International Journal of Mechatronics, Electrical and Computer Technology

Vol. 3(9), Oct, 2013, pp 224-249, **ISSN**: 2305-0543
Available online at: http://www.aeuso.org

A New Fuzzy Sliding Mode Controller with PID Sliding Surface for Underwater Manipulators

Hossein Nejatbakhsh Esfahani[1*] and Vahid Azimirad[2]

[1]Msc Student, Mechatronic Engineering, Tabriz University, Tabriz, Iran
[2]Asst. Prof., Mechatronic Engineering, Tabriz University, Tabriz, Iran

*Corresponding Author's E-mail: hnejatbakhsh.esf@gmail.com

Abstract

Design of an accurate and robust controller is challenging topic in underwater manipulator control. This is due to hydrodynamic disturbances in underwater environment. In this paper a sliding mode control (SMC) included a PID sliding surface and fuzzy tunable gain is designed. In this proposed controller robustness property of SMC and fast response of PID are incorporated with fuzzy rules to reduce error tracking. In the control law, for remove of chattering, the exponential function is used. And also system is analyzed in terms of stability by direct lyapunov method. By tuning gains with fuzzy logic, the proposed controller does not require an accurate model of underwater manipulator dynamics. Hence the modeling and simulation studies are done for an underwater manipulator to verify the effectiveness of the proposed method. Both new proposed controller and conventional SMC are simulated. The results of simulation show the high performance of proposed controller in comparison to conventional SMC.

Keywords: Robust control, Sliding Mode Control, Fuzzy Logic, Gain Tuning, Underwater Manipulator

1. Introduction

OCEANIC environment covers a large part of the earth, which included marine structures, oil/gas pipe lines and mines. Therefore role of underwater manipulation has been increased in

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underwater intervention. In addition robotic manipulator can be mounted on a mobile platform like Autonomous Underwater Vehicle (AUV) or Remotely Operated Vehicle (ROV) that in this way Underwater Vehicle-Manipulator Systems (UVMS) made up that will have so many usages in underwater manipulation. Some influences that make difficult to control underwater manipulator include the uncertainties due to hydrodynamics forces and ocean currents disturbances. In recent studies, there isn't a reliable and robust controller for underwater manipulators. E.Liceaga-c *et al.* used a variable structure system (VSS) for design a robust controller in being of uncertainty that was created by added mass [1]. In that paper external factor of drag damping and added corriolis has been ignored in designing of this controller. B.Levesque *et al.* presented a stochastic adaptive controller that was a model based design [2]. This controller could represent efficient robustness in a turbulent flow, but it hasn't proper precision for trajectory tracking goals. The control system based on machine vision was proposed by J.S.smith *et al.* [3].

This system hasn't a robust property in presence of uncertainties for the reason of using PID controller. Furthermore, Catalin F.Baicu *et al.* used a hybrid, robust-adaptive controller for tracking of a single link underwater manipulator [4]. A PD control method was used for robust controller that hasn't proper robustness in presence of disturbances which are under the sea. Also an estimator that is based on a Lyapunove was used at an adaptive controller for estimating of dynamic parameters that has a low precision related to the intelligent estimators. Timothy W.Mclain *et al.* improved an exact model of hydrodynamic forces that were used at a single link manipulator [5]. Minho Lee *et al.* presented scheme of a robust control with multi layer neural network and with learning algorithm of an error back propagation [6]. In this paper a Sliding Mode Controller (SMC) has been used for robust control in presence of disturbances that were created by drag and friction. Sung-uk Lee *et al.* improved an underwater manipulator for inspection and maintain a nuclear reactor [7]. This manipulator has 4 degree of freedom and it has been mounted on a ROV. This system has been used for

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removing loose parts from the bottom of a vessel of a nuclear reactor. Irfan Abd Rahman *et al.* presented modeling of parameters for an underwater manipulator; also, they survey and studied the effect of hydrodynamic forces on torque of a puma560 manipulator by simulation with MATLAB [8]. Guohua Xu *et al.* used a robust and exact SMC controller for tracking of the underwater manipulator. They used saturation function for destroying chattering. In this system, there isn't parameter estimator for the controller and SMC parameters have been adjusted with try and error [9]. Moreover, Liguan wang *et al.* presented a new controlling method that was based on Cerebellar Model Articulation Controller (CMAC) that this is a neural network based on models of human memory and neuromuscular control [10]. This system has ability to an exact tracking but don't have high robustness. Shunmugham R.Pandian *et al.* designed a Fuzzy-Neural controller for an underwater manipulator that was used a PD controller with Fuzzy gain regulator and a dynamic estimator with using of neural network [11].

Nurhan Gursel *et al.* presented modeling and controlling of a two degree of freedom underwater manipulator with a flexible link [12]. They used an integral control method with a Fuzzy controller for tracking. Furthermore, they presented an exact modeling for drag forces on flexible link. In order to avoid manual gain tuning and trial and error, in this paper we used fuzzy logic method for tuning gains. As is well known, fuzzy logic controllers are efficient intelligent controllers for various applications. Several researchers have studied sliding mode fuzzy control (SMFC) for different applications [13], [14]. However, little research has so far been conducted on SMFC's for underwater manipulators. In rest of the paper, the dynamics of the underwater manipulator is modeled in section 2 that it includes uncertain added mass, drag force, buoyancy and frictional forces. The section 3 presents the characteristics of a conventional SMC with PID sliding surface. Section 4 presents the robust fuzzy SMC-PID using fuzzy self-tuning control gain. The computer simulation results are shown in section 5. Finally, the conclusion is presented in section 6.

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Vol. 3(9), Oct, 2013, pp 224-249, **ISSN**: 2305-0543

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2. Underwater Manipulator

Underwater manipulators are used for robotic applications inside water. Fig.1 illustrates the n-D.O.F. underwater planar manipulator mounting on the vehicle. The coupled effect between manipulator and vehicle is neglected and ROV/AUV is assumed stationary during manipulator moves.

