda}_3 = 29.8$.
- Rule 2: If θ is M then $\tilde{\lambda}_3 = 15$.
- Rule 3: If θ is B then $\tilde{\lambda}_3 = 0.1$.

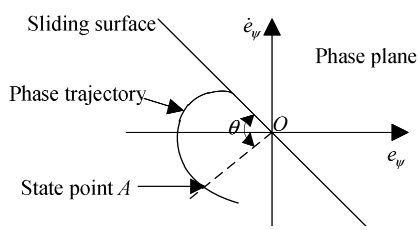

Fig. 3. The approaching angle θ.

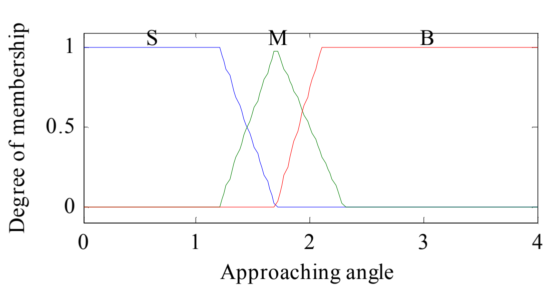

Fig. 4. Membership functions for input θ.

So far we have designed the fuzzy adaptive control scheme for boundary layer thicknesses in the three subsystems. This scheme of boundary layer thicknesses can strike a balance between the chattering and following precision, rather than blindly pursue less chattering. Then control laws of the AUV based on the FASMC method can be obtained by replacing λ_i in (7) with $\tilde{\lambda}_i$, where $i = 1, 2, 3$.

IV. Numerical Simulation

Select the initial states of the AUV as: $x = 5\text{m}$, $y = -3\text{m}$, $\psi = \pi/4\text{rad}$, $u = 0\text{m/s}$, $v = 0\text{m/s}$, $r = 0\text{m/s}$. The desired surge velocity $u_d = 1\text{knot}$. Select the parameters of the control laws in (7) as: $k_1 = 1$, $k_2 = 20$, $k_3 = 1$, $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 0.1$, $a_1 = 0.12$, $b_1 = 5$, $a_2 = 0.005$, $b_2 = 0.005$, $a_3 = 0.02$, $b_3 = 0.02$. Hydrodynamic coefficients were selected in [3]. The sine curve $y = 15\sin(0.15x)$ was selected as a desired path. All simulations were based on MATLAB.

Solution process of path following can be summarized as: calculating the surge speed error s_1, position error x_e and approaching angle θ by the initial state values, then the fuzzy adaptive outputs $\tilde{\lambda}_i$ $(i = 1, 2, 3)$ can be obtained by solving fuzzy controllers; calculating the control force F_X, torque T and virtual control input $\dot{s}$, and then solving (2) and (4) so that the new states of the AUV can be obtained.

The simulations were carried out based on the SMC and FASMC methods respectively. It could be seen from Fig. 5 that a smoother process of convergence had been obtained by FASMC method. This meant that the saturation of the input torque would decrease. Moreover, smaller steady-state error could be obtained due to the suitable switching gain and boundary layer thickness. In addition, the following precision of FASMC method was slightly inferior to SMC method in some position of the AUV, for example, in the vicinity of $x = 34$ and $x = 75$, but smoother input torque had been obtained. Fig. 6 illustrated the control effects of the yaw angle ψ, a better following precision had been obtained when using FASMC method. Meanwhile, the above analysis could be verified in Fig. 8 and Fig. 9.

