ADAPTIVE FUZZY HIERARCHICAL SLIDING MODE CONTROLLER FOR AUV LACKING COMPLIANT STRUCTURE

ĐIỀU KHIỂN TRƯỢT TẦNG THÍCH NGHI MỜ CHO AUV THIẾU CƠ CẤU CHẤP HÀNH

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ABSTRACT

The recent international marine vehicles that have been published are mostly three-level floating ship models: Motion in the 0x,0y direction and the ship's navigation angle. Current, researches on Autonomous Underwater Vehicles are very modest, with the addition of a motion component in the 0z direction and a navigation angle with the intention of making the device capable of diving. The goal of this study is to develop a control algorithm for AUV diving equipment lacking a MIMO (Multiple Input Multiple Output) actuator using the Adaptive Fuzzy Hierarchical Sliding Mode Controller (AFHSMC) technique. Because this system is nonlinear, functionally uncertain, and heavily influenced by noise from the environment, scientists always face difficulties in developing control and quality improvement strategies. That's also why the authors of this paper chose to conduct their own research.

Keywords: *Autonomous Underwater Vehicles, MIMO, Adaptive Fuzzy Hierarchical Sliding Mode Controller (AFHSMC).*

TÓM TẮT

Phương tiện hàng hải gần đây được công bố quốc tế đa phần là mô hình tàu nổi gồm 3 bậc: Chuyển động theo phương 0x,0y và góc điều hướng của tàu. Những nghiên cứu về thiết bị ngầm tự hành hiện nay rất khiêm tốn, khi có thêm thành phần chuyển động theo phương 0z và góc điều hướng với mục đích có thể giúp thiết bị có thể lặn được. Trong nghiên cứu này nhóm tác giả tập trung xây dựng thuật toán điều khiển trên cơ sở kỹ thuật điều khiển Adaptive Fuzzy Hierarchical Sliding Mode Controller (AFHSMC) áp dụng cho thiết bị lặn AUV là hệ thiếu cơ cấu chấp hành MIMO (Multiple Input Multiple Output). Đây hệ thống phi tuyến bất định kiểu hàm số và chịu ảnh hưởng của nhiễu môi trường rất lớn nên các phương pháp điều khiển và nâng cao chất lượng luôn là những thách thức với các nhà khoa học. Đó cũng là động lực cho việc lựa chọn nghiên cứu của nhóm tác giả trong bài báo này.

Từ khóa: *Phương tiện ngầm tự hành, MIMO, điều khiển trượt tầng thích nghi mờ (AFHSMC).*

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1. INTRODUCTION

Underwater vehicles are now being developed in a wide range of kinds, shapes, and applications, including military, rescue, ocean bottom study, exploration, and exploitation of marine resources [1, 2]. Underwater vehicles (UV) come in a wide variety of forms, but they can generally be divided into two categories based on their capacity for human control: manned and unmanned vehicles. Autonomous UV and remote-controlled UV are the two categories of unmanned UV [3].

Research on Controller of Autonomous Underwater Vehicles (UV) evolves alongside control theory and is analyzed in a variety of ways. However, there are three major types of control algorithms, which are summarized below: Linear Model Controller (PID, LQR) [4, 5], Nonlinear Model Controller (Sliding Mode Controller (SMC) [6], Backsepping Controller, Hierarchical Sliding Mode Controller (HSMC), Adaptive Controller), and intelligent controller are all examples of Nonlinear Model Controller (Neural Network Controller, Fuzzy Controller...) [7, 8].

For nonlinear systems, the Hierarchical Sliding Mode Controller (HSMC) is a promising option [9]. However, it may result in high frequency oscillations that impact the actuators, waste energy, and oscillations on the rudder of the AUV that induce instability while switching the skid owing to vibrations. However, the research team suggests using Adaptive Fuzzy Controller approach for sliding surface parameters to approximation parameters that are difficult to quantify in order to increase the optimal control quality in order to address the aforementioned issue [10].