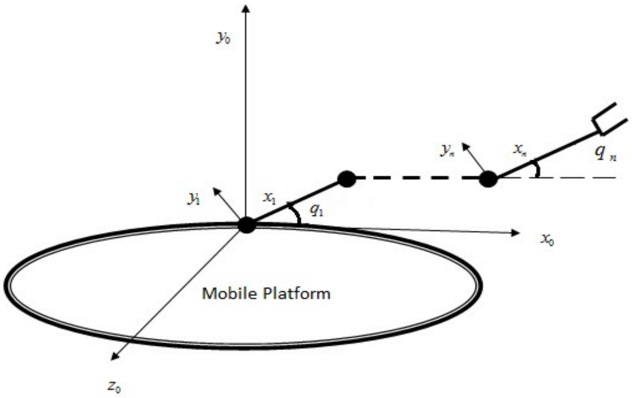

Figure 1: Schematic of UVMS

The added mass force results from the interaction of fluid in the prompt proximity of an underwater link which is accelerating relative to the fluid. The added mass coefficient is dependent on body, geometry and motion. When the underwater manipulator is accelerated, the mass of links is increased by the added mass. The dynamics of an underwater manipulator is highly nonlinear and time-varying. The dynamic equations of motion are developed by using Lagrange formulation as follow:

$$\frac{d}{dt}\left(\frac{dT}{d\dot{q}_i}\right)-\left(\frac{dT}{dq_i}\right)=\tau \qquad (1)$$

Added mass of the underwater manipulator has been included in the dynamic in the form of kinetic energy. Total kinetic energy of the system can be written as:

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$$T = T_{RB} + T_{AM} \tag{2}$$

Where T_{RB} = kinetic energy of manipulator due to rigid body $= \frac{1}{2} v_{cm_i}^T M_{RB} v_{cm_i}$, and T_{AM} = kinetic energy of manipulator due to added mass$= \frac{1}{2} v_{cm_i}^T M_{AM} v_{cm_i}$.

The added mass matrix for each cylindrical link of a manipulator can be represented as [15]:

$$M_{AM_i} = diag(0, a_i, a_i, 0, b_i, b_i) \tag{3}$$

Where

$$a_i = \frac{\pi}{4} \rho l_i r_i^2 ,\ b_i = \frac{1}{3} a_i l_i^2$$

Substituting the total kinetic energy in Eq.1, we obtain dynamic equation of motion which include rigid body and added mass as follows:

$$M(q)\ddot{q} + C(q,\dot{q}) = \tau \tag{4}$$

$$M(q) = \begin{bmatrix} l_2^2 m_{T2} + 2 l_1 l_2 m_{T2} c_2 + l_1^2 (m_{T1} + m_{T2}) & l_2^2 m_{T2} + l_1 l_2 m_{T2} c_2 \\ l_2^2 m_{T2} + l_1 l_2 m_{T2} c_2 & 0 \end{bmatrix} \tag{5}$$

$$C(q,\dot{q}) = \begin{bmatrix} -l_1 l_2 m_{T2} s_2 \dot{q}_1 \dot{q}_2 - l_1 l_2 m_{T2} s_2 (\dot{q}_1 + \dot{q}_2) \dot{q}_2 \\ l_1 l_2 m_{T2} s_2 \dot{q}_1^2 \end{bmatrix} \tag{6}$$

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The added mass of the links (m_A) for cylindrical manipulator are expressed in follow equation as per Fossen [15].

$$m_{Ai} = \pi \rho r_i^2 l_i$$
$$m_{Ti} = m_i + m_{Ai} \tag{7}$$

In this paper, the two-dimensional motion of an underwater manipulator with respect to the x-y plane is considered, as shown in the fig.2. The drag force on a link is relative to the square of the link's velocity [17]. The drag force always has a positive magnitude in the calculation of the underwater manipulator dynamics. With respect to the motion direction of the underwater manipulator, the drag force acts in the opposite direction in a real environment. Therefore, the sign of the drag force direction has to be determined according to the motion of the underwater manipulator. The motion direction of the underwater manipulator can be identified by the sign of the translational velocities. Drag torques are expressed in (8):

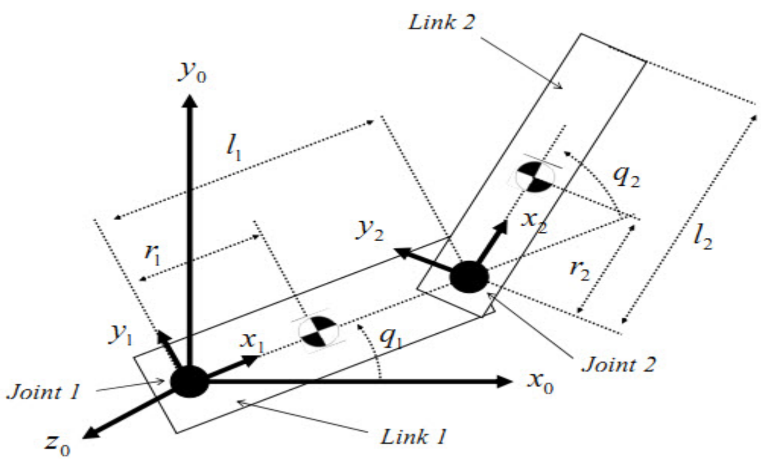

Figure 2: Two-link underwater manipulator

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TABLE 1: PARAMETERS OF UNDERWATER MANIPULATOR

Symbol	Quantity	value
l_1	length of the link 1	0.5 m
l_2	length of the link 2	0.4 m
r_1	radius of the link 1	0.04 m
r_2	radius of the link 2	0.04 m
ρ	density of the sea water	1025 kg / m^3
v_{cm_i}	center of mass velocity of the link i	
v_i	translational velocity of the link i	
d_1	drag coefficient of the link1	1.1
d_2	drag coefficient of the link2	1.1
dia_1	diameter of the link1	0.08 m
dia_2	diameter of the link2	0.08 m
k_{c1}	coulomb coefficient of the link1	0.2
k_{c2}	coulomb coefficient of the link2	0.5
k_{v1}	Viscous coefficient of the link1	0.3
k_{v2}	Viscous coefficient of the link2	0.5
m_1	Mass of the link1	5 kg
m_2	Mass of the link2	2 kg
m_{A1}	Added mass of the link1	2.57 kg
m_{A2}	Added mass of the link2	2.06 kg
m_{T1}	Total mass of the link1	7.57 kg
m_{T2}	Total mass of the link2	4.06 kg