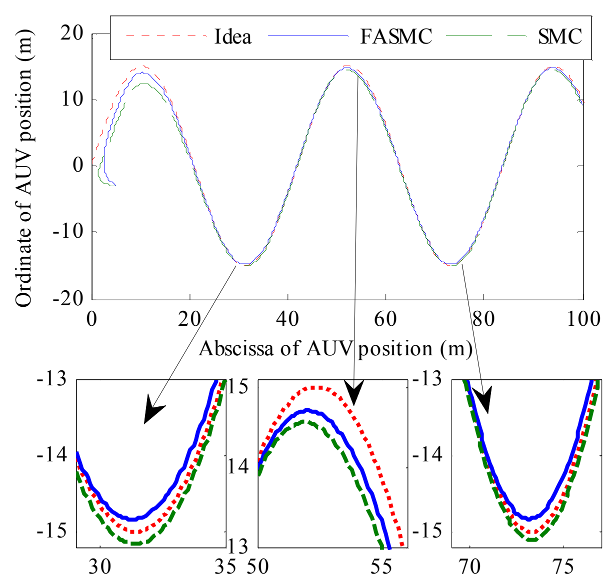

Fig. 5. Path following of AUV.

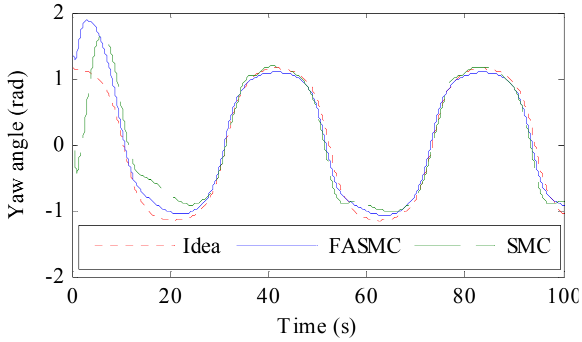

Fig. 6. Yaw angle control of AUV.

Velocity control of the AUV shown in Fig. 7. The following error of surge velocity was smaller when using FASMC method. Moreover, the sway velocity v and yaw angular velocity r also became smoother. The position errors x_e, y_e and yaw angle error were depicted in Fig. 8. The control force and torque were depicted in Fig. 9, the saturation level and chattering of control inputs were reduced significantly by FASMC method, which meant more in line with the actual situation of the path following in engineering.

In this paper, we used the novel reaching law to adjust the switching gains adaptively, while the boundary layer thicknesses could be obtained adaptively by the fuzzy outputs. The purpose of this was to achieve a balance between the switching gain and boundary layer thickness, thus achieving a balance between following precision and chattering. Therefore, the simulation results illustrated the compromise between following precision and chattering.

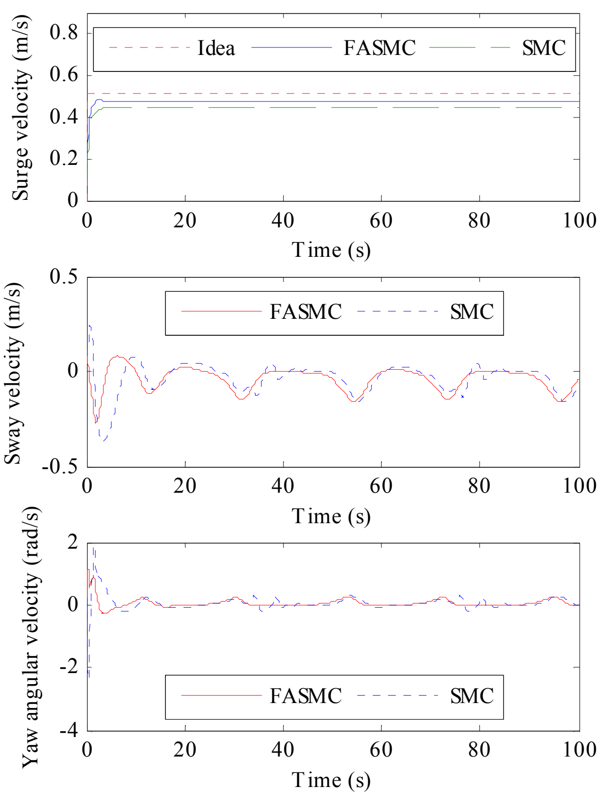

Fig. 7. Velocity control of AUV.