To achieve better results in controlling complex systems such as AUVs, the Adaptive Fuzzy Hierarchical Sliding Mode Controller combines the benefits of both sliding mode control and fuzzy control methods. It also allows to adjust the control parameters based on the change of parameters in the system, hence it is called "adaptive". The Adaptive Fuzzy Hierarchical Sliding Mode Controller can effectively meet the control requirements of complex autonomous systems such as AUVs by employing such intelligent control methods [11, 12].

More importantly, the stability of the control system is guaranteed by the use of Lyapunov theory. The viability of the proposed strategy has been demonstrated in numerous digital simulation situations where the results have been acquired. The study team has organized the remaining portions of the publication as follows: Part 2 introduces the AUV model. The suggested controller is described in Section 3, along with an analysis and discussion of the controller's stability. Before coming to any conclusions in Section 5, Section 4 summarizes the evaluation of the suggested algorithm.

2. AUTONOMOUS UNDERWATER VEHICLE MODEL

2.1. Motion Modelling

In order to efficiently control motion of an autonomous underwater vehicle (AUV), we consider a model with six degrees of freedom (DoFs) including surge, sway, heave, roll, pitch and yaw [5], which present for both the position and orientation of the marine device. Parameters of the model are summarized in Table 1.

Table 1. The parameters in an autonomous underwater vehicle model.

Parameters	Force and Moments	Velocities	Positions and Angles
Motion in x direction (surge)	X	u	x
Motion in y direction (sway)	Y	v	y
Motion in z direction (heave)	Z	w	z
Rotation about x axis (roll)	K	p	ϕ
Rotation about y axis (pitch)	M	q	θ
Rotation about z axis (yaw)	N	r	ψ

To simplify the small types of AUV we can remove 2 unnecessary degrees of freedom: angle θ(pitch) and angle Φ(roll). Hence the equations of movement of the AUV 4 degrees of freedom are expressed through the quantities (propulsion, a steering wing, two auxiliary rudders combined with a pump system for floating diving). Coordinate position (x, y), direction of AUV (ψ - yaw) and position on axis z (diving depth) [10].

The nonlinear dynamic equations for the four degrees of freedom AUV is as follows:

$$\begin{cases} \dot{\eta} = J(\eta)v \\ M\dot{v} + C(v)v + D(v)v = \tau \end{cases} \quad (1)$$

2.2. Dynamics of Under-Actuated AUV Systems

In this case the AUV is an underactuated system, consisting of 2 input signals and 4 output signals. Therefore, we separate the mathematical model into two parts, including the underactuated and full actuated system. Position vector η will be separated into 2 parts $\eta = [\eta_1 \quad \eta_2]^T$ and $\eta_1 = [x \quad y]^T$ for a state of full actuated and $\eta_2 = [z \quad \psi]^T$ for a state of underactuated. Similarly, velocity vector v is divided into two parts with $v = [v_1 \quad v_2]^T$. The diving gear dynamic equation was rewritten as follows:

$$\begin{cases} \dot{\eta}_1 = J_{11}v_1 + J_{12}v_2 \\ \dot{\eta}_2 = J_{21}v_1 + J_{22}v_2 \\ M_{11}\dot{v}_1 + (C_{11} + D_{11})v_1 + M_{12}\dot{v}_2 + (C_{12} + D_{12})v_2 = \tau \\ M_{21}\dot{v}_1 + (C_{21} + D_{21})v_1 + M_{22}\dot{v}_2 + (C_{22} + D_{22})v_2 = 0 \end{cases} \quad (2)$$

We have the dynamic equations of AUV as follows:

$$\begin{cases} \dot{\eta}_1 = J_{11}v_1 \\ \dot{v}_1 = \bar{M}^{-1}(-\bar{C}_1 v_1 - \bar{C}_2 v_2) + \bar{M}^{-1}\tau \\ \dot{\eta}_2 = J_{22}v_2 \\ \dot{v}_2 = -M^{-1}{}_{22}\begin{bmatrix} M_{21}\bar{M}^{-1}(-\bar{C}_1 v_1 - \bar{C}_2 v_2) \\ +(C_{21} + D_{21})v_1 + (C_{22} + D_{22})v_2 \end{bmatrix} \\ -M^{-1}{}_{22}M_{21}\bar{M}^{-1}\tau \end{cases} \quad (3)$$