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$$T_{d1} = \frac{\rho}{2} d_1 dia_1 \int_0^{l_1} v_1^2 sign(v_1) dx_1$$

$$T_{d2} = \frac{\rho}{2} d_2 dia_2 \int_0^{l_2} v_2^2 sign(v_2) dx_2$$

$$D(q,\dot{q}) = \begin{bmatrix} T_{d1} \\ T_{d2} \end{bmatrix} \tag{8}$$

Where #

$v_i, i = 1,2$ represent translational velocities of the ith link, $T_{di}, i = 1,2$ shows drag torque of the ith link, $d_i, i = 1,2$ is the drag coefficients of the ith link and $dia_i, i = 1,2$ is diameter of the ith link. The buoyancy force is equal to the weight of the fluid displaced by the link and acts through the center of buoyancy of the link. Also buoyant force is in the opposite direction of gravitational force.

$$F_U(q) = G(q) - B(q) = mg - \rho g v \tag{9}$$

Calculating the force ($F_U(q)$) in all of the motion directions, we calculate the potential energy (u). Therefore the matrix $h(q)$ is expressed as:

$$h(q) = -\frac{d}{dt}\left(\frac{\partial u}{\partial \dot{q}}\right) + \frac{\partial u}{\partial q} = \frac{\partial u}{\partial q} = \begin{bmatrix} (m_2 - \nabla_2) l_2 g c_{12} + (m_1 + m_2 - \nabla_1 - \nabla_2) l_1 g c_1 \\ (m_2 - \nabla_2) l_2 g c_{12} \end{bmatrix} \tag{10}$$

∇ or ρv is the mass of water displaced by the link and v is the volume of the body of water, m_i is the mass of the i[th] link and g is the gravitational constant. Friction has a very nonlinear behavior which due to sealing joints should be considered in the dynamic equation of an underwater manipulator. Frictional force $F(\dot{q})$ included two parts of viscous (F_v) and coulomb (F_c) frictions.

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$$F_{vi} = k_{vi}\dot{q}_i \quad (11)$$
$$F_{ci} = k_{ci}sign(\dot{q}_i) \quad (12)$$

$$F(\dot{q}_i) = F_{vi} + F_{ci} \quad (13)$$

Combining equations of (4), (8), (9), (13) we can write the final form of the dynamic equations of motion the underwater manipulator:

$$M(q)\ddot{q} + C(q,\dot{q}) + D(q,\dot{q}) + h(q) + F(\dot{q}) = \tau \quad (14)$$

Where $M(q)$ is the 2×2 inertia matrix including rigid body and added mass terms, $C(q,\dot{q})$ is the 2×1 vector of centrifugal and corriolis forces which included rigid body and added mass terms, $D(q,\dot{q})$ is the 2×1 vector of drag torques, $h(q)$ is the 2×1 vector of gravity and buoyancy forces, $F(\dot{q})$ is the 2×1 vector of frictional forces and τ is the 2×1 vector of torques acting on underwater manipulator. c_i, s_i, s_{ij}, c_{ij} In above equations are equals to $\cos(q_i), \sin(q_i), \sin(q_i + q_j), \cos(q_i + q_j)$ respectively. Table 1 gives the parameters of both links during moves in underwater.

3. SMC with PID sliding surface

Sliding mode control is a variable structure controller (VSC). In fact a VSC is an effective design for trajectory tracking in presence of uncertainties. The objective of trajectory tracking control is to design control algorithm for achieving the proper input torque such the position q can track desired path q_d. Defining the tracking error and it's first and second derivatives as

$$e = q_d - q \quad (15)$$
$$\dot{e} = \dot{q}_d - \dot{q} \quad (16)$$

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$$\ddot{e} = \ddot{q}_d - \ddot{q} \tag{17}$$

$q, \dot{q}$ are assumed to be measurable and actual. Equation (14) can be rewritten as

$$\ddot{q} = M^{-1}(\tau - c(q,\dot{q}) - D(q,\dot{q}) - h(q) - F(\dot{q})) \tag{18}$$

Substituting equation (18) into equation (17) yields

$$\ddot{e} = \ddot{q}_d - M^{-1}(\tau - c(q,\dot{q}) - D(q,\dot{q}) - h(q) - F(\dot{q})) \tag{19}$$

Select the PID sliding surface as:

$$s = \dot{e} + \lambda_1 e + \lambda_2 \int e \tag{20}$$

Where λ_1 and $\lambda_2 = \frac{\lambda_1^2}{2}$ are the $n \times n$ constant and positive definite matrices and $s = [s_1 \dots s_n]^T$ is the vector of PID sliding surfaces. Let

$$\begin{aligned} &\tau = \tau_{eq} + \tau_1\ , \ (\tau_1 = k_1 \exp(\frac{-\alpha}{|s|}) sign(s) + k_2 s) \\ &k_1 = N_1 k_{fuzz} \\ &k_2 = N_2 k_{fuzz} \end{aligned} \tag{21}$$

Where τ_{eq} is the control law for sliding mode and τ_1 is the control law for reaching mode. Also τ_1 includes a exponential

Function to eliminate the control signal chattering. Differentiating equation (20) with respect to time and replacing from equation (19), we obtain

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$$\begin{aligned}\dot{s} &= \ddot{e} + \lambda_1\dot{e} + \lambda_2 e \\ &= \ddot{q}_d - M^{-1}(\tau - C(q,\dot{q}) - D(q,\dot{q}) - h(q) - F(\dot{q})) \\ &+\lambda_1\dot{e} + \lambda_2 e = 0\end{aligned} \tag{22}$$

Thus, we can obtain τ_{eq} as

$$\tau_{eq} = \hat{M}(\ddot{q}_d + \lambda_1\dot{e} + \lambda_2 e) + \hat{C} + \hat{D} + \hat{h} + \hat{F} \tag{23}$$

Where $\hat{M}$, $\hat{C}$, $\hat{D}$, $\hat{h}$, $\hat{F}$ denote nominal value of M , C , D , h, F ,respectively, and accordingly τ_{eq} is the closest estimation for response of the equation (22). Because of uncertainty in dynamic equation of underwater manipulator, one can define

$$\begin{aligned}&\tilde{M} = M - \hat{M}, \tilde{C} = C - \hat{C}, \tilde{h} = h - \hat{h}, \\ &\tilde{D} = D - \hat{D}, F = F - \hat{F}\end{aligned} \tag{24}$$

