

SLIDING MODE-PID FUZZY CONTROLLER WITH A NEW REACHING MODE FOR UNDERWATER ROBOTIC MANIPULATORS

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Abstract— Design of an accurate and robust controller is a challenging topic in an 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 removing of chattering, the exponential function is used. And also the 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 in presence of unmodeled dynamic (variable masses of links) and external disturbance. 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— Sliding Mode Control, Fuzzy Logic, Gain Tuning, Underwater Manipulator.

I. 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 underwater intervention. In addition, robotic manipulator is 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 applications in underwater manipulation. In recent studies, there is not a reliable and robust controller for the underwater manipulators. Liceaga Castro and Qiao (1991) used a variable structure system (VSS) for design a robust controller. Levesque and Richard (1993) presented a stochastic adaptive controller that was a model based design. This controller could represent efficient robustness in a turbulent flow, but it does not have a proper precision for trajectory tracking goals. The control system based on machine vision was proposed by Smith *et al.* (1994). This system does not have a robust property in presence of uncertainties for the reason of using PID controller. Furthermore, Baicu *et al.* (1995) used a hybrid, robust-adaptive controller for tracking of a single link under-

water manipulator. A PD control method was used for robust controller that does not have a proper robustness in presence of disturbances which are under the sea. McLain and Rock (1996) improved an exact model of hydrodynamic forces that were used at a single link manipulator. Lee and Choi (2000) presented scheme of a robust control with multi layer neural network and with learning algorithm of an error back propagation. Lee *et al.* (2007) improved a four DOF underwater manipulator for inspection and maintain a nuclear reactor. This system has been used for removing loose parts from the bottom of a vessel of a nuclear reactor. Rahman *et al.* (2007) 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. Xu *et al.* (2007) used a robust and exact SMC controller for tracking of the underwater manipulator. They used saturation function for destroying chattering. In this system, there is not a parameter estimator for the controller and SMC parameters have been adjusted with try and error. Moreover, Wang *et al.* (2008) 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. But it does not have high robustness. Pandian and Sakagami (2010) 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. Gumusel and Ozmen (2011) presented modeling and controlling of a two degree of freedom underwater manipulator with a flexible link. They presented an exact modeling for drag forces on flexible link. Several researchers have studied sliding mode fuzzy control (SMFC) for different applications (El-Bakly and Fouda, 2009; Ryu and Park, 2001). However, little research has so far been conducted on SMFC's for the underwater manipulators. The rest of the paper is organized as follows; the dynamics of the underwater manipulator is modeled in Section II that it includes uncertain added mass, drag force, buoyancy and frictional forces. The section III presents the characteristics of a conventional SMC with PID sliding surface. Section IV presents the robust fuzzy SMC-PID using fuzzy self-tuning control gain. The computer simulation results are shown in section V. finally, the conclusion is presented in section VI.

II. UNDERWATER MANIPULATOR

The coupled effect between manipulator and vehicle is neglected and ROV/AUV is assumed stationary during manipulator movement. Fig.1 illustrates the n-D.O.F. 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 dynamic equations of motion are developed by using Lagrange formulation as follow:

$$\frac{d}{dt} \left(\frac{dT}{d\dot{q}} \right) - \left(\frac{dT}{dq} \right) = \tau \quad (1)$$

where $q \in R^2$ is the joint position of robotic manipulator, and $\dot{q} \in R^2$ is the joint velocity vector of robotic manipulator.

The vector of kinetic energy of the system is written as:

$$T = T_{RB} + T_{AM} \quad (2)$$

where $T_{RB} = \frac{1}{2} \mathbf{v}_{cm_i}^T \mathbf{M}_{RB} \mathbf{v}_{cm_i}$ is kinetic energy of manipulator due to rigid body, and $T_{AM} = \frac{1}{2} \mathbf{v}_{cm_i}^T \mathbf{M}_{AM} \mathbf{v}_{cm_i}$

is kinetic energy of manipulator due to added mass. The added mass matrix for each cylindrical link of a manipulator is represented as:

$$\mathbf{M}_{AM_i} = \text{diag}(0, a_i, a_i, 0, b_i, b_i) \quad (3)$$

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 includes rigid body and added mass as follows:

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

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

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

The added mass of the links (m_A) for cylindrical manipulator are expressed by Fossen (2002) in follow equation as per Fossen:

$$\begin{aligned} m_{Ai} &= \pi \rho r_i^2 l_i \\ m_{Ti} &= m_i + m_{Ai} \end{aligned} \quad (7)$$