3. ADAPTIVE FUZZY HIERARCHICAL SLIDING MODE CONTROLLER

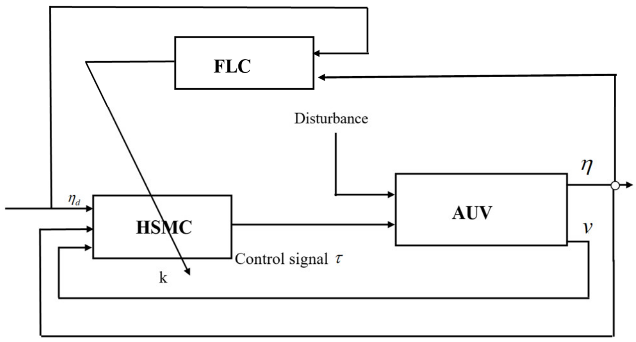


Figure 1. Control system model AFHSMC

Input signal $\eta_d = [x, y, z, \psi]^T$ are the position vector of the device in axes Ox, Oy, Oz and the directional angle of the AUV rotates around the axis Oz; Send to backstepping controller and fuzzy logic controller to output control signal τ.

FLC: Fuzzy logic controller; Disturbance: Due to currents and ocean currents.

To solve the above problem, the paper proposes to use Backstepping controller, because it is one of the suitable methods to control systems lacking actuators.

$$\begin{cases} \dot{\eta}_1 = J_{11}v_1 \\ \dot{v}_1 = f_1(\mathbf{X}) + g_1(\mathbf{X})\tau_1 \\ \dot{\eta}_2 = J_{22}v_2 \\ \dot{v}_2 = f_2(\mathbf{X}) + g_2(\mathbf{X})\tau_2 \end{cases} \quad (4)$$

$$\begin{aligned} &X = [\eta_1 \quad v_1 \quad \eta_2 \quad v_2]^T \\ &f_1(X) = \bar{M}^{-1}(-\bar{C}_1 v_1 - \bar{C}_2 v_2) \\ &g_1(X) = \bar{M}^{-1} \\ &f_2(X) = -M^{-1}{}_{22}\left[M_{21}\bar{M}^{-1}(-\bar{C}_1 v_1 - \bar{C}_2 v_2) + (C_{21} + D_{21})v_1 + (C_{22} + D_{22})v_2\right] \\ &g_2(X) = -M^{-1}{}_{22}M_{21}\bar{M}^{-1} \end{aligned} \quad (5)$$

The error vector between the output signal and the set signal is defined as follows:

$$e(t) = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \end{bmatrix} = \begin{bmatrix} \eta_1 - \eta_{1d} \\ v_1 \\ \eta_2 - \eta_{2d} \\ v_2 \end{bmatrix} \quad (6)$$

Definition of the sliding surface

$$\begin{cases} s_1 = k_1 e_1 + e_2 (k_1 > 0) \\ s_2 = k_2 e_3 + e_4 (k_1 > 0) \\ S = \lambda s_1 + \beta s_2 (\lambda, \beta > 0) \end{cases} \quad (7)$$

According to the Hierarchical Sliding Mode Controller (HSMC) control method for the system without actuator, the controller signal is divided into two components:

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

With:

+ τ_{eq} is the signal that the Hierarchical Sliding Mode Controller structure uses to control the subsystem.

+ τ_{sw} is the signal used to control the switching of the system sliding layer.