Consider a candidate Lyapunov function as

$$v(s) = \frac{1}{2}s^2 \tag{25}$$

Taking the derivative of $v(s)$ in (25), gives

$$\begin{aligned}\dot{v} &= s\dot{s} \\ &= s(\ddot{q}_d - M^{-1}(\tau - C(q,\dot{q}) - D(q,\dot{q}) - h(q) - F(\dot{q})) \\ &+\lambda_1\dot{e} + \lambda_2 e)\end{aligned} \tag{26}$$

With the follow condition, system states will reach the defined PID sliding surface $s = 0$ (20) in finite time.

$$\begin{aligned}\dot{v} &= s\dot{s} \\ &= s(\ddot{q}_d - M^{-1}(\tau - C(q,\dot{q}) - D(q,\dot{q}) - h(q) - F(\dot{q})) \\ &+\lambda_1\dot{e} + \lambda_2 e) \\ &\le -\eta\,|\,s\,|\end{aligned} \tag{27}$$

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Substituting equation (21) and (23) into equation (27) yields

$$s(\ddot{q}_d - M^{-1}(\hat{M}(\ddot{q}_d + \lambda_1\dot{e} + \lambda_2 e) + k_1\exp(\frac{-\alpha}{|s|})sign(s) + k_2 s$$
$$-\tilde{C} - \tilde{h} - \tilde{D} - \tilde{F})$$
$$+\lambda_1\dot{e} + \lambda_2 e \le -\eta\,|s| \tag{28}$$

We assume s is positive and equation (28) can be rewritten as

$$\tilde{M}(\ddot{q}_d + \lambda_1\dot{e} + \lambda_2 e) + M\eta + \tilde{C} + \tilde{h} + \tilde{D} + \tilde{F}$$
$$\le k_1\exp(\frac{-\alpha}{\left|\dot{e} + \lambda_1 e + \lambda_2\int e\right|}) + k_2(\dot{e} + \lambda_1 e + \lambda_2\int e) \tag{29}$$

k_1, k_2 are diagonal positive definite matrices and are defined such that the above equation is satisfied. Also the maximum values of k_1, k_2 are limited according to the system actuators power.

4. Design of Sliding Mode-PID Fuzzy

In the conventional SMC, control gains are dependent on uncertainties. This dependency is a defect for complex dynamics system. For solving the problem we design a fuzzy controller in this section. Also by using fuzzy logic, gains are tuned base on the distance of the states to the sliding surface. The main advantage of fuzzy control is that the tracking error and control effort are reduced. The configuration of our Sliding Mode-PID Fuzzy Control (SM-PIDFC) scheme is shown in fig.3; it includes an equivalent control law part and a two-input single-output SM-PIDFC in which Mamdani's fuzzy algorithm is used.

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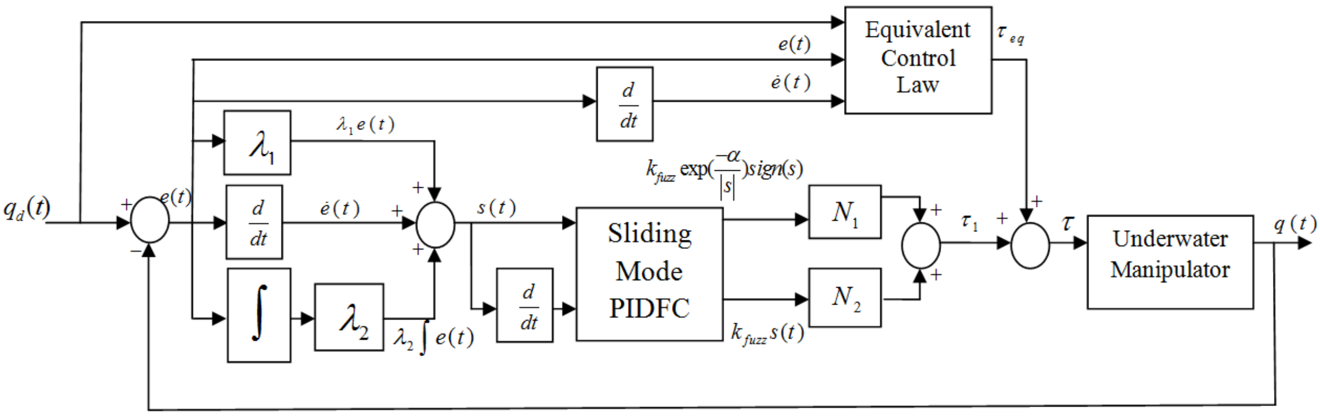

Figure 3: Block diagram of the proposed controller

k_1, k_2 in equation (21) are expressed as follow:

$$k_1 = N_1 k_{fuzz}$$
$$k_2 = N_2 k_{fuzz} \quad (30)$$

Where N_1, N_2 are the normalization factor of the output variable, and k_{fuzz} is the output of the SM-PIDFC, which is determined by inference on input linguistic variables $s(t)$ and $\dot{s}(t)$. The membership function of input linguistic variables and the membership functions of output linguistic variable are shown in fig.4 and 5, respectively. $s(t), \dot{s}(t)$ and k_{fuzz} are decomposed into five, three and three fuzzy partitions respectively. The fuzzy controller consists of four steps: Fuzzification, Rules evaluation, Aggregation and Defuzzification. The fuzzy rule base has been given in table 2 in which the following symbols have been used: NB: Negative Big; NS: Negative Small; ZE: Zero; PS: Positive Small; PB: Positive Big; N: Negative; Z: Zero; P: Positive; M: Medium; B: Big; S: Small. These linguistic fuzzy rules are defined heuristically in the following form:

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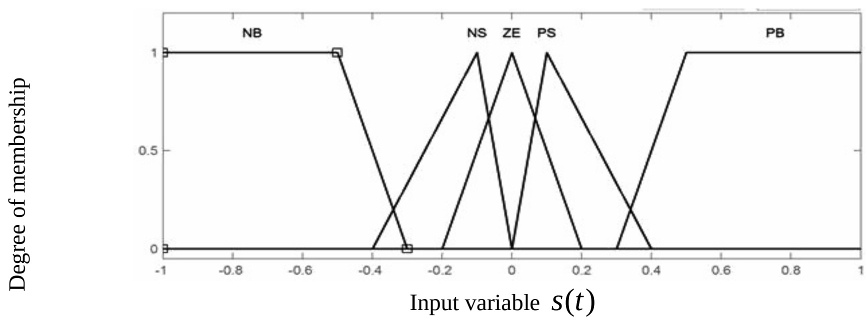
- -

$$R^{(l)}: IF\ \ s(t)\ is\ A_1^l\ \ and\ \ \dot{s}(t)\ is\ \ A_2^l$$
$$THEN\ \ k_{fuzz}\ \ is\ \ B^l$$

