

# Fuzzy Sliding Mode with Region Tracking Control for Autonomous Underwater Vehicle

Mohd Bazli Mohd Mokhar, Zool Hilmi Ismail\*

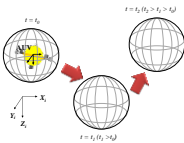
Center for Artificial Intelligence and Robotics, Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia  
Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

\*Corresponding author: zool@fke.utm.my

## Article history

Received :15 June 2014  
Received in revised form :  
15 September 2014  
Accepted :15 October 2014

## Graphical abstract



## Abstract

This paper presents fuzzy sliding mode control with region tracking control for a single autonomous underwater vehicle. The vehicle is needed to track a certain moving region whilst under the influence of wave current. The fuzzy logic is used to tune the gain and to reduce the effect of chattering effect, the signum function is replaced by saturation function. Simulation result is presented to demonstrate the performance of the proposed tracking control of the AUV.

**Keywords:** Underwater vehicle; sliding mode control; fuzzy logic; region tracking

© 2015 Penerbit UTM Press. All rights reserved.

## 1.0 INTRODUCTION

Underwater vehicles play an important part in military, oil and gas sector nowadays. However, the environment underwater is also not very known to men, so the underwater vehicle or robot that get sent there have to be fully autonomous in order to be able to do the mission without fail. Therefore, many research in the recent years focusing on how to improve the performance of underwater vehicle especially in regulate and tracking control system.

A lot of controllers have been proposed for the purpose of improving the control system of AUV such as PID, sliding mode control, adaptive, fuzzy logic, neural network and combination of these controllers. Proportional-Derivative (PD) control plus gravity compensation [1] is the simplest set-point technique for controlling an AUV. However, the weakness of PD control plus gravity compensation is that it is difficult to obtain the exact model of gravitational and buoyancy forces as the dynamic of AUV depend on the condition of the subsea. In addition, the wave current could easily sway away the AUV from its destination. The conventional set point method as this method required more energy so that the vehicle can stay on its point whilst being drag out with wave current. Another method called region tracking method is proposed by Li [2] to overcome this weakness. In this method, the target is a region instead of a point. By redefine the target as a region, the AUV can stay as long as needed without having to activate its controller as long as the wave current does not drag itself out of the region. This method also is applied to a swarm robot as proposed by Hou [3]. Zool proposed using boundary region instead of region in [4] because there are AUV missions that need boundary as objective such as monitoring the exterior pipeline underwater and etc.

Sliding mode control is one of controller usually used for AUV control system as it robust against uncertainty and

disturbance. However, the main weakness of sliding mode is the chattering effect. So, most of research using sliding mode control focus on eliminated the chattering effect. One of the usual methods to reduce the chattering effect is by substitute the signum function with saturation function. In [5], Santhakumar and Asokan proposed combine and using best the PID and sliding mode control. In the initial phase, SMC will be operating however when the system is in reaching phase, PID controller will be used to bring the system to steady state. Bessa [6] in the other hand, proposed an adoption of properly design boundary layer to overcome the chattering effect. Soylu [7], proposed using adaptive term instead the sign term to eliminated the chattering effect and Sun, also using the same approaches as Soylu added with backstepping technique for tracking control of an AUV in [8].

Fuzzy logic has been extensively used in the recent years compared when it was first introduced by Zadeh around forty years ago[9]. The application of fuzzy logic is range from consumer product to control application. For control purposes, fuzzy logic has been designed as a tuning gain algorithm for control method such as PID and sliding mode control. The use of fuzzy logic to tune the gains in PID controller is reported in [10, 11] and sliding mode gain in [12]. In [13], fuzzy logic is used to model the equation switching term in sliding mode controller instead using signum function.

In this paper, we presented fuzzy sliding mode control with region tracking control for a single AUV. Simulation results on AUV with 6 degrees of freedom are presented to demonstrate the effectiveness of the proposed controller. The rest of the paper is organized as follow: Section 2 describes the kinematic and dynamic properties of an AUV. In Section 3, the fuzzy sliding mode control with region function formulation is briefly explained. In Section 4, numerical simulation results are provided to demonstrate the performance of the proposed controllers compared with conventional sliding mode control. Finally, the paper is closed with

some concluding remarks in Section 5. Figure 1 shows illustration of region tracking control for a single AUV.