In order to ensure the stability of the system of automatic scuba diving equipment SAUV, consider the Lyapunov function for the closed system as follows:

$$V = \frac{1}{2} S^2 \quad (9)$$

The derivative V with respect to time:

$$\frac{\partial V}{\partial t} = S.\dot{S} \quad (10)$$

From (5), (6), (7) and (10) we have the following equation:

$$\frac{\partial V}{\partial t} = S.\dot{S} = S.\left[\lambda \dot{s}_1 + \beta \dot{s}_2\right]$$

$$= S.\begin{bmatrix} \lambda(k_1 J_{11} v_1 + f_1 + g_1 \tau_2 - k_1 \dot{x}_{1d}) \\ +\beta(k_2 J_{22} v_2 + f_2 + g_2 \tau_2 - k_2 \dot{x}_{3d}) \end{bmatrix}$$

Since x_{1d}, x_{3d} are constant values, so $\dot{x}_{1d} = \dot{x}_{3d} = 0$. It turns out:

$$\frac{\partial V}{\partial t} = S.\dot{S} = S.\left[\lambda(k_1 J_{11} v_1 + f_1 + g_1 \tau_2) + \beta(k_2 J_{22} v_2 + f_2 + g_2 \tau_2)\right]$$

$$= S.\begin{bmatrix} \lambda(k_1 J_{11} v_1 + f_1 + g_1(\tau_{eq1} + \tau_{sw1} + \tau_{eq2} + \tau_{sw2})) \\ +\beta(k_2 J_{22} v_2 + f_2 + g_2(\tau_{eq1} + \tau_{sw1} + \tau_{eq2} + \tau_{sw2})) \end{bmatrix}$$

$$= S.\begin{bmatrix} \lambda(k_1 J_{11} v_1 + f_1 + g_1 \tau_{eq1}) + \beta(k_2 J_{22} v_2 + f_2 + g_2 \tau_{eq2}) \\ +\tau_{sw1}(\lambda g_1 + \beta g_2) + \tau_{sw2}(\lambda g_1 + \beta g_2) \\ +\lambda g_1 \tau_{eq2} + \beta g_2 \tau_{eq1} + k.S + \delta \operatorname{sgn}(S) \\ -(k.S + \delta \operatorname{sgn}(S)) \end{bmatrix} \quad (11)$$

To ensure the stability of the system through the Lyapunov stability principle so that $\frac{\partial V}{\partial t}$ is negative, we choose the control signals as follows:

$$\begin{cases} \tau_{eq1} = \dfrac{-(k_1 J_{11} v_1 + f_1)}{g_1} \\ \tau_{eq1} = \dfrac{-(k_2 J_{22} v_2 + f_2)}{g_2} \\ \tau_{sw2} = -\tau_{sw1} - \dfrac{\lambda g_1 \tau_{eq2} + \beta g_2 \tau_{eq1}}{\lambda g_1 + \beta g_2} - \dfrac{k.S + \delta \operatorname{sgn}(S)}{\lambda g_1 + \beta g_2} \end{cases} \quad (12)$$

Substituting (12) into equation (11) we have: $\frac{\partial V}{\partial t} = S.\dot{S} = -(k.S + \delta \operatorname{sgn}(S)) < 0$ satisfying the Lyapunov stability principle.

The control signal is determined according to the following formula:

$$\tau = \tau_{eq1} + \tau_{sw1} + \tau_{eq2} + \tau_{sw2}$$
$$= -\frac{\lambda f_1 + \beta f_2 + \lambda k_1 J_{11} v_1 + \beta k_2 J_{22} v_2 + k.S + \delta \operatorname{sgn}(S)}{\lambda g_1 + \beta g_2} \quad (13)$$

When choosing α, β to be fixed, there is a lot of shaking in the system. In order to reduce the shaking phenomenon, the paper proposes a method to adjust α and β based on fuzzy system. The fuzzy system is designed to change 1` based on the adjustment of two parameters α and β. In fact, just changing one of the two parameters can also change the sliding surface, so α has a linear constraint with β:

$$\beta = k\alpha \quad (14)$$

As a result, depending on the value of k, the second sliding layer changes. It is suggested to employ a fuzzy logic system to determine the k-factor of this second floor sliding surface in order to select a suitable sliding layer. The fuzzy logic system has e1 and e1 as inputs, and k is the output. The goal of the method is to eliminate chattering by setting k so that the state trajectories shift to the origin on the sliding layer. The sliding surfaces vary as a result of the change in k, which also affects the value of β (14). Figure 2, where the values of k are sequentially k_{11}, k_{12},…., k_{1n}, illustrates the concept.