The drag force on a link is relative to the square of the link's velocity that is proved by Shinohara (2011). The sign of the drag force direction has to be determined according to the motion of the underwater

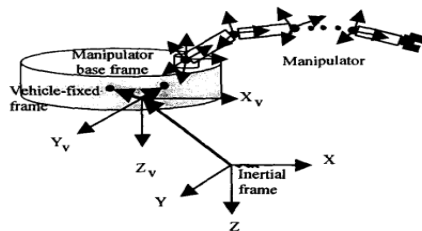


Fig.1 schematic of UVMS

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 link 1	0.2
k_{c2}	coulomb coefficient of the link 2	0.5
k_{v1}	Viscous coefficient of the link 1	0.3
k_{v2}	Viscous coefficient of the link 2	0.5
m_1	Mass of the link 1	5 kg
m_2	Mass of the link 2	2 kg
m_{A1}	Added mass of the link 1	2.57 kg
m_{A2}	Added mass of the link 2	2.06 kg
m_{T1}	Total mass of the link1	7.57 kg
m_{T2}	Total mass of the link 2	4.06 kg

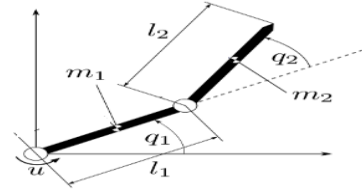


Fig. 2. Two-link underwater manipulator

manipulator is identified through the sign of the translational velocities. Drag torques are expressed in (8):

$$T_{d1} = \frac{\rho}{2} d_1 dia_1 \int_0^{l_1} v_1^2 \text{sign}(v_1) dx_1 \quad (8)$$

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

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

where v_i , $i=1,2$ represent translational velocities of the i th link, T_{di} , $i=1,2$ shows drag torque of the i th link, d_i , $i=1,2$ is the drag coefficients of the i th link and dia_i , $i=1,2$ is diameter of the i th link. Buoyant force is in the opposite direction of gravitational force.

$$F_p(q) = G(q) - B(q) = mg - \rho g v_w \quad (9)$$

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

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

where ∇ or ρv_w is the mass of water displaced by the link and v_w is the volume being displaced by the body of link, m_i is the mass of the i^{th} link and g is the gravitational constant. Frictional force $F(\dot{q})$ included two parts of viscous (F_v) and coulomb (F_c) frictions.

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

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

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

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

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

where $M(q) \in \mathbb{R}^{2 \times 2}$ is inertia matrix including rigid body and added mass terms, $C(q, \dot{q}) \in \mathbb{R}^2$ is vector of centrifugal and coriolis forces which included rigid body and added mass terms, $D(q, \dot{q}) \in \mathbb{R}^2$ is vector of drag torques, $h(q) \in \mathbb{R}^2$ is vector of gravity and buoyancy forces, $F(\dot{q}) \in \mathbb{R}^2$ is vector of frictional forces, $T_d \in \mathbb{R}^2$ is the external disturbance, and $\tau \in \mathbb{R}^2$ is vector of torques acting on underwater manipulator. c_i , s_i , s_{ij} and c_{ij} represent $\cos(q_i)$, $\sin(q_i)$, $\sin(q_i + q_j)$ and $\cos(q_i + q_j)$ respectively. Table 1 gives the parameters of both links during moves in underwater.

III. 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. Defining the tracking error results in:

$$e = q_d - q \quad (15)$$

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

$$\ddot{e} = \ddot{q}_d - \ddot{q} \quad (17)$$

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

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

Substituting Eq. (18) into Eq. (17) yields

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

Select the PID sliding surface as

$$s = \dot{e} + \lambda_1 e + \lambda_2 \int e \quad (20)$$

where λ_1 and $\lambda_2 = \lambda_1^2/2$ 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. Letting:

$$\tau = \tau_{eq} + \tau_1, \quad (\tau_1 = k_1 \exp\left(\frac{-\alpha}{|s|}\right) \text{sign}(s) + k_2 s) \quad (21)$$

$$k_1 = N_1 k_{fuzz}$$

$$k_2 = N_2 k_{fuzz}$$

where τ_{eq} is the control law for sliding mode and τ_1 is the control law for reaching mode. Structure of τ_1 is the main reason of chattering as undesired oscillation around the sliding surface. Thus, to overcome this problem, the structure of τ_1 should be modified by reducing the variations rate of τ_1 around the sliding surface. Now, we introduce a control law that includes an exponential term that make the reaching trajectory smooth, consequently, prevents the oscillation of the states around sliding surface. Comparing a-conventional structure and b- proposed structure trajectories in Fig. 3 can give better understanding.