Where A_1^l and A_2^l are the labels of the input fuzzy sets. B^l is the labels of the output fuzzy sets. l=1,2…,15 denotes the number of the fuzzy IF-THEN rules. Fuzzy implication is modeled by Mamdani's minimum operator, the conjunction operator is Min, the t-norm from compositional rule is Min and for the aggregation of the rules the Max operator is used. In this paper the centroid deffuzification method is used and calculated by the following equation:

$$z = \frac{\sum_{i=1}^{n} c_i \mu_{A_i}(x)\mu_{B_i}(y)}{\sum_{i=1}^{n} \mu_{A_i}(x)\mu_{B_i}(y)} \tag{31}$$



(a) $s(t)$

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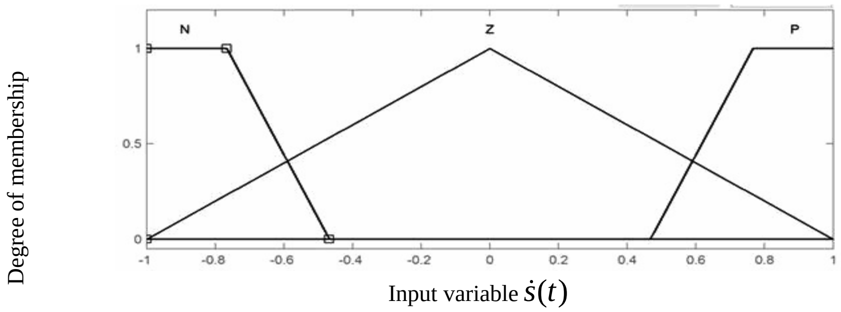
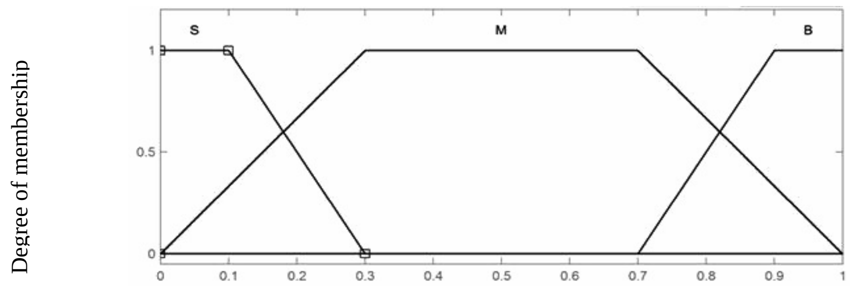


Input variable $\dot{s}(t)$

(b) $\dot{s}(t)$

Figure 4: Input Membership Function



Output variable k_{fuzz}

Figure 5: Output Membership Function

TABLE 2: FUZZY RULE BASE

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**

The fuzzy control surface of the output k_{fuzz} is shown in fig.6.

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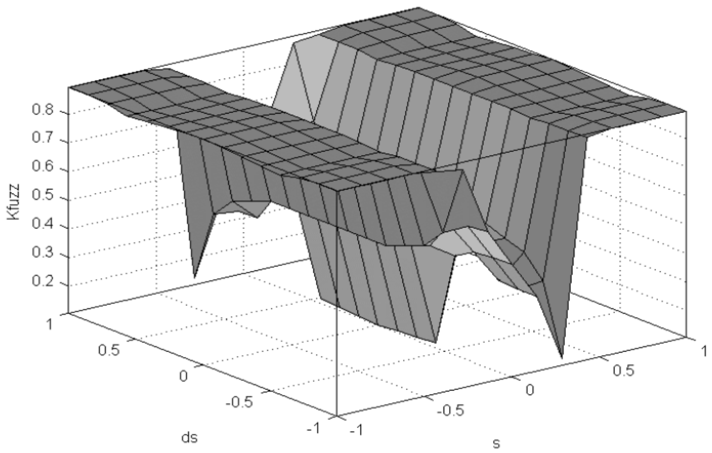

Figure 6: Control surface of k_{fuzz}

5. Simulation Results

In this section, the simulation results of the proposed controller, which is performed on the two link underwater manipulator, are presented. In this case study for angle of joints 1, 2 cosine and sine trajectories with zero initial conditions are chosen respectively. These trajectories generated a circle desired path in x-y plane. Using the values given in Table 1 simulation is carried out for conventional SMC and sliding mode-PIDFC controller. Fig.7 shows the trajectory tracking, tracking error and control inputs when system is subjected to conventional SMC.

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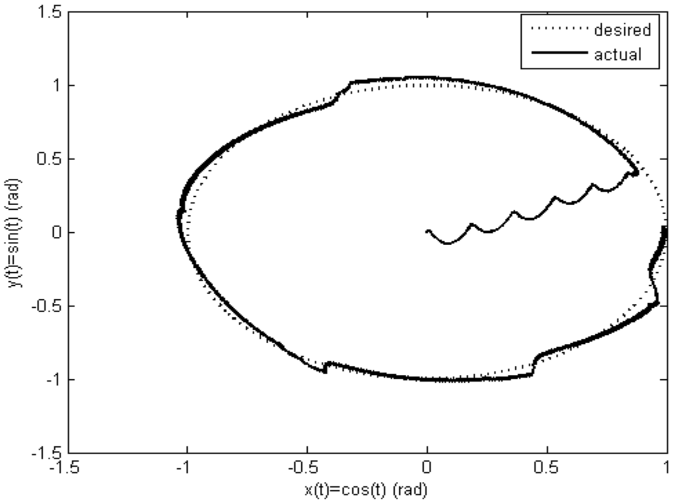

