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COMPARISON OF TWO TYPE OF FUZZY SLIDING MODE WITH REGION TRACKING CONTROL FOR AUTONOMOUS UNDERWATER VEHICLE

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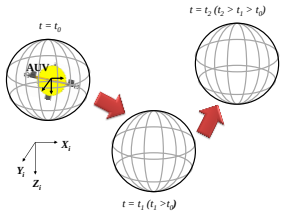
Graphical abstract



Abstract

This paper presented two type of 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 first fuzzy logic proposed is used to tune the gain and to reduce the chattering effect; the signum function is replaced by saturation function. In second fuzzy type sliding mode controller, the switching term or reaching law is modeled using fuzzy logic. Simulation result is presented to demonstrate the performance of the two proposed tracking control of the AUV and the performance is compared.

Keywords: Underwater vehicle, sliding mode control, fuzzy logic, region tracking

Abstrak

Kertas kerja ini membentangkan dua jenis kawalan *fuzzy sliding mode* dengan kawalan pengesanan rantau untuk satu kenderaan bawah air bebas. Kenderaan ini perlu mengikut rantau tertentu yang bergerak sambal berada di bawah pengaruh ombak gelombang. Fuzzy logic pertama digunakan untuk menala gandaan dan mengurangkan kesan chattering, fungsi signum digantikan dengan fungsi ketepuan. Dalam kawalan fuzzy kedua, terma persuisan atau peraturan sampai dimodelkan menggunakan logik fuzzy. Hasil simulasi dibentangkan untuk menunjukkan pencapaian kedua-dua kawalan gerakan AUV dan pencapaian tersebut dibandingkan

Kata kunci: Kenderaan bawah air, kawalan sliding mode, lojik fuzzy, pengesanan rantau

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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 model 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.

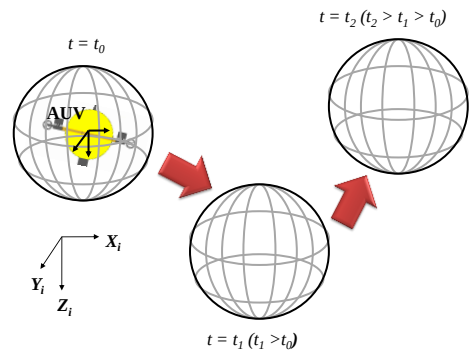


Figure 1 Region tracking control for a single AUV

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]

$$\begin{bmatrix}\dot{\eta}_1\\ \dot{\eta}_2\end{bmatrix} = \begin{bmatrix}J_1(\eta_2) & 0_{3\times3}\\ 0_{3\times3} & J_2(\eta_2)\end{bmatrix}\begin{bmatrix}v_1\\ v_2\end{bmatrix} \Leftrightarrow \dot{\eta} = J(\eta_2)v \qquad (1)$$

where $\eta_1 = [x \quad y \quad z]^T \in \mathbb{R}^3$ and $\eta_2 = [\phi \quad \theta \quad \psi]^T \in \mathbb{R}^3$ 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,$[u \quad v \quad w]^T \in \mathbb{R}^3$ and $v_2 = [p \quad q \quad r]^T \in \mathbb{R}^3$, 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

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

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 τ 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:

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

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:

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

or

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

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

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

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

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

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:

$$\tau = \tau_{eq} + \tau_{sw} \tag{8}$$

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

$$\tau_{sw} = -K\mathrm{sgn}(s) \tag{9}$$

K is the positive definite diagonal gain matrix that is defined based on the upper bounds on the system parameter uncertainties, and $\mathrm{sgn}(\cdot)$ 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

$$s = v - v_r \tag{10}$$

v_r in equation 10 can be define as

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

Differentiate the sliding manifold to get

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

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

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

Let $s = 0$, yield an equivalent control

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

3.1 Fuzzy Gain Scheduling Sliding Mode Control

In order to reduce the chattering effect in proposed controller, the signum function in the switching term, τ_{sw} with saturation function and gain, is tune using fuzzy yield

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

where δ is the boundary layer.