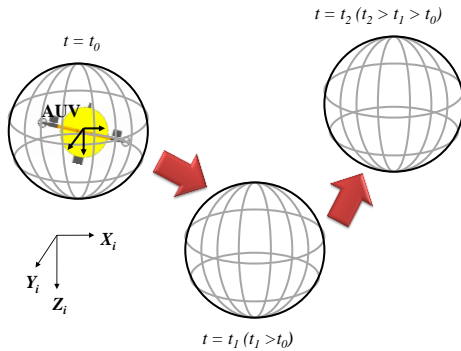


Figure 1 Region tracking control for a single AUV

## 2.0 KINEMATIC AND DYNAMIC MODEL OF AN AUV

### 2.1 Kinematic Model

The relationship between inertial and body-fixed vehicle velocity can be described using the Jacobian matrix  $J(\eta_2)$  in the following form [6].

$$\begin{bmatrix} \dot{\eta}_1 \\ \dot{\eta}_2 \end{bmatrix} = \begin{bmatrix} J_1(\eta_2) & 0_{3 \times 3} \\ 0_{3 \times 3} & J_2(\eta_2) \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \Leftrightarrow \dot{\eta} = J(\eta_2)v \quad (1)$$

where  $\eta_1 = [x \ y \ z]^T \in \mathbb{R}^3$  and  $\eta_2 = [\phi \ \theta \ \psi]^T \in \mathbb{R}^3$  denote the position and the orientation of the vehicle, respectively, expressed in the inertial-fixed frame.  $J_1$  and  $J_2$  are the transformation matrices expressed in terms of the Euler angles. The linear and angular velocity vectors,  $[u \ v \ w]^T \in \mathbb{R}^3$  and  $v_2 = [p \ q \ r]^T \in \mathbb{R}^3$ , respectively, are described in terms of the body-fixed frame.

### 2.2 Dynamic Model

The investigation of dynamic equation of motion for an underwater vehicle has been previously reported in [14]. The underwater vehicle dynamic equation can be expressed in closed form as

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

where  $v \in \mathbb{R}^6$  is the velocity state vector with respect to the body-fixed frame,  $M$  is the inertia matrix including the added mass term,  $C(v)$  represents the matrix of the Coriolis and centripetal forces including the added mass term,  $D(v)$  denotes the hydrodynamic damping and lift force,  $g(\eta)$  is the restoring force and  $\tau$  is the vector of generalized forces acting on the vehicle. The dynamic equation in (2) preserves the following properties [14]:

Property 1: The inertia matrix  $M$  is symmetric and positive definite such that  $M = M^T > 0$ .

Property 2:  $C(v)$  is the skew-symmetric matrix such that  $C(v) = -C^T(v)$ .

Property 3: The hydrodynamic damping matrix  $D(v)$  is positive definite, i.e.:  $D(v) = D^T(v) > 0$ .

## 3.0 FUZZY SLIDING MODE CONTROL WITH REGION TRACKING CONTROL

In region-based control law, the desired moving target is specified by a region instead of a point. First, a dynamic region of specific shape is defined and this can be viewed as a global objective of the proposed control law. Let us define a desired region as the following inequality equation functions as follow:

$$\mathcal{F}(\delta\eta) \leq 0 \quad (3)$$

where  $\delta\eta = (\eta - \eta_d) \in \mathbb{R}^6$  are the continuous first partial derivatives of the dynamic region;  $\eta_d(t)$  is the time-varying reference point inside the region shape. It is assumed that  $\eta_d(t)$  is bounded functions of time.