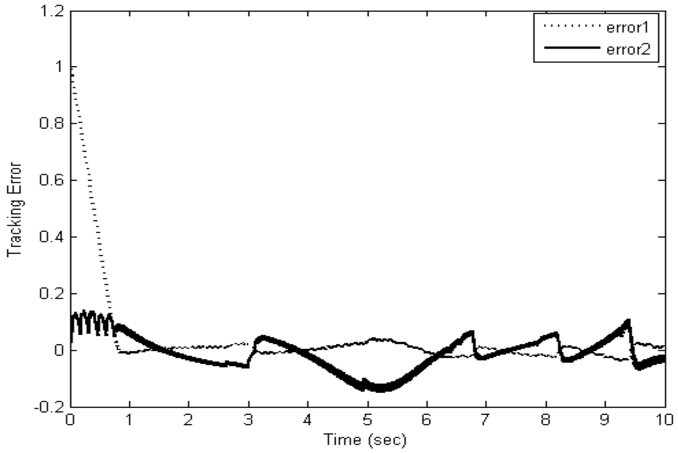

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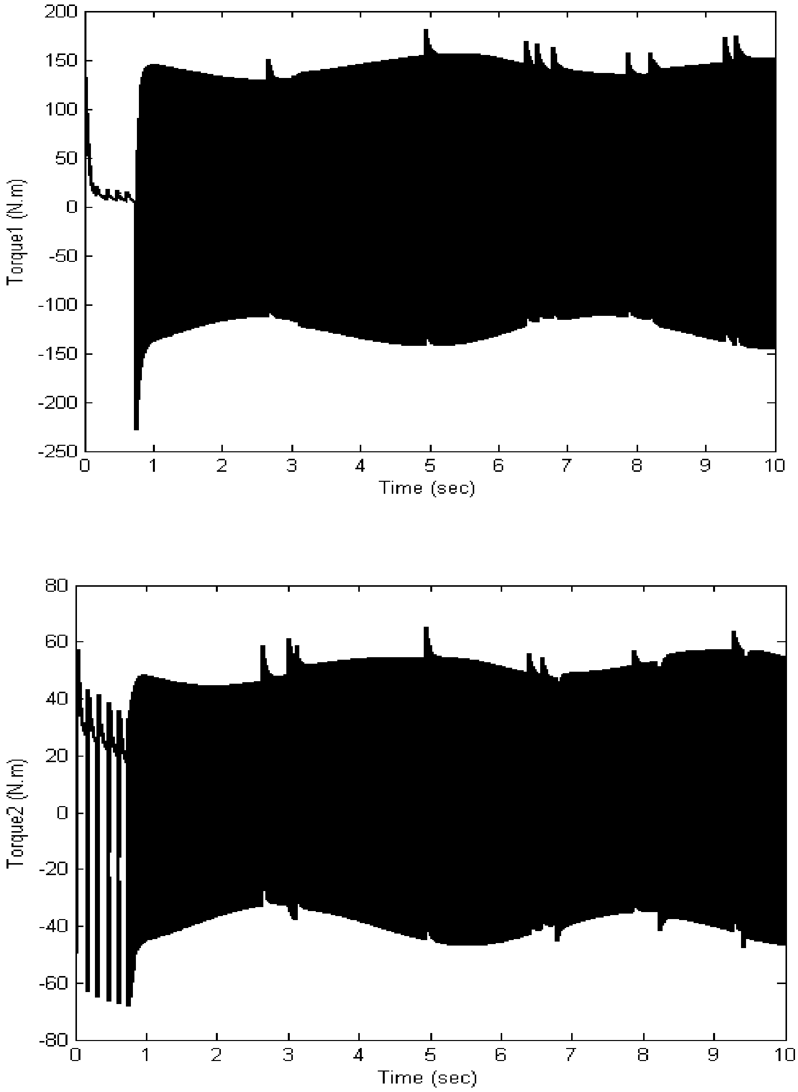

Figure 7: Conventional Sliding Mode Controller

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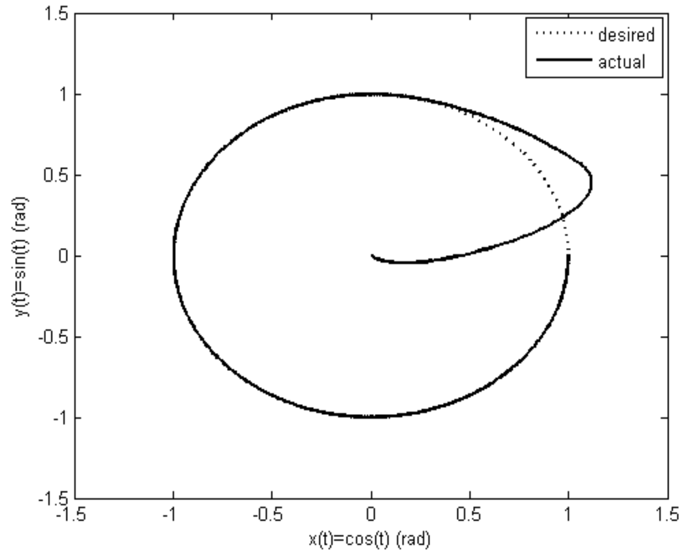
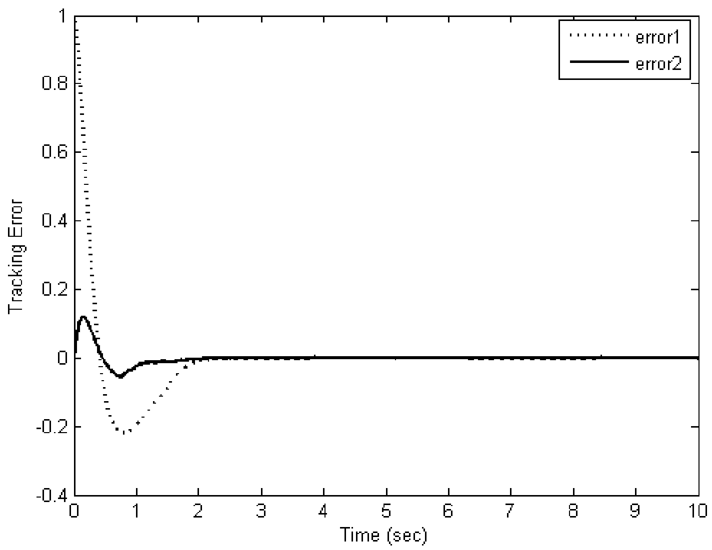
Fig. 8 shows the trajectory tracking, tracking error, control input and fuzzy controller outputs when system is subjected to SM-PIDFC with the function $sign(s)$.