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. Figures 2, 3 and 4 show the membership function for the inputs and output

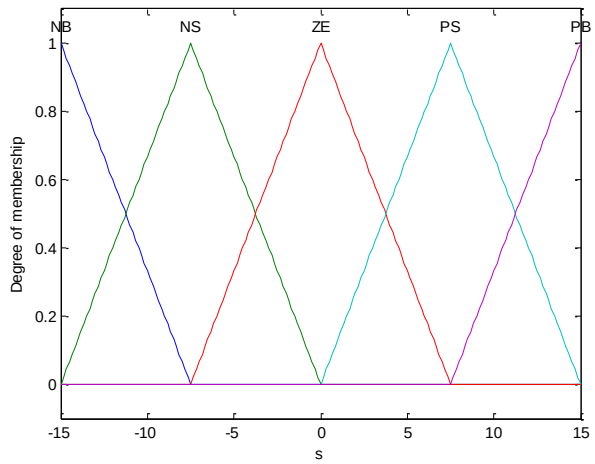


Figure 2 Membership function of input *s*

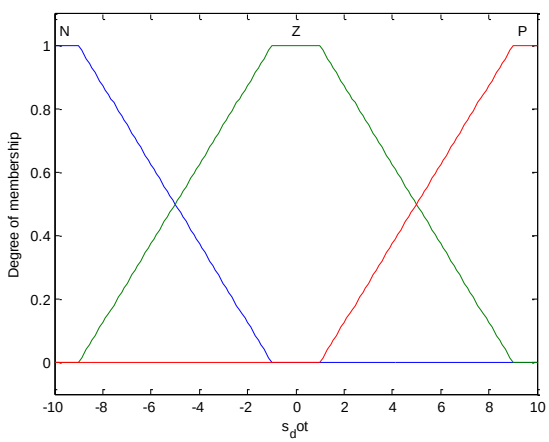


Figure 3 Membership function of input $\dot{s}$

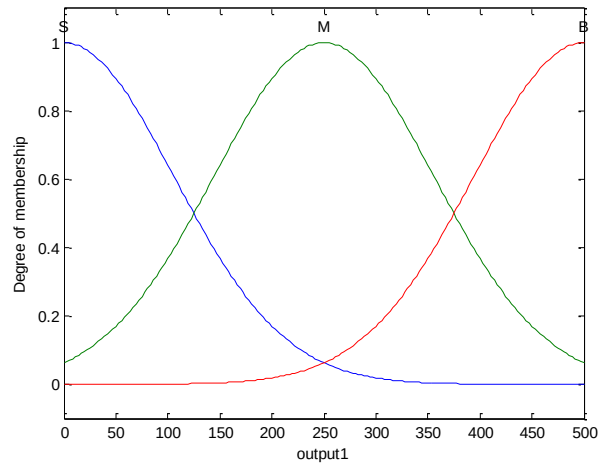


Figure 4 Membership function of output, K_{fuzzy}

Table 1 below 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.

Table 1 Fuzzy rule base for K_{fuzzy}

S_dot \ s	NB	NS	ZE	PS	PB
N	B	B	M	S	B
Z	B	M	S	M	B
P	B	S	M	B	B

Therefore, the proposed fuzzy gain scheduling sliding-mode control law with region formulation can be written as follows:

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

3.2 Adaptive Fuzzy Sliding Mode Control

In the second proposed fuzzy sliding mode control with region formulation, the reaching law or the switching term is selected as below

$$\tau_{sw} = k_f u_{fs} \tag{17}$$

where k_f is the normalization factor of the output variable, u_{fs} is the output of the FSMC which is determine from membership function, s and $\dot{s}$ as follows

$$u_{fs} = FSMC(s, \dot{s}) \tag{18}$$

The input for membership functions, s and $\dot{s}$ and output, u_{fuzzy} from adaptive fuzzy sliding mode is shown in Figures 5, 6 and 7.