The potential energy function for the desired regions is as follows:

$$P_p(\delta\eta) = \frac{k_p}{2} [\max(0, \mathcal{F}(\delta\eta))]^2 \quad (4)$$

or

$$P_p(\delta\eta) \triangleq \begin{cases} 0, & \mathcal{F}(\delta\eta) \leq 0 \\ \frac{k_p}{2} \mathcal{F}^2(\delta\eta), & \mathcal{F}(\delta\eta) > 0 \end{cases} \quad (5)$$

Partially differentiate the equation (5) with respect to  $\partial\eta$  gives

$$\left( \frac{\partial P_p(\delta\eta)}{\partial \eta} \right)^T = k_p \max(0, \mathcal{F}(\delta\eta)) \left( \frac{\partial \mathcal{F}(\delta\eta)}{\partial \eta} \right)^T \quad (6)$$

Now, let (6) be represented as a region error  $\Delta\xi$  in the following form

$$\Delta\xi = \max(0, \mathcal{F}(\delta\eta)) \left( \frac{\partial \mathcal{F}(\delta\eta)}{\partial \eta} \right)^T \quad (7)$$

When the AUV are outside the desired region, the control force  $\Delta\xi$  described by (10) is activated to attract the AUV toward the desired region. When the AUV is inside the desired region, then the control force is zero or  $\Delta\xi = 0$ .

The sliding mode can be define as follows:

$$\tau = \tau_{eq} + \tau_{sw} \quad (8)$$

where  $\tau$  corresponds to a generalized force acting at the centre of mass of the AUV.  $\tau_{eq}$  and  $\tau_{sw}$  symbolize the equivalent control law and the switching control law. It is well-known that the switching term  $\tau_{sw}$  is defined as follows

$$\tau_{sw} = -K \text{sgn}(s) \quad (9)$$

$K$  is the positive definite diagonal gain matrix that is defined based on the upper bounds on the system parameter uncertainties, and  $\text{sgn}(\cdot)$  is the nonlinear signum function. Sliding mode control design involves two step, first is to get the sliding manifold,  $s$  and second is to get equivalent control,. The sliding manifold is defines as

$$s = v - v_r \quad (10)$$

$v_r$  in equation 10 can be define as

$$v_r = J^{-1}(\dot{\eta}_d - S^{-1}\dot{S}\delta\eta) - J^{-1}\Delta\xi \tag{11}$$

Differentiate the sliding manifold to get

$$\dot{s} = \dot{v} - \dot{v}_r \tag{12}$$

Multiply both side of (12) by inertia matrix  $\hat{M}$  and substituting (2) into resulting equation yields

$$\hat{M}\dot{s} = \tau_{eq} - (\hat{M}\dot{v}_r + \hat{C}(v)v + \hat{D}(v)v + \hat{g}(\eta)) \tag{13}$$

Let  $s = 0$ , yield an equivalent control

$$\tau_{eq} = \hat{M}\dot{v}_r + \hat{C}(v)v + \hat{D}(v)v + \hat{g}(\eta) \tag{14}$$

Membership functions for  $s$  and  $\dot{s}$  are presented in Figure 2 and 3 respectively. In order to reduce the chattering effect in proposed controller, the signum function in the switching term,  $\tau_{sw}$  with saturation function and gain, is tune using fuzzy yield

$$\tau_{sw} = -K_{fuzzy}sat(s/\delta) \tag{15}$$

where  $\delta$  is the boundary layer and the membership function of output  $K_{fuzzy}$  is shown in Figure 4.

When the value of gain,  $k$  is decreased its value near the sliding surface can damp the chattering amplitude, while if the value of gain is choose to be as large as allowed can reduce the reaching time [15]. So, to maintain the facts mention before, a fuzzy controller is designed for the purpose of tuning the suitable gain accordingly. The figures below show the membership function for the inputs and output.