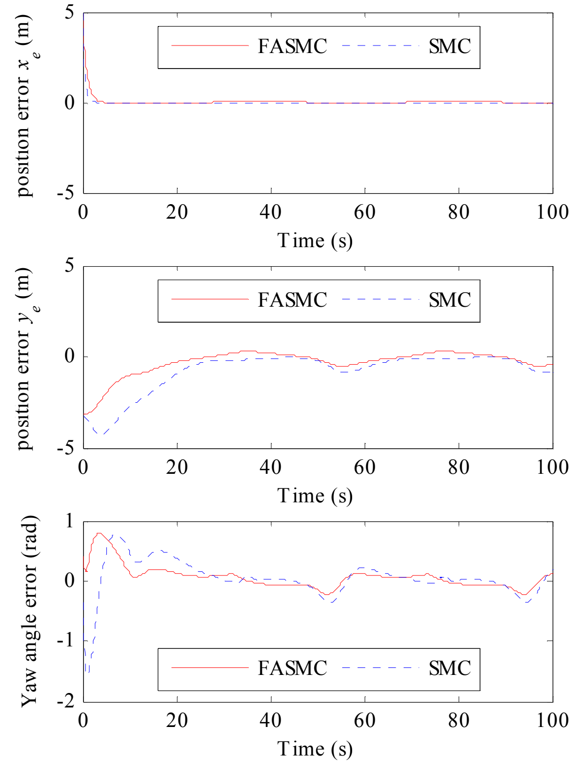

Fig. 8. Following errors.

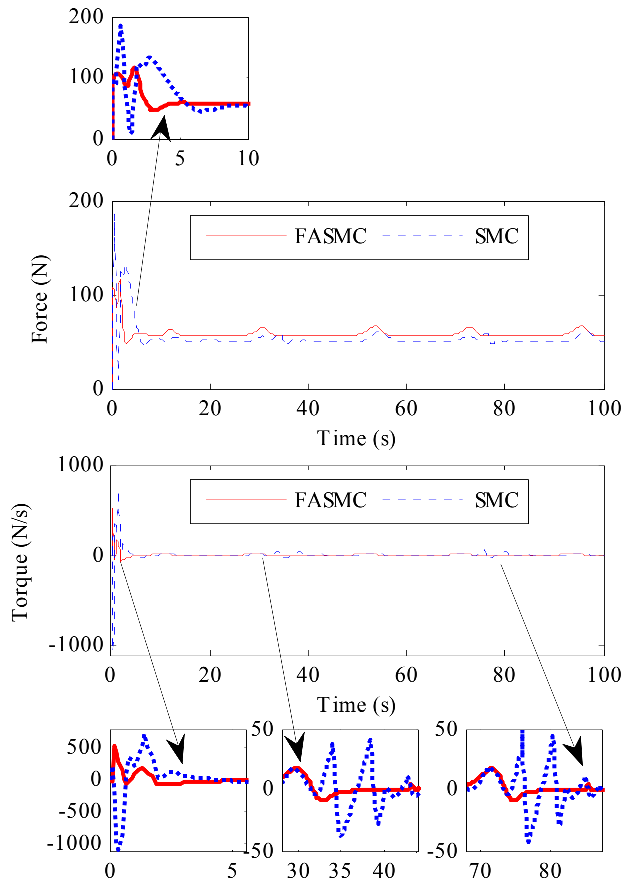

Fig. 9. Control inputs.

V. Conclusion

A control scheme based on FASMC method for path following system of an under-actuated AUV was proposed in this paper. In this scheme, a better balance between the following precision and chattering was achieved by the novel reaching law and fuzzy adaptive outputs, rather than blindly pursue less chattering. The adaptive algorithm was simple but effective, which was easy to implement. Simulation results showed the effectiveness of this control scheme. In the future work, some mathematical derivation and stability analysis will be added, thereby making this scheme more complete.