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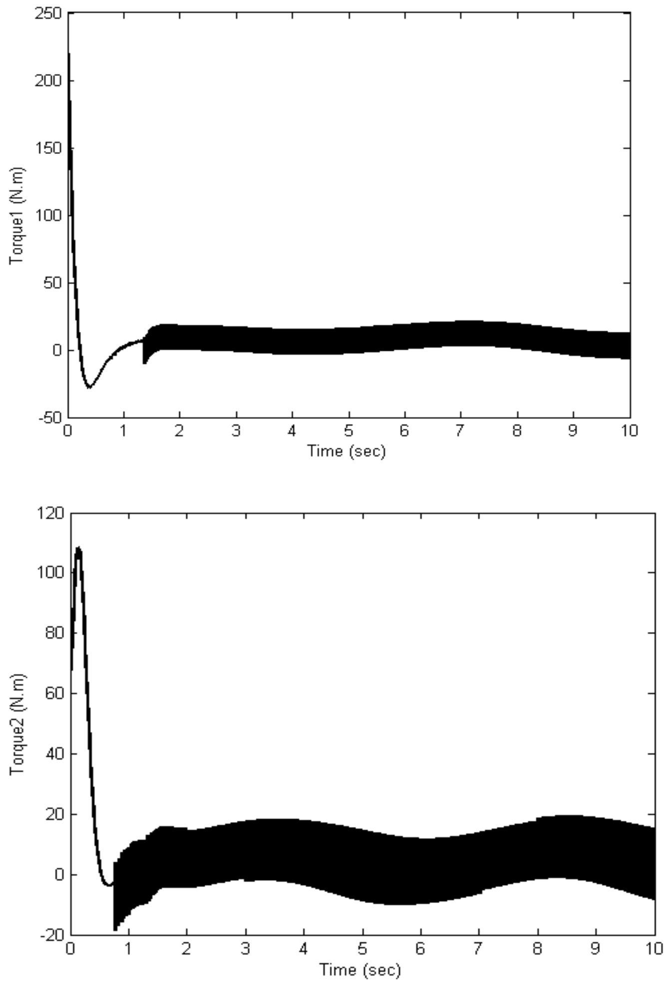

Figure 8: SM-PIDFC with $sign(s)$ function

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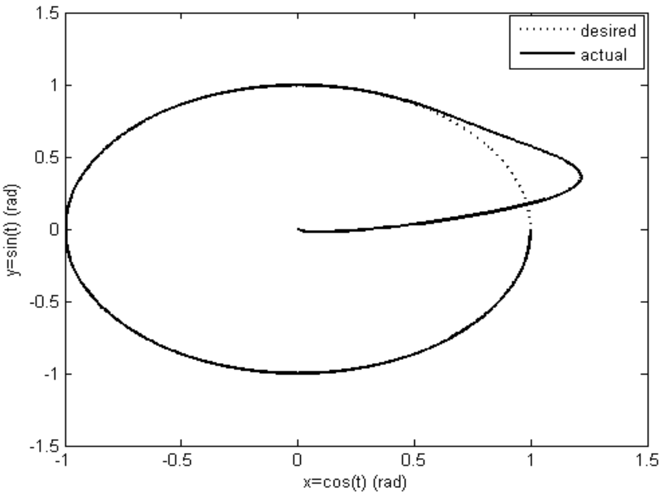
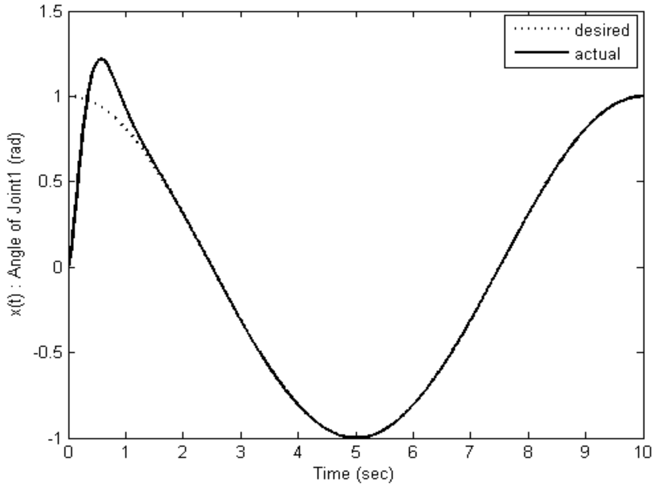
Also Fig. 9 shows the trajectory tracking, tracking error, control input and fuzzy controller outputs when system is subjected to SM-PIDFC for q_1 and q_2 with the function $\exp(\frac{-\alpha}{|s|})sign(s)$.





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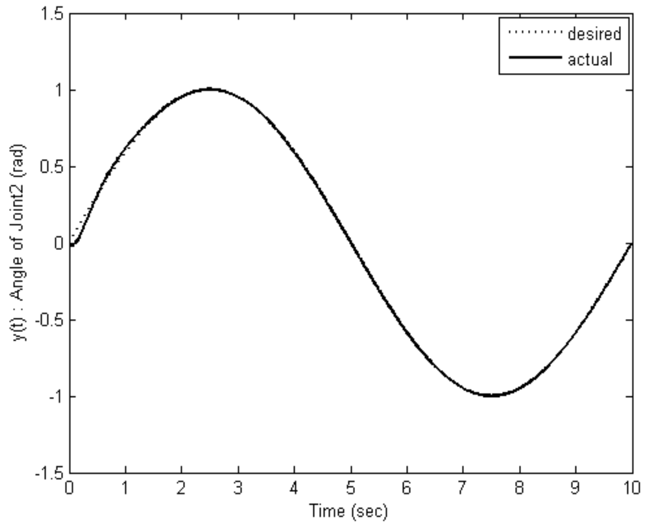