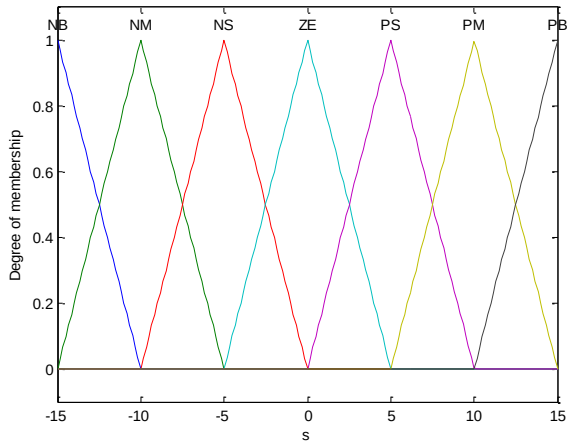


Figure 5 Membership function of input s

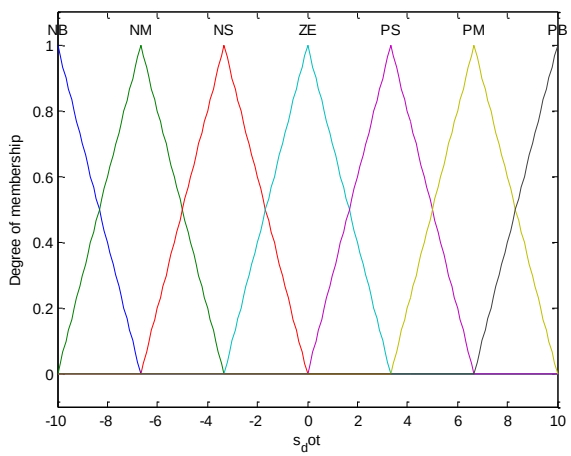


Figure 6 Membership function of input $\dot{s}$

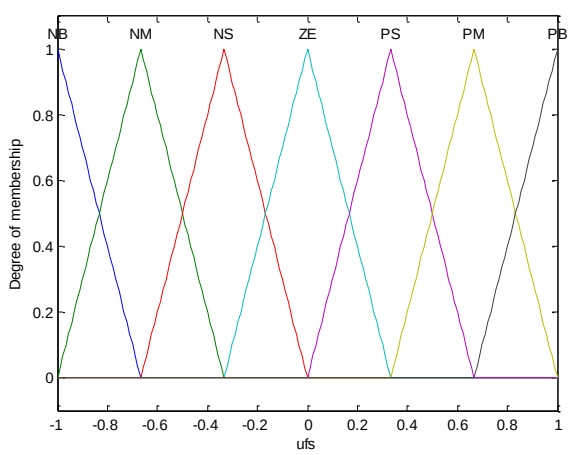


Figure 7 Membership function of output, u_{fs}

Table 2 below shows fuzzy rule base for tuning u_{fs} where N indicate Negative, ZE indicate Zero, P indicate Positive, B indicate Big, M indicate Medium and B indicate Big.

Table 2 Fuzzy rule base for u_{fs}

u_{fs}		s						
		PB	PM	PS	ZE	NS	NM	NB
$\dot{s}$	PB	PB	PB	PB	PB	PM	PS	ZE
	PM	PB	PB	PB	PM	PS	ZE	NS
	PS	PB	PB	PM	PS	ZE	NS	NM
	ZE	PB	PM	PS	ZE	NS	NM	NB
	NS	PM	PS	ZE	NS	NM	NB	NB
	NM	PS	ZE	NS	NM	NB	NB	NB
	NB	ZE	NS	NM	NB	NB	NB	NB

Therefore, the proposed adaptive fuzzy sliding-mode control law with region formulation can be written as follows:

$$\tau = \tau_{eq} - k_f u_{fs} - J^T(\eta)\Delta\xi \qquad 19$$

4.0 SIMULATION RESULTS

In this section, a simulation studies is carried out to test the efficiency of the both 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

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

where (30) represents the inequality equation of a region with κ_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 fuzzy gain scheduling SMC and for adaptive fuzzy SMC, a constant current, $v_d = [0\ \ 0.007\ 0]^T\ m/s$ is set. 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.