Differentiating Eq. (20) with respect to time and replacing from Eq. (19), we obtain

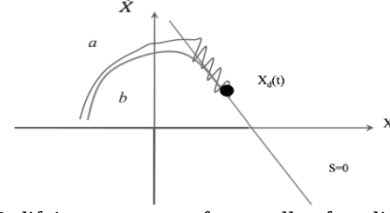


Fig. 3. Modifying structure of controller for elimination of chattering a-Conventional structure b- Proposed structure

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

Thus, we can obtain τ_{eq} as

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

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 Eq. (22). Because of uncertainty in dynamic equation of underwater manipulator, one can define:

$$\tilde{M} = M - \hat{M}, \quad \tilde{C} = C - \hat{C}, \quad \tilde{h} = h - \hat{h}, \quad (24)$$

$$\tilde{D} = D - \hat{D}, \quad \tilde{F} = F - \hat{F}$$

Consider a candidate Lyapunov function as

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

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

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

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

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

Substituting Eqs. (21) and (23) into Eq. (27) yields

$$\begin{aligned} &s(\ddot{q}_d - M^{-1}(\hat{M}(\ddot{q}_d + \lambda_1 \dot{e} + \lambda_2 e) + k_1 \exp\left(\frac{-\alpha}{|s|}\right) \text{sign}(s) + k_2 s) \\ &\quad - \tilde{C} - \tilde{h} - \tilde{D} - \tilde{F}) \\ &\quad + \lambda_1 \dot{e} + \lambda_2 e \leq -\eta |s| \end{aligned} \quad (28)$$

We assume s is positive and Eq. (28) is rewritten as

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

where 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 actuators.

IV. DESIGN OF SLIDING MODE-PID FUZZY

Through the 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.4; it includes an equivalent control law

part and a two-input single-output SM-PIDFC in which Mamdani's fuzzy algorithm is used.

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

$$\begin{aligned} k_1 &= N_1 k_{fuzz} \\ k_2 &= N_2 k_{fuzz} \end{aligned} \quad (30)$$

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 Figs. 5 and 6, 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:

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

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. $l=1,2,\dots,15$ 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 defuzzification method is used and calculated by the following equation:

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

The fuzzy control surface of the output k_{fuzz} is shown in Fig. 7.

Table 2. Fuzzy Rule Base

$\begin{smallmatrix} S \\ \dot{S} \end{smallmatrix}$	NB	NS	ZE	PS	PB
N	B	B	M	S	B
Z	B	M	S	M	B
P	B	S	M	B	B

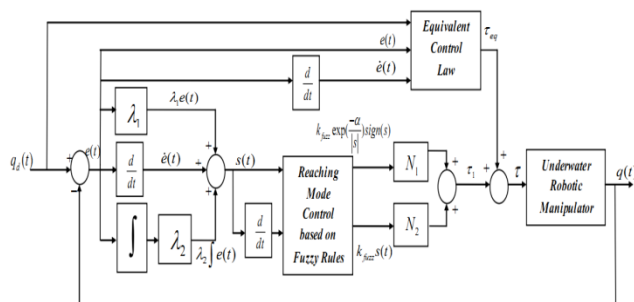


Fig. 4. block diagram of the proposed controller

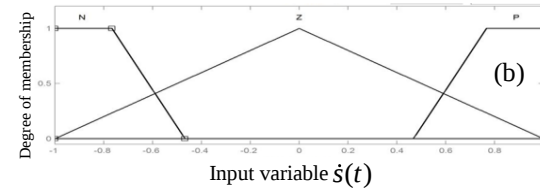
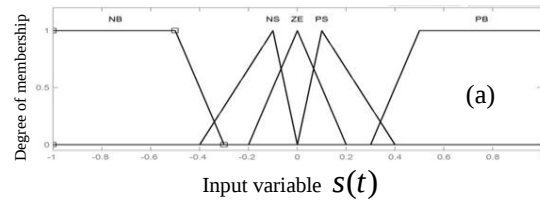