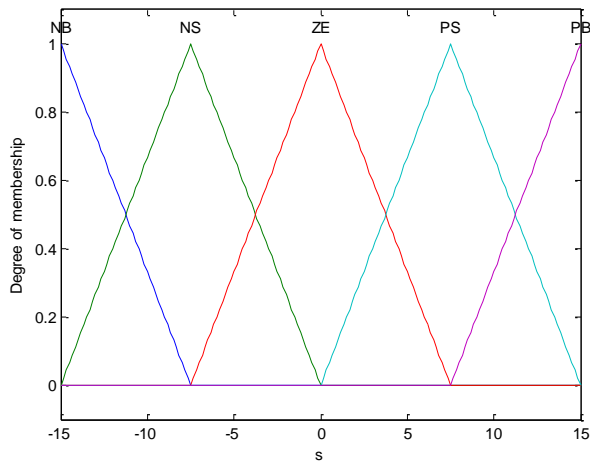


Figure 2 Membership function of input  $s$

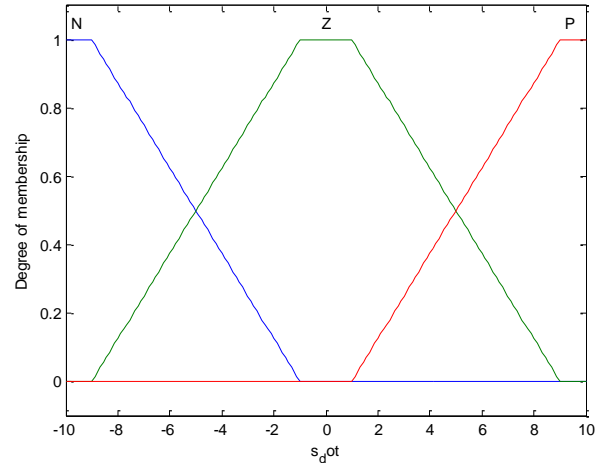


Figure 3 Membership function of input  $\dot{s}$

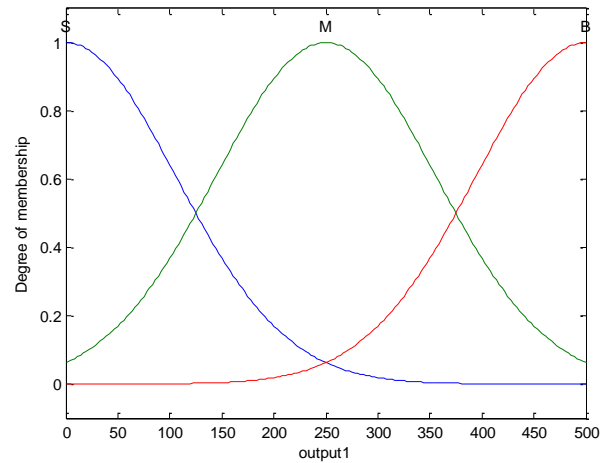


Figure 4 Membership function of output,  $K_{fuzzy}$

Table 1 Fuzzy rule base

$s$ / $s_{dot}$	NB	NS	ZE	PS	PB
N	B	B	M	S	B
Z	B	M	S	M	B
P	B	S	M	B	B

Table 1 shows fuzzy rule base for tuning  $K$  where N indicate Negative, ZE indicate Zero, P Indicate Positive, B indicate Big, M indicate Medium and B Indicate Big. Therefore, a proposed sliding-mode adaptive control law with region formulation can be written as follows:

$$\tau = \tau_{eq} - K_{fuzzy}sat(s/\delta) - J^T(\eta)\Delta\xi \tag{16}$$

4.0 SIMULATION RESULTS

In this section, a simulation studies is carried out to test the efficiency of the proposed fuzzy sliding mode controller under the influence of wave current. The vehicle is required to track a certain region in this simulation. An ODIN with full 6-DOF [16] is chosen as autonomous underwater vehicle model for numerical simulation. The numerical values for the matrices of the vehicle dynamic equations are available in [16]. In simulation, the following inequality functions are defined for a spherical region

$$\mathcal{F}(\delta\eta_1) = (x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 \leq \kappa_r^2 \quad (17)$$

where (30) represents the inequality equation of a region with  $\kappa_r$  is defined as a scalar tolerance. An underwater vehicle is required to track a straight-line trajectory with green (cross-section lines) trajectory is the horizontal basis position initialized at  $[1.5 \ 0 \ -1.2]^T$ m. The solid blue lines represent the position of an AUV at various time instances.