Acknowledgment

This work is supported jointly by National Natural Science Foundation (NNSF) of China under grant number 51309067/E091002 and the Fundamental Research Funds for the Central Universities under grant number HEUCFX41402.

References

[1] E. Sarda and M. Dhanak, "Unmanned recovery of an AUV from a surface platform manuscript, Oceans '13 Mts/Ieee San Diego," OCEANS 2013 MTS/IEEE San Diego Conf.: An Ocean in Common, San Diego, CA, 2013.

[2] F. Wang, L. Wan, Y. Li, Y. Su, and Y. Xu, "A survey on development of motion control for underactuated AUV," Ship Building of China, vol. 51, pp. 227–241, 2010.

[3] L. Ma and W. Cui, "Path following control study of an autonomous underwater vehicle controlled by non-singular terminal sliding mode," Ship Building of China, vol. 47, pp. 76–82, 2006.

[4] Y. Tian, A. Zhang, and W. Li, "3D path-following of underactuated autonomous underwater vehicles," Proceedings of the 30th Chinese Control Conference, Yantai, China, 2011.

[5] H. J. Wang, Z. Y. chen, H. M. Jia, J. Li, and X. H. Chen, "Three-dimensional path-following control of underactuated autonomous underwater vehicle with command filtered backstepping," Acta Automatica Sinica, vol. 41, pp. 631–645, 2015.

[6] J. K. Liu and F. C. Sun, "Research and development on theory and algorithms of sliding mode control," Control Theory and Applications, vol. 24, pp. 407–418, 2007.

[7] H. Zhang, J. Fan, F. Meng, and J. Huang, "A new double power reaching law for sliding mode control," Control and Decision, vol. 28, pp. 289–293, 2013.

[8] A. Wang, X. Jia, and S. Dong, "A new exponential reaching law of sliding mode control to improve performance of permanent magnet synchronous motor," IEEE Transactions on Magnetics, vol. 49, pp. 2409–2412, 2013.

[9] J. Jiang, Q. Chen, J. Guo, and W. Fan, "Sliding mode stable tracking control for mobile satellite communication system based on a new reaching law," Control and Decision, vol. 26, pp. 1904–1908, 2011.

[10] P. Lesniewski and A. Bartoszewicz, "Hyperbolic tangent based switching reaching law for discrete time sliding mode control of dynamical systems," International Workshop on Recent Advances in Sliding Modes (RASM), Istanbul, Turkey, 2015.

[11] G.V. Lakhekar and R.G. Roy, "Heading control of an underwater vehicle using dynamic fuzzy sliding mode controller," International Conference on Circuit, Power and Computing Technologies (ICCPCT), Nagercoil, India, 2014.

[12] G.V. Lakhekar and V. D. Saundarmal, "Novel adaptive fuzzy sliding mode controller for depth control of an underwater vehicles," IEEE International Conference on Fuzzy Systems (FUZZ), Hyderabad, 2013.

[13] Y. Liu, C. Guo, Q. Ren, and Z. Guo, "Soft variable structure control based on sigmoid functions for autonomous underwater vehicles," Electric Machines and Control, vol. 16, pp. 90–95, 2012.

[14] L. Yang, Y. Zhang, and X. Chen, "Sliding mode control with fuzzy boundary layer for a class of uncertain nonlinear systems," Journal of System Simulation, vol. 21, pp. 7262–7265, 2009.

[15] E. Borhaug, A. Pavlov, and K. Y. Pettersen, "Cross-track formation control of underactuated surface vessels," 45th IEEE Conference on Decision and Control, vol. 1, pp. 5955–5961, San Diego, CA, 2006.

[16] L. Lapierre and B. Jouvencel, "Nonlinear path-following control of an AUV," Ocean Engineering, vol. 34, pp. 1734–1744, 2007.

[17] E. Zhang, S. Shi, W. Gao, and Z. Weng, "Recent researches and developments on fuzzy control system," Control Theory and Applications, vol. 18, pp. 7–11, 2001.