Fig. 5. Input Membership Function

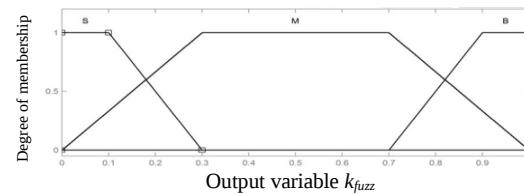


Fig. 6. Output Membership Function

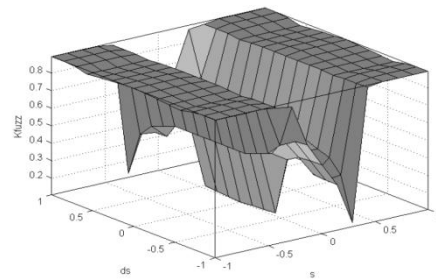


Fig. 7. Control surface of k_{fuzz}

V. SIMULATION RESULTS

In this section, we show the design process of the proposed sliding mode-PID fuzzy control algorithm on a two-link manipulator. In the case study for angle of joints 1, 2 $\exp(1-t/4) \sin(3t)$ and $\exp(1-t/4) \cos(3t)$ trajectories are chosen respectively. The initial conditions are set as:

$$q = [1, 0]^T, \quad \dot{q} = [0, 0]^T.$$

The external disturbance is:

$$T_d = \begin{bmatrix} 3.2 + 2 \cos(0.02t) \\ 3.5 + 1.7 \sin(0.02t) \end{bmatrix}.$$

Also in simulation of three kind of controller, we applied an unmodeled dynamic in form of variable mass due to added effect in underwater condition. This unmodeled dynamic is expressed as follow:

$$m_1 = 3 + 2 \sin(t).$$

$$m_2 = 1 + 2 \sin(t)$$

Using the values given in Table 1 simulation is carried out for conventional SMC and sliding mode-PIDFC controller. Fig.8 shows the trajectory tracking, tracking error and control inputs when system is subjected to conventional SMC.

Figure 9 shows the trajectory tracking, tracking error, control input and fuzzy controller outputs when system is subjected to SM-PIDFC with the function $\text{sign}(s)$.