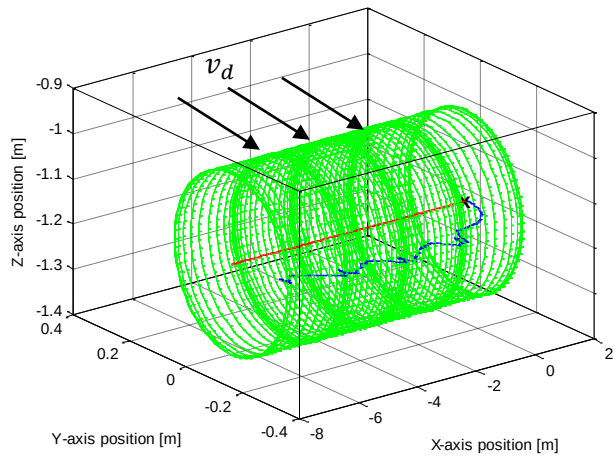
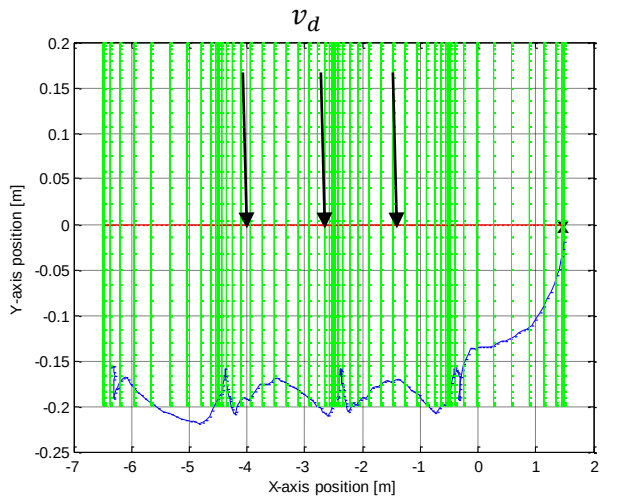
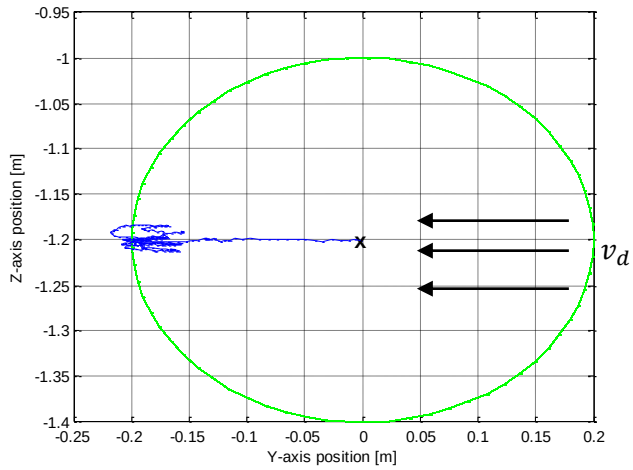


Figure 8 A 3-dimension view of simulation study; **x** marks the initial position of an AUV



(a)



(b)

Figure 9 Planar trajectories of an AUV using fuzzy gain scheduling SMC controller for simulation study illustrated in (a) XY-plane and (b) YZ-plane