A constant and unidirectional current velocity designated with the arrows in figures below is set to  $v_d = [0 \ 0.04 \ 0]^T$  m/s. For both simulation, the region radius is set to,  $\kappa_r = 0.2$ . The orientation is kept constant with the allowable errors are set to 0.1 rad, and the initial values are  $\eta_2(0) = [0 \ 0 \ 0]^T$  rad.

From Figure 5 and Figure 6, it has been shown that the proposed controller effectiveness under the influence of constant wave current.

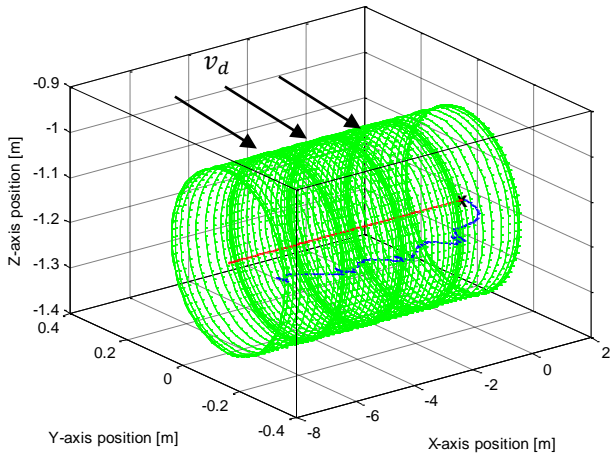
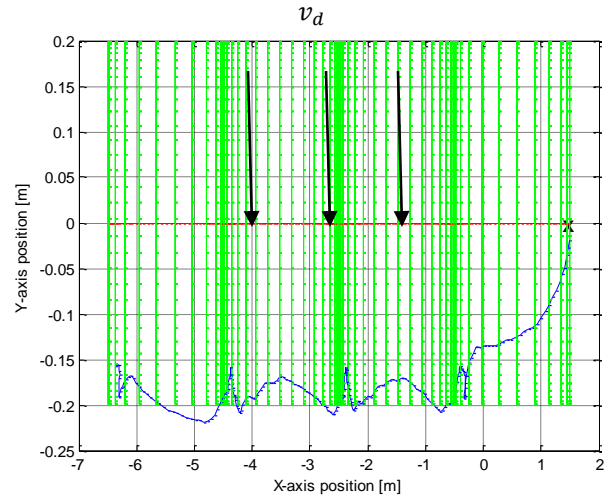
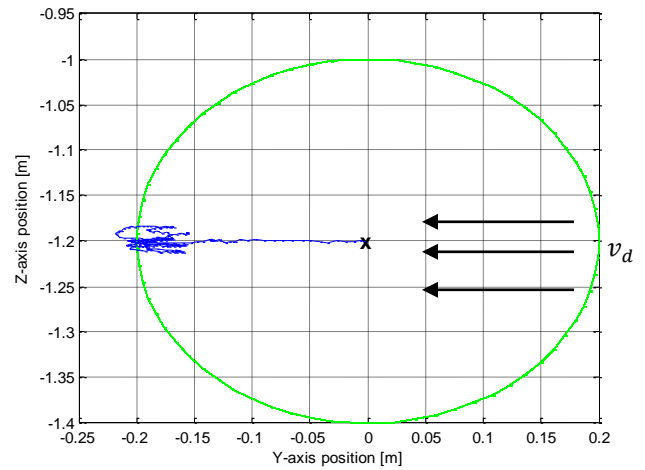


Figure 5 A 3-dimension view of simulation study; x marks the initial position of an AUV



(a)



(b)

Figure 6 Planar trajectories of an AUV for simulation study that are illustrated in (a) XY-plane and (b) YZ-plane

5.0 CONCLUSION

In this paper, a new region based tracking control method has been proposed for an autonomous underwater vehicle. This control technique enables an AUV to perform a specific underwater tracking task. It has been shown that AUV is able to track a desired moving region. Moreover, an AUV is capable to navigate into a moving region under constant external disturbance. Simulation results have been presented to demonstrate the performance of the proposed tracking controller.

