International Journal of Electronics Engineering (ISSN: 0973-7383)
Volume 12 • Issue 1 pp. 28-38 Jan - June 2020 www.csjournals.com

Adaptive Fuzzy Sliding Mode Controller Design For Robot Manipulators

Sunil Kalshetti[1], Dr.S.K.Dixit[2]
[1]Assistant Professor, [2] Professor
Electronics & Telecom. Department., Walchand Institute of Technology, Solapur, Maharashtra, India

ABSTRACT: This paper intends to design and develop an adaptive fuzzy sliding mode controller for robotic manipulator. Robotic manipulators are nonlinear having most of the dynamic parameters which are uncertain. Hence there is requirement for designing a high performance nonlinear controller for handling uncertainties. Today, strong mathematical tools are used in new control methodologies to design adaptive nonlinear robust controller with acceptable performance. One of the best nonlinear robust controllers which can be used in uncertainty nonlinear systems is sliding mode controller (SMC) but this controller has some intrinsic drawbacks namely the chattering phenomenon, equivalent dynamic formulation and sensitivity to the noise. This research will be focusing on applying artificial intelligence integrated with the sliding mode controller. As it is not feasible to match up the SMC functions with system model each time, this paper implements a Fuzzy Inference System (FIS) to replace the system model. Further, it proposes the self-adaptiveness in a latest algorithm called as Grey Wolf Optimization (GWO) to formulate the adaptive fuzzy membership functions. Further, it compares the effectiveness of the proposed method with the desired experimental model and the conventional methods like SMC, Fuzzy SMC and GWO-SMC. Hence, the replacement of SAGWO-FSMC to the fuzzy model helps to aid the SMC to control the robotic manipulator, proved effectively by the comparative analysis.

Keywords: External disturbances, fuzzy model, joint angles, PUMA 560 robotic arm, robotic manipulator, Sliding Mode Control, SAGWO,

1. INTRODUCTION

In general, robotic manipulators [1][4] are widely applied in the industrial environment for executing dangerous or routine works. Robotic manipulators[12][14] have been encounter nonlinearities[7][9] and various uncertainties in their dynamic models, such as friction, disturbance, load change due to which it is very difficult to reach excellent performance when the control algorithm is completely based on the robotic plant model. In addition, it is much complex to accomplish better performance while the control design is entirely dependent on the robotic plant design [21] [22]. The trajectory tracking [4][5] accuracy is the most important function of an industrial manipulator. Thus, a robot motion tracking control is one of the challenging problems due to the highly coupled nonlinear and time varying dynamics. Robotic control system design has been an important issue in control engineering. Several kinds of control schemes have already been proposed in the field of robotic control over the past decades. Feedback linearization technique can compensates some of the coupling nonlinearities in the dynamics. Although a global feedback linearization is theoretically possible, a practical insight is restricted. Uncertainties also arise from imprecise knowledge of the kinematics, dynamics and also due to joint [4][5] and link flexibility, actuator dynamics, friction, sensor noise, and unknown loads.

These dynamical uncertainties make the controller design for manipulators a difficult task in the framework of classical control method. Conventional control techniques for robotic manipulators include the computed torque control, adaptive control [19], sliding mode control[16], and fuzzy control[5][12]. The adaptive control has a fixed structure and adaptable parameters and is very effective in coping with structured uncertainties and maintaining a uniformly good performance over a limited range, but it does not solve the problem of unstructured uncertainties. The sliding mode control is a robust nonlinear control scheme that is effective in overcoming the uncertainties and has a fast transient response. However, chattering problem [3][5] is a major drawback of sliding mode control. Hence boundary layer [3] is used to avoid chattering phenomenon.