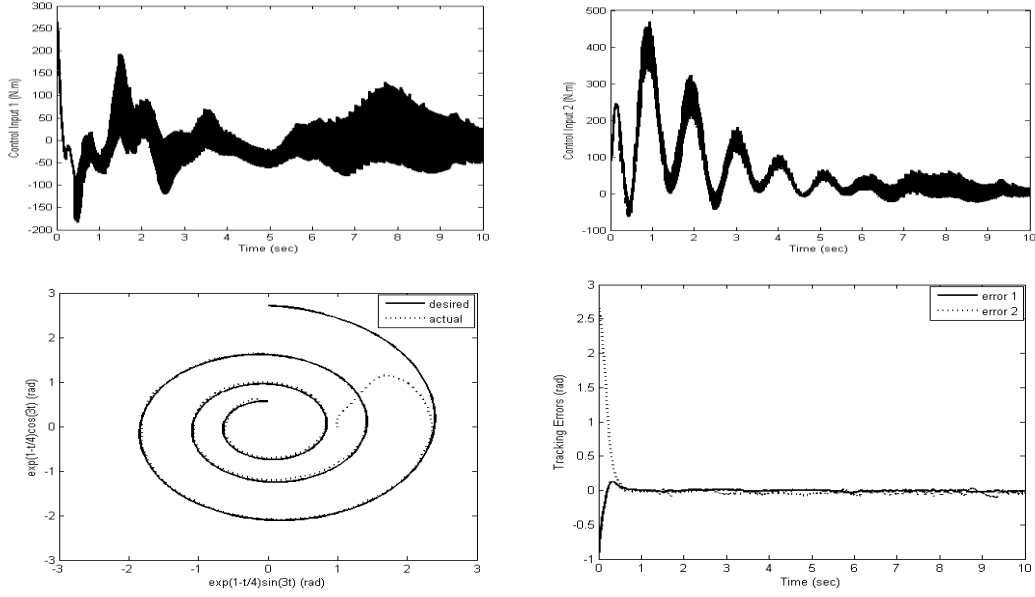


Fig. 8. Conventional Sliding Mode Controller

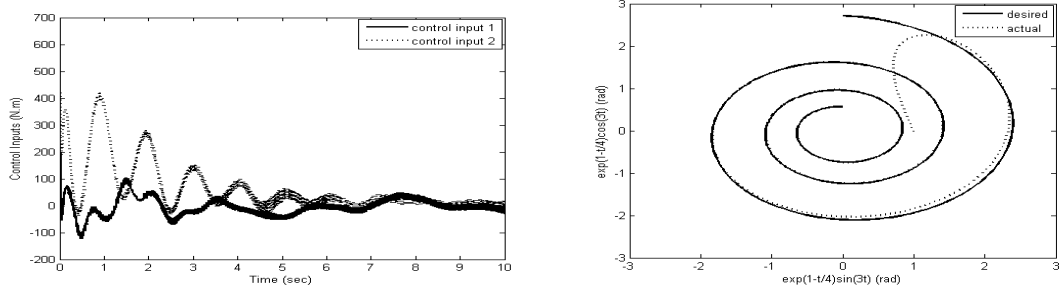
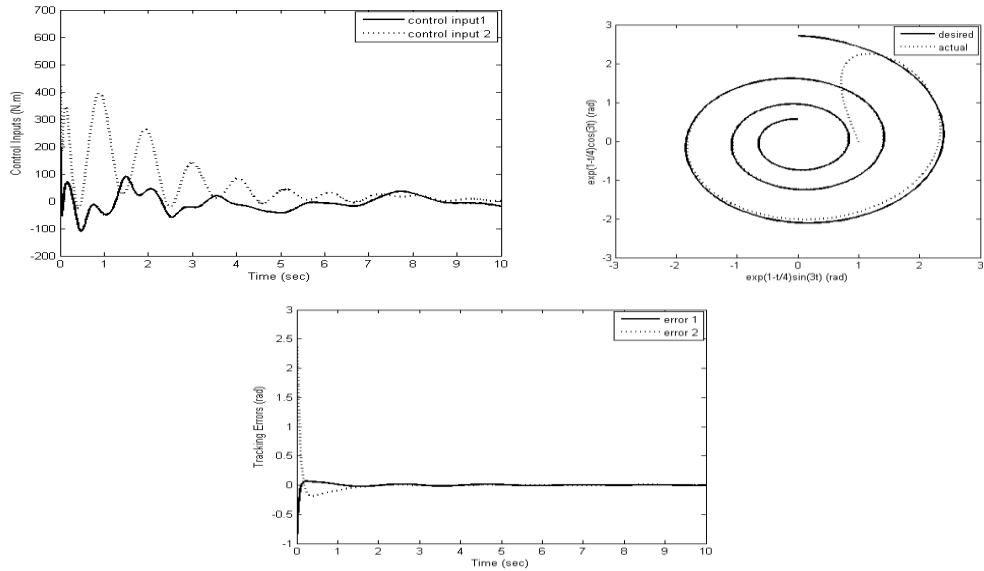
Fig. 9. SM-PIDFC with $\text{sign}(s)$ Fig. 10 SM-PIDFC with $\exp(-\alpha/|s|) \text{sign}(s)$ function.

Figure 10 shows the trajectory tracking, tracking error, control input and fuzzy controller outputs when system is subjected to SM-PIDFC with the function $\exp(-\alpha/|s|) \text{sign}(s)$.

VI. DISCUSSION

According to highly nonlinear terms of hydrodynamic forces, a conventional sliding mode controller could not

be used. On the other hand the high frequency of inputs can damage the actuators. Figures 9 and 10 show the results of new proposed controller. Figure 9 is related to controller with the function $\text{sign}(s)$ and Fig. 10 is related to the controller with the function $\exp(-\alpha/|s|) \text{sign}(s)$. Using Fuzzy controller with intelligent determination of gain in sliding mode controller causes to

Table 3: Tracking Error Norms

Controller	Tracking Error Norm of Link 1	Tracking Error Norm of Link 2
Conventional SMC	2.3	9.9
SM-PIDFC with $\text{sign}(s)$ function	1.7	5.3
SM-PIDFC with $\exp(-\alpha s)$ $\text{sign}(s)$ function	1.7	5.3

Table 4: percentage of reduced chattering in comparison to conventional SMC

Controller	Reduced Chattering of Link 1	Reduced Chattering of Link 2
SM-PIDFC with $\text{sign}(s)$ function	45%	15%
SM-PIDFC with $\exp(-\alpha s)$ $\text{sign}(s)$ function	49%	18%

decrease of chattering and tracking error (Fig. 9). But still chatterings are not eliminated completely. But using $\exp$ function (as it is shown in Fig. 10) results in elimination of high frequency oscillation of input torques. Furthermore the controller cost decreases.

VII. CONCLUSION

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 3 gives the tracking error norms. Also Table 4 gives the percentage of reduced chattering in comparison to conventional SMC.

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