Acknowledgement

This work was supported in part by the Ministry of Higher Education, Malaysia and Universiti Teknologi Malaysia under Grant no Q.J130000.2509.05H54.

## References

- [1] Takegaki, M. and Arimoto, S. 1981. A New Feedback Method for Dynamic Control of Manipulators. *ASME Journal of Dynamic Systems, Measurement and Control*. 103(2): 119–125.
- [2] Li, X., Hou, S. P. and Cheah, C. C. 2010. Adaptive Region Tracking Control for Autonomous Underwater Vehicle. In *Proc of the 11th Int. Conf. on Control, Automation, Robotics and Vision*. Singapore.
- [3] S. P. Hou, C. C. Cheah and J. J. E. Slotine. 2009. Dynamic Region Following Formation Control for a Swarm of Robots. In *Proc. of the 2009 IEEE Int. Conf. on Robotics and Automation*.
- [4] Ismail, Z. H. and Dunnigan, M. W. 2011. A Region Boundary-Based Control Scheme for an Autonomous Underwater Vehicle. *Ocean Engineering*. 38(17): 2270–2280.
- [5] Santhakumar, M. and Asokan, T. 2010. Investigation on The hybrid Tracking Control of an Underactuated Autonomous Underwater Robot *Advanced Robotics*. 24(11): 1529–1556.
- [6] Bessa, W. M., Dutra, M. S. and Kreuzer, E. 2010. An Adaptive Fuzzy Sliding Mode Controller for Remotely Operated Underwater Vehicles. *Robotics and Autonomous Systems*. 58(1): 16–26.
- [7] Soyly, S. Buckham, B. J. and Podhorodeski, R. P. 2008. A Chattering-Free Effect Sliding-Mode Controller for Underwater Vehicles with Fault-Tolerant Infinity-Norm Thrust Allocation. *Ocean Engineering*. 35: 1647–1659.
- [8] Bing Sun, Daqi Zhu and Weichong Li. 2012. An Integrated Backstepping and Sliding Mode Tracking Control Algorithm for Unmanned Underwater Vehicles. *UKACC International Conference on Control*.
- [9] John, R., Coupland, S., 2007. Type-2 Fuzzy Logic: A Historical View. *Computational Intelligence Magazine, IEEE*. 2(1): 57–62.
- [10] Bo Hu, Hai Tian, Jiani Qian, Guochao Xie, Linlang Mo and Shuo Zhang. A Fuzzy-PID Method to Improve the Depth Control of AUV. *Proceedings of 2013 IEEE International Conference on Mechatronics and Automation*. August 4–7, Takamatsu, Japan
- [11] Wei Zhang, Hongtao Wand, Xinqian Bian, Zheping Yan and Guoqing Xia. 2012. The Application of Self-Tuning Fuzzy PID Control Method to Recovering AUV. *IEEE Oceans*.
- [12] Lakhekar, G. V. and Saundarmal, V. D. 2013. Novel Adaptive Fuzzy Sliding Mode Controller for Depth Control of an Underwater Vehicles. *IEEE International Conference on Fuzzy Systems (FUZZ)*, 7–10 July 2013
- [13] Shuxiang Guo, Juan Du, Xichuan Lin and Chunfeng Yue. 2012. Adaptive Fuzzy Sliding Mode Control for Spherical Underwater Robots. *Mechatronics and Automation (ICMA)*. 1681–1685.
- [14] Fossen, T. I. 1994. *Guidance and Control of Ocean Vehicles*. 1st. edition ed. New York: John Wiley and Sons.
- [15] Neha Kapoor and Jyoti Ohri. 2013. Fuzzy Sliding Mode Controller (FSMC) with Global Stabilization and Saturation Function for Tracking Control of a Robotic Manipulator. *Journal of Control and Systems Engineering*. 1(2): 50–56.
- [16] Choi, S., Yuh, J. and Keevil, N. 1993. Design of Omni-Directional Underwater Robotic Vehicle. *OCEANS '93, Engineering in Harmony with Ocean, Proc.*