Recently the development of artificial intelligent control for robotic manipulators has received considerable interest. The most popular intelligent-control approaches are the neural network control and fuzzy control [29]. The merit of the fuzzy control is that it can explicitly use human knowledge and experience in its control strategy. The drawback is the less theoretical analysis of stability for the general fuzzy controllers. To overcome the demerits and take advantage of the attractive features of conventional control and intelligent control, this research proposes an adaptive fuzzy sliding mode controller (AFSMC) for the trajectory control of robotic manipulators [1]. Besides advantage of stability and robustness of sliding mode control, the proposed method suppresses the input chattering in sliding mode by using the fuzzy control with adaptive tuning algorithm[1] [3] [5] [6] [19] [29].

Sliding Mode Controller has been widely applied to various types of non-linear systems [21] [23] [24]. SMC's popularity is due to its robustness against the change in parameters and the external disturbances in both theoretical and practical applications. However, the action of discontinuous part in traditional SMC leads the whole controller to face a troublesome condition known as "chattering" and the traditional type of SMC requires the whole dynamic functions of the system[18][20]. Moreover, in order to achieve the non-chattering SMC, the sign[5][14] function should be changed to saturation function to employ the adaptation of a thin boundary layer close by the sliding manifold to minimize or attenuate the chattering. However, this method damages the perfect tracking of the SMC; hence, the steady state error will always exist. Furthermore, to overcome the mentioned problem, some adaptive strategies recommended which can compensate the disturbances in order to increase the tracking performance.

In recent decades, the Fuzzy Logic as a technique based on expert knowledge has been applied to a wide range of controllers for solving the complex problems. Although Fuzzy controller is free from huge mathematical operations but sometimes more mathematical treatment is needed [21][29]. However it should be noted that sometimes Fuzzy Logic Controller [11] is much more tranquiller. Today's, applying techniques that combine the fuzzy theory with nonlinear controllers, for instance using fuzzy sliding mode controller are most common. The applications of fuzzy logic controller can not only be used in the systems with hard modeling, but they can also be used for systems with high mathematical analysis. The robust model of fuzzy combination, so called adaptive fuzzy sliding mode was introduced to reject the chattering phenomenon and compensate unknown dynamic parameters in the systems by another fuzzy logic controller [7][10][12].

2. LITERATURE REVIEW

2.1 Related Works

In 1996, F.C. Sun Z.Q. Sun [1] has used the adaptive fuzzy system as an adaptive approximator for robot nonlinear dynamics. A new adaptive fuzzy controller based on sliding mode is proposed in this paper for the robot control of trajectory tracking. The main contributions of the paper include (1) proving that the fuzzy systems using the representative point and its derivative as inputs can approximate the plant nonlinear dynamics in the neighborhood of the switching hyper plane; (2) presenting a new control scheme based on sliding mode for the trajectory tracking control of robot with unknown nonlinear dynamics .

In 1994, Chung-Chun Kung and Chia-Chang Liao [2] have proposed the fuzzy-sliding mode controller design for tracking control of non-linear system. The fuzzy sliding mode control can decrease the chattering phenomenon and decrease the sensitivity to plant uncertainties in the hitting phase of conventional sliding mode control.

In 2002, Chung Chun Kung, Tung-Yun Kao, and Ti-Hung Chen [3] has proposed the adaptive fuzzy sliding mode controller design. The distance-based fuzzy sliding mode controller (D-FSMC) design method is adopted. The stability of the suggested control system is proved via Lyapunov stability theorem.

In 2003, Yuzheng Guo and Peng-Yung Woo [4] proposed the an adaptive fuzzy sliding mode controller for robotic manipulators. The stability and the convergence of the overall system are proved by the Lyapunov method. It is a good solution to the chattering problem in the classical sliding mode control. It is also noticed that the chosen parameters of the controller have impact on the system performance.

In 2010 , T. C. Kuo [5] has designed the adaptive fuzzy controller for robotic manipulators with sliding mode control. This method is proposed for three axis SCARA manipulator. It possesses the advantage of adaptive control, fuzzy control and sliding mode control. Based on the concept of sliding mode fuzzy rules are developed adaptation method to alleviate the input chattering effectively by using developed adaptation laws. The stability of three axis SCARA manipulator is guaranteed by using lyapunov method. This method proposes the adaptive fuzzy sliding mode control method for trajectory control of a three link robot manipulator.