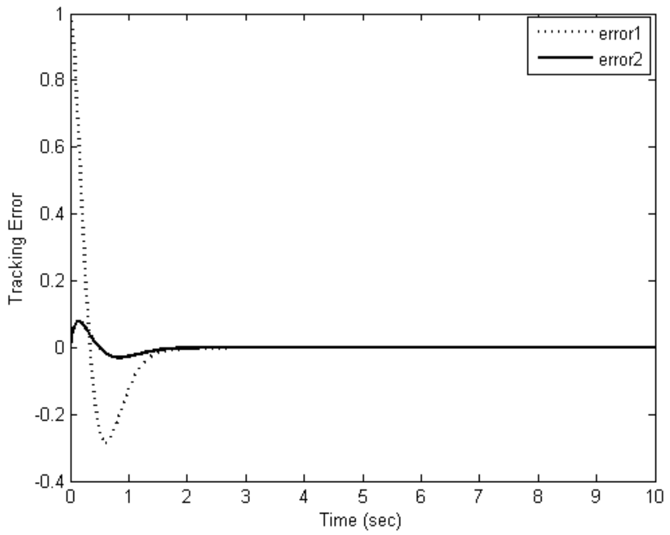

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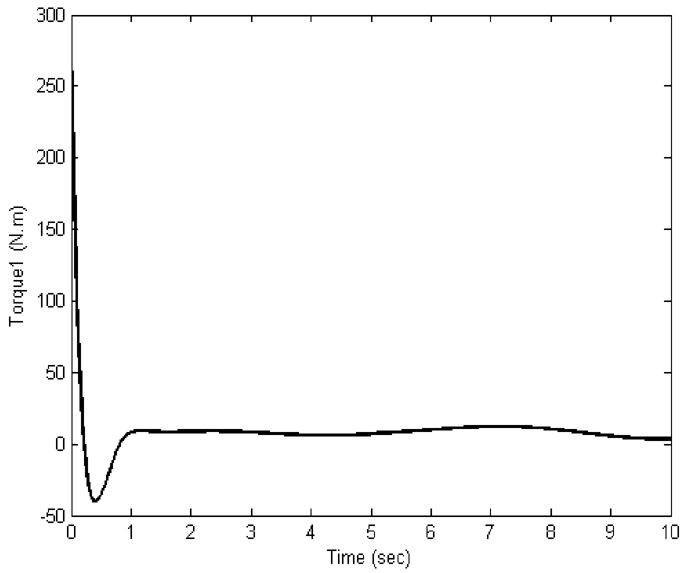

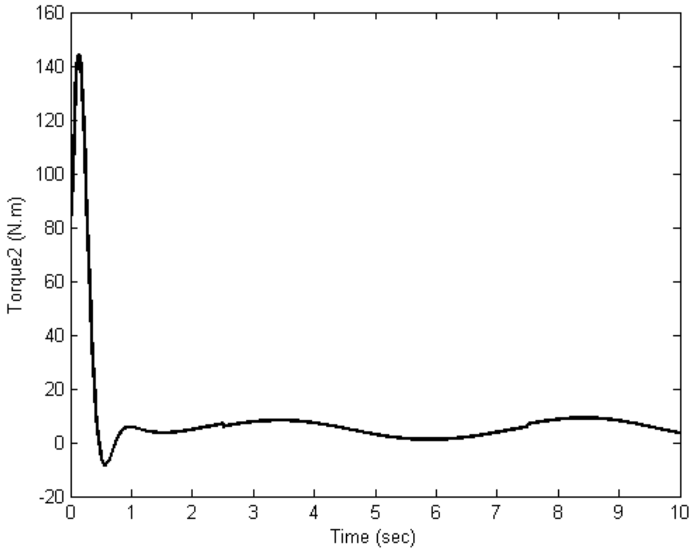

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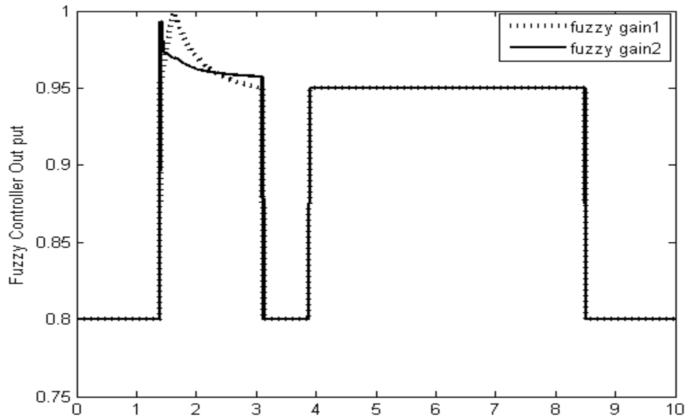

Figure 9: SM-PIDFC with $\exp(\frac{-\alpha}{|s|})sign(s)$ **function**

Conclusion

In this paper, a sliding mode-PID fuzzy controller for underwater manipulator has been presented. The proposed controller is designed based on the PID sliding surface and uses fuzzy rules to adaptively tune the gains. In the control law, for removing of chattering, the exponential function has been used. This controller is simple, easy to implement, and robust. In order to confirm the effectiveness of the proposed algorithm, simulations were performed on the trajectory tracking of a 2-DOF underwater manipulator. The results show that the proposed sliding mode-PID fuzzy controller provides accurate and robust tracking performance of the underwater manipulator without any of the chattering, which is superior to the one obtained with a conventional SMC. Table 2 gives the percentage of tracking errors.

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TABLE 2: PERCENTAGE OF TRACKING ERRORS

CONTROLLER	PERCENTAGE OF TRACKING ERROR
Conventional SMC	10%
SM-PIDFC with $sign(s)$ function	2%
SM-PIDFC with $\exp(\frac{-\alpha}{\lvert s \rvert})sign(s)$ function	0.8%

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Authors

H. Nejatbakhsh Esfahani was born in Isfahan, Iran, 1986. He received his B.Sc. degree in Instrumentation and Control Engineering in 2009 from University of Applied Science and Technology. Also He received his M.Sc. degree in Mechatronics Engineering in 2012 from University of Tabriz, Tabriz, Iran. His research interests include: robotics, adaptive and robust control, intelligent control, and nonlinear control.

V. Azimirad was born in Tabriz Iran. He received his B. Sc. in Mechanical Engineering from the Tabriz University. He earned his master's and doctoral degrees in mechanical engineering at the Iran University of Science and Technology. Much of his work has focused on path planning of robots. He is particularly interested in the area of mobile robotics and biomedical systems.