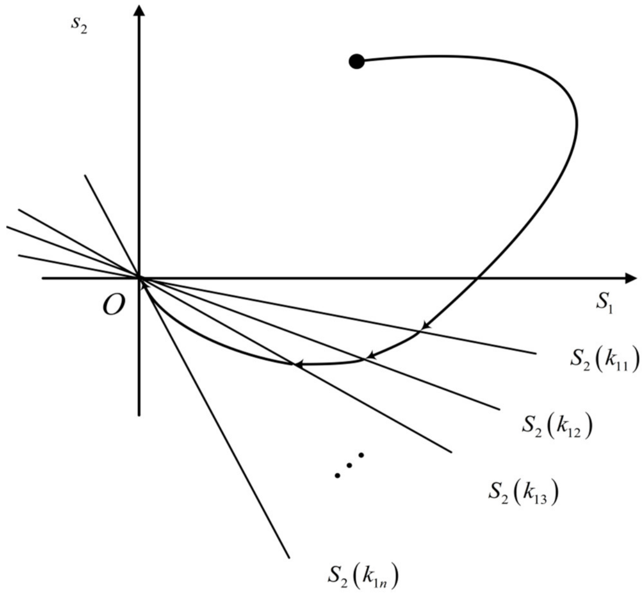


Figure 2. Changing K of the sliding layer

Because the design of the fuzzy system is mainly based on the operator's experience, corresponding to a selected value α > 0, we obtain a fuzzy system that conforms to the setting law. The input of the fuzzy logic system is e_1, and the output is α. We apply the above method to AUV.

Each input language variable consists of 3 triangular fuzzy sets with the names of the fuzzy sets digitized as [−1 0 1], respectively. The membership function of the input language variables is shown in Figure. 3. The constant output variables have digitized names of [−2 −1 0 1 2], corresponding to the values [c_1 c_2 c_3 c_4 c_5] = [3 2.5 2 2.5 3]. The inference rule system is as in Table 2.

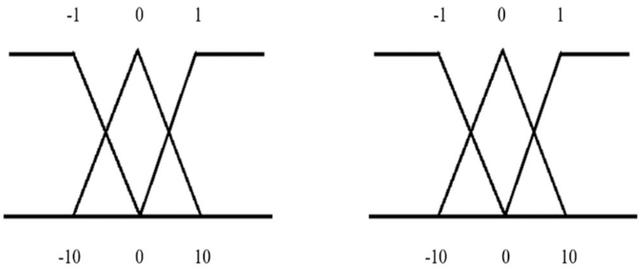


Figure 3. Fuzzy set of input language variables

Table 2. Inference system for adaptive Backstepping controller

λ_1		e_1		
		-1	0	1
$\dot{e}_1$	1	0	-1	-2
	0	1	0	-1
	-1	2	1	0

4. SIMULATION RESULTS AND DISCUSSIONS

Table 3. The parameters of AUV system

Prameters	Values	Prameters	Values	Prameters	Values
m	18.5kg	$\dot{X}_u$	6.83 x 10^{-6}	$\dot{Z}_w$	0.32 x 10^{-6}
k	100	$X_{u\|u\|}$	-0.58	Z_0	0
δ	5	$\dot{X}_w$	-1.13 x 10^{-6}	$Z_{w\|w\|}$	1.15 x 10^{-6}
k_1	0.05	Y_v	0.08	N_r	-12,32
k_2	5	Y_r	-1.03	$N_{r\|r\|}$	0.5 x 10^{-6}
x_g	0.5	$\dot{Y}_v$	-0.85	$\dot{N}_v$	0.32
y_g	0.5	$\dot{Y}_{v\|v\|}$	-0.62	$\dot{N}_r$	-2.15
X_u	6.53	Z_w	4.57	I_z	1.57
$\dot{Z}_w$	-0.32 x 10^{-6}	$\dot{Z}_u$	0.32		