In 2013, S. Barghandan and M. A. Badamchizadeh [6] has proposed the new method for Adaptive Fuzzy Sliding Mode Controller (AFSMC) for a quadrotor helicopter and then this controller is developed by Parallel Fuzzy System (AFSMCP). Because oscillations in input signal and external disturbances, weights vector of fuzzy system may have unwanted changes and even it can be drifted to very large amounts. To eliminate of undesirable increases of weight vector while the adaptation law is being proceed, a parallel fuzzy system is used in addition of main fuzzy system. This fuzzy system controlled the speed and variation rate of main fuzzy system. In this technique, weights vector of main fuzzy system will be forced to follow the consequent weights vector of the parallel fuzzy system [6].

3.MODELLING OF PUMA 560 ROBOT

3.1 Robotic Variables and Coordinate System

Fig. 1 shows the structure of PUMA 560 robot, which holds the arrangement of six revolute joints. The middle line of the trunk line L_1 concurs with the axis of the joint 1. Accordingly, the measurement regarding the angle of the joint 1, θ_1 begins from the positive y-axis, that is in the counter clockwise direction. Regarding the joint 2, the respective axis is assigned to be perpendicular to and converges the axis of joint 1. In addition, it concurs with the middle line of the shoulder. In general, the shoulder is considered to be an offset, with length b_1. The measurement of the particular length is among the upper arm and the trunk. When θ_1 equivalent to zero, the respective offset is parallel to the x-y plane and is in the direction of the negative x-axis. Around the joint 2, the upper arm and link L_2 get revolved, at an angle of θ_2 .

3.2 Robotic Model

The representation of the dynamics of a serial n-link robot is given in Eq. (1) where u indicates the joint displacements in $n \times 1$ vector, $\dot{u}$ indicates the joint velocities in $n \times 1$ vector, τ indicate the torque of the actuators, in $n \times 1$ vector, $M(u)$ indicates the symmetric positive definite inertia matrix in $n \times n$ vector, $c(u, \dot{u})$ indicate the torques of centripetal and Coriolis in $n \times 1$ vector and $g(u)$ indicates the torque of the gravitation in $n \times 1$ the vector. Moreover, $g(u)$ is generated as the gradient of the potential energy $U(u)$, due to gravity.

$$M(u)\ddot{u} + c(u, \dot{u}) + g(u) = \tau \qquad (1)$$

Assume that the joints of robot are correlated along with the revolute joints. Let u_d be the necessary joint positions, u_d is considered as the function of the double differentiable vector. The actuator torque is approximated by introducing the control issu so that Eq. (2) is accomplished that promotes the suitable control aim.

$$\lim_{t \to \infty} u(t) = u_d(t) \qquad (2)$$

The current simulation considers the DOF PUMA-560 robot, with the arrangement of six joints. In addition based on [33], the kinematical and dynamical properties of the arm are established. The motors of PUMA are provided with commercially applicable DC motors. Therefore, the comparison regarding the power and size of the PUMA motors delivers the electrical parameters of the motors.