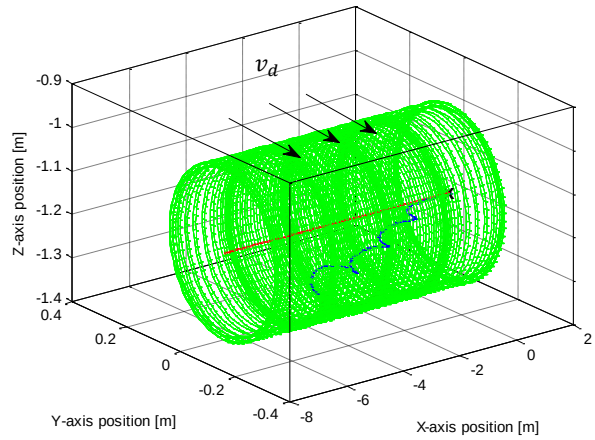
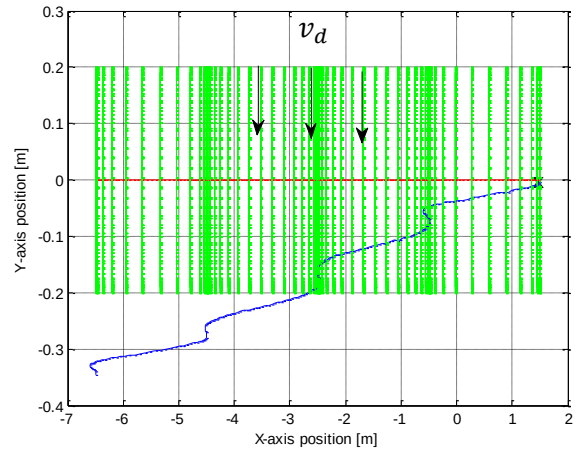
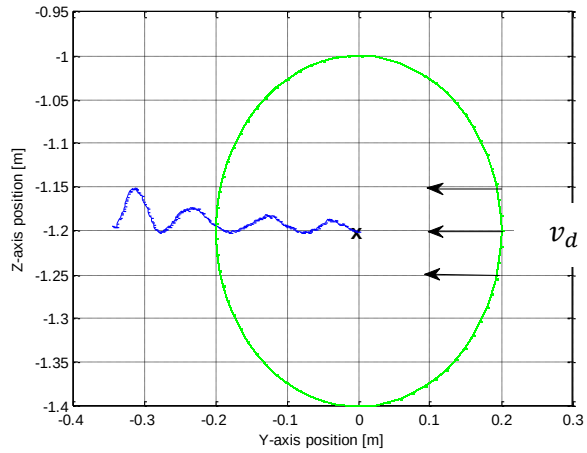


Figure 10 A 3-dimension view of simulation study; **x** marks the initial position of an AUV



(a)



(b)

Figure 11 Planar trajectories of an AUV using adaptive fuzzy SMC controller for simulation study illustrated in (a) XY-plane and (b) YZ-plane

From Figure 8 and Figure 9, it has been shown that the proposed fuzzy gain scheduling SMC controller is effective under the influence of constant wave current. However, as seen in Figures 10 and 11, for adaptive fuzzy SMC, the underwater vehicle cannot perform as well as fuzzy gain scheduling SMC. Even with smaller current, $v_d = [0\ \ 0.007\ 0]^T\ m/s$ compared to fuzzy gain scheduling, the AUV cannot deal with external disturbance and the vehicle itself is carried out of the region. Furthermore, the computational time for adaptive fuzzy SMC takes longer than the fuzzy gain scheduling SMC.

5.0 CONCLUSION

In this paper, robust tracking control laws with region formulation for an autonomous underwater vehicle have been presented. Both of proposed controllers are supposed to enable an AUV to perform a specific underwater tracking task. However, only the gain scheduling SMC shows a robust performance compared to adaptive fuzzy SMC. Simulation results have been presented to demonstrate the performance of both proposed tracking controllers.

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