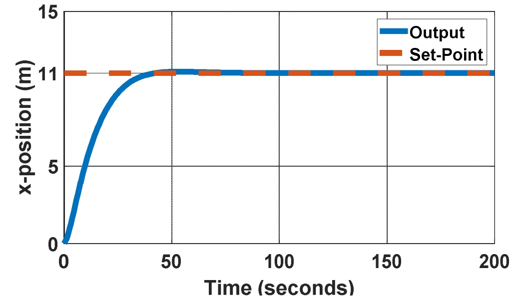
The AFHSMC law parameters are chosen by:

$c_1 = \text{diag}\{0.15 \quad 0.12\}$; $c_2 = \text{diag}\{90 \quad 90\}$;

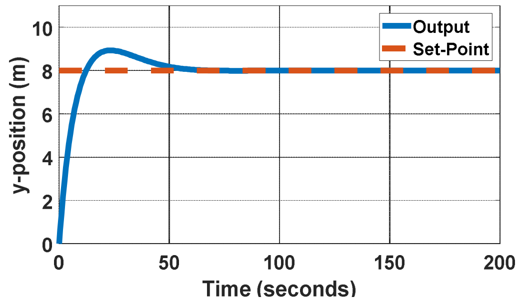
$c_3 = \text{diag}\{0.2 \quad 0.2\}$; $c_4 = \text{diag}\{0.1 \quad 0.1\}$;

The adaptive law parameters are proposed as [c_1 c_2 c_3 c_4 c_5] = [3 2.5 2 2.5 3]

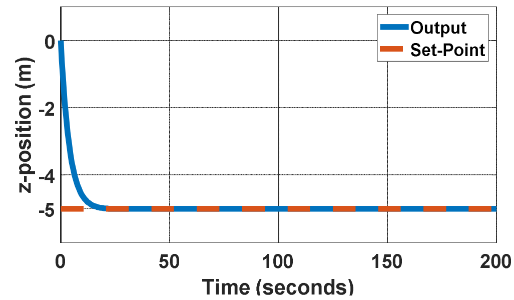
Case 1: The AUV dives to a depth of -5(m) from the surface water and simultaneously moves to the desired position with the values set as follows: $\eta_{1d} = [11 \quad 8]^T$ and $\eta_{2d} = [-5 \quad 0.6]^T$



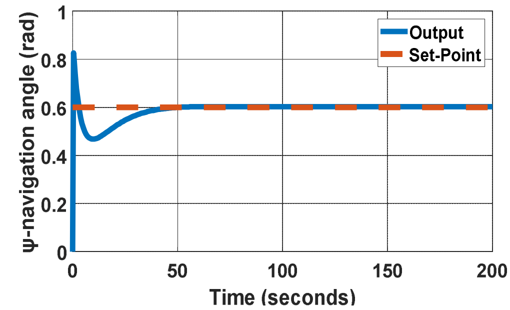
(a) Position in the Ox direction



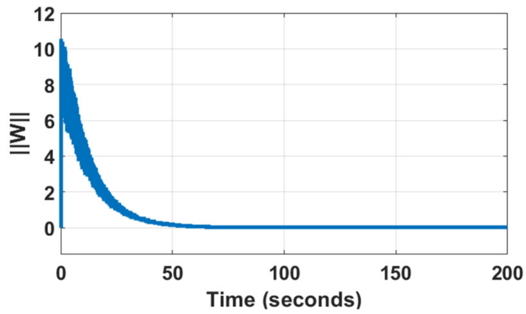
(b) Position in the Oy direction



(c) Position in the Oz direction



(d) Navigation angle of AUV

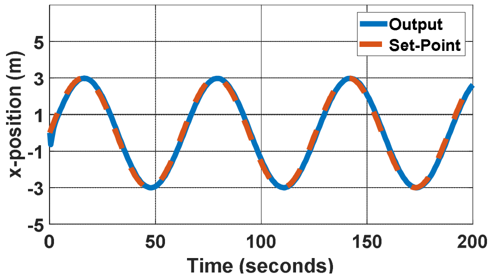


(e) Norm of weight parameter

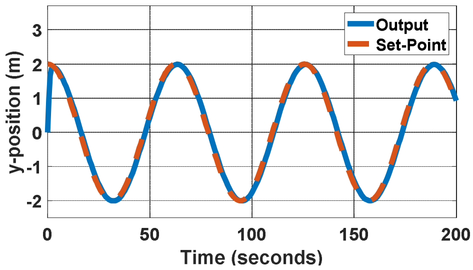
Figure 4. Simulation results in the case 1