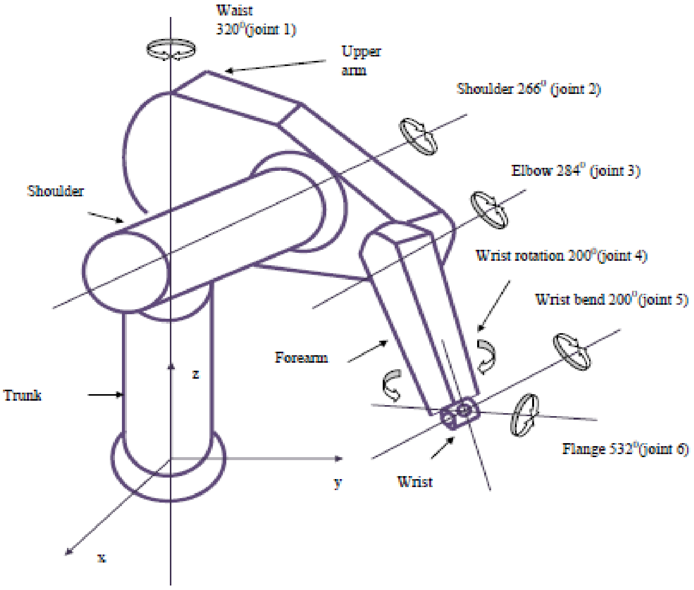


Figure1. Structure of PUMA 560 robot arm

4. DESIGN OF ADAPTIVE FUZZY SLIDING MODE CONTROLLER FOR ROBOT MANIPULATOR

4.1 Proposed Controlling Scheme

The architecture [15] of the controlling scheme based on the adaptive fuzzy system is shown in fig. 2.The adopted approach is introduced to fine-tune the joint angles of the "PUMA 560 robot arm". The proposed simulation model is developed to tune the joint angles of the PUMA 560 robot arm. Here, the actual feedback is generated from the real PUMA 560 system, which is connected to the equivalent control law generator. In addition, the required actual feedback and trajectory are exploited to calculate the differential error function (DE) and error function (E). To the next, the sliding surface generator generates the activating signal based on the computed error function. Meanwhile, the sliding mode constants are adjusted by the proposed adaptive fuzzy system with a meta-heuristic algorithm SAGWO algorithm [11], which can further produce the joint angle as in the fixed format with reduced error.

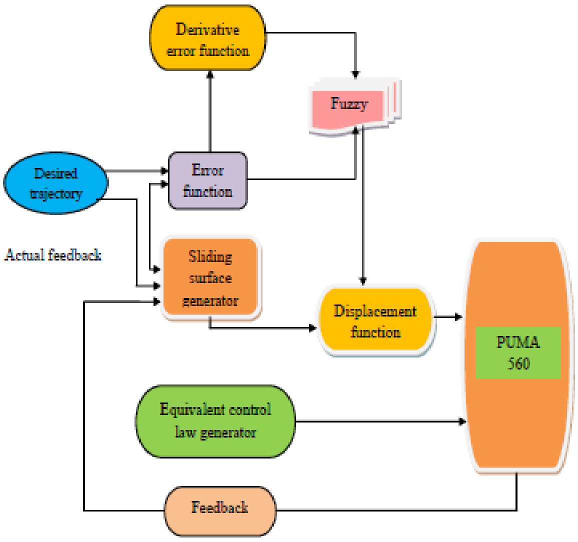


Figure 2. **Architecture of adaptive fuzzy based SMC control scheme**

To the fuzzy system, two inputs such as E and DE are applied. As per the limits of the given inputs, they are assigned as Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB), Negative Small (NS), Negative Medium (NM) and Negative Big (NB). Here, the limits of Z, PS, PM, NS and NM are based on the triangular membership function and the limits PB and NB are based on the trapezoidal membership function. The fuzzy system produces the related rules with the aforementioned input confines that are regarded as the constants of sliding mode [10][19]. Thus, the produced sliding mode variables are entirely dependent on exploited *E* and *DE*. Here, Table 1 portrays the sliding mode variables or rules produced by the fuzzy system.

Table 1. Rules or SMC constants generated by fuzzy system

E/DE	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

The demonstration of the fuzzy membership function is shown in fig. 3.

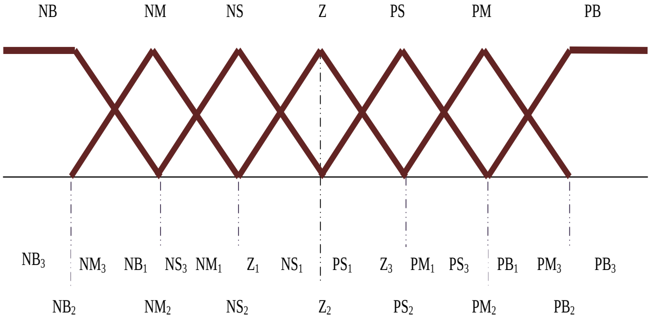


Figure 3. **Demonstration of fuzzy membership function**

Meanwhile, the triangular membership function is represented in Eq. (3), where r refers to the lower limit, s refers to the upper limit, t indicates some value and x indicates the desired variable, where $r < t < s$. Likewise, the representation of the trapezoidal membership function is shown in Eq. (4), where u and v indicates the lower and upper support limit, where $r < u < v < s$. The bounds of membership function for SMC is shown in Table II.

$$\mu_1(x) = \begin{cases} 0, & x \le r \\ \dfrac{x-r}{t-r}, & r < x \le t \\ \dfrac{s-x}{s-t}, & t < x < s \\ 0, & x \ge s \end{cases} \tag{3}$$

$$\mu_2(x) = \begin{cases} 0, & (x < r)\, or\, (x > s) \\ \dfrac{x-r}{u-r}, & r \le x \le u \\ 1, & u \le x \le v \\ \dfrac{s-x}{s-v}, & v \le x \le s \end{cases} \tag{4}$$

Table 2. Bounds of membership function for SMC

x	**r**	**t**	**s**	**u**	**v**
NM	NB_1	$(NB_2$-$NB_1)/2$	NB_2	-	-
NS	NM_1	$(NM_2$-$NM_1)/2$	NM_2	-	-
PS	PM_1	$(PM_2$-$PM_1)/2$	PM_2	-	-
PM	PB_1	$(PB_2$-$PB_1)/2$	PB_2	-	-
NB	-	-	-	NB_1	NM_2
PB	-	-	-	PM_2	PB_1

4.2 Adaptive Membership Function using Grey Wolf Optimization

Fundamentally, the membership function is defined as a “curve that defines how each point in the input space is mapped to a membership value between 0 and 1”. The output of fuzzy produces a certain membership function with the produced rules that creates more error according to the traditional fuzzy dependent SMC [31]. As a result, SAGWO model is suggested here to vary the membership function adaptively that have to reduce the error among the desired and actual value.

GWO algorithm [32] is a recent meta- heuristic algorithm that operates depending on the principle behind the hunting characteristics of grey wolves, for catching the prey. Accordingly, three wolves namely α , β and δ holds the role of hunting the corresponding preys. The pattern of hunting is dependent on 3 phases that comprise of (a) tracking, (b) following and (c) catching the prey. On considering the diverse wolves, α is allocated as the leader of the entire wolves that takes the decision concerning sleeping, resting time and hunting of wolves. In addition, the second and third level wolf β and δ aids the leader to take the required decisions. On the other hand, a wolf termed ω is allowed only for eating. Fig. 4 illustrates the solution encoding constraints of SAGWO model, in which J denotes the collective solution vector to the GWO.

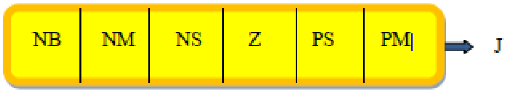


Figure 4. Solution encoding

Thus the membership function after integrating the fuzzy system with the GWO algorithm is collectively represented as in Eq. (5) where J indicates the solution vector to the GWO as per fig. 4.

$$\mu = \mu(J) \tag{5}$$

The objective function of the proposed SAGWO based SMC in PUMA 560 robotic arm is expressed in Eq. (6), which is the error between the actual and the desired joint angles. In eq. (6), θ_i^D indicates the desired joint angle and θ_i^A indicates the actual joint angle. The formulation for the desired joint angle is shown in Eq. (7), where ε indicates the control signals from SMC and