According Figure 4, the AFHSMC is applied to AUV with proper control quaily in term of position, velocity and navigation angle. Specifically, the duration for the system to track the position trajectoies in 0x,0y,0z and navigation angle in case 1 that are 36s, 46s, 12s, 39s. However, it still has the overshot of AUV system in Fig 4.b, Fig 4.d which are 11.25%, 21.67% but the error of diving AUV system is almost zero or 5% less than the desired error band. Besides, the norm of both weight parameters converges to zero. After that, in order to verify stability of the control performance in the AUV.

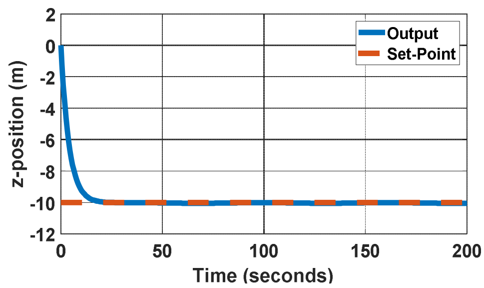
Case 2: The AUV dives to a depth of -10(m) from the surface water and simultaneously moves to the desired position with the values set as follows: $\eta_{1d} = \left[3\sin(0.01t) \quad 2\cos(0.01t)\right]^T$ and $\eta_{2d} = \left[-10 \quad 0\right]^T$



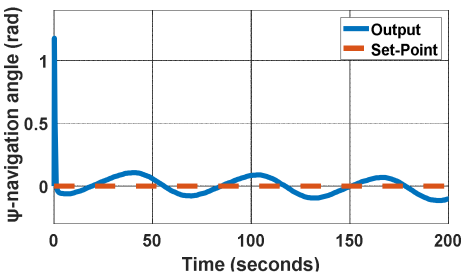
(a) Position in the 0x direction



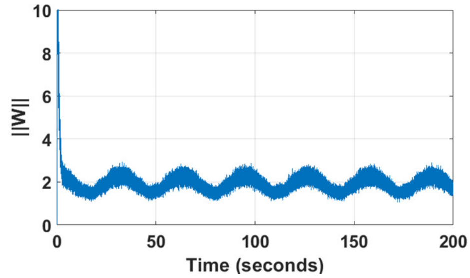
(b) Position in the 0y direction



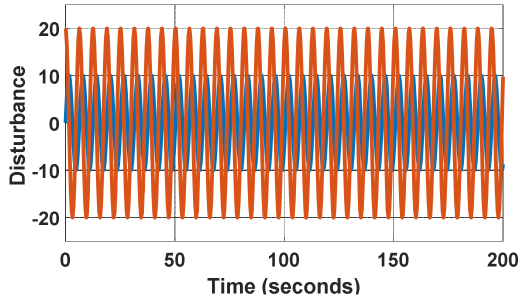
(c) Position in the 0z direction



(d) Navigation angle of AUV



(e) Norm of weight parameter



(f) External disturbance

Figure 5. Simulation results in the case 2

As expected, the proposed controller responded quite well to the external disturbance and kept the system very robust. The obtained results shown in Figure 5 prove the stability of the system regardless of noise. Especially, the control quality in 0x, 0y of tracking the trajectory proposed by the periodic function very well in Fig 5.a and Fig 5.b. Likewise, position quality in 0z and navigation angle are quite acceptable. Hence, the results obtained by the standard Adaptive Fuzzy Hierarchical Sliding Mode Controller (AFHSMC) law can be considered as the ideal.

5. CONCLUSION

According to the article, the Adaptive Fuzzy Hierarchical Sliding Mode Controller (AFHSMC) has advantages in terms of noise stability and shortened transient times. To increase the control quality for AUVs with functional amorphous components, the controller blends contemporary control techniques with intelligent control to create a closed system. The stability of the system is demonstrated by the Lyapunov theorem. Different simulation outcomes that yet guarantee the needed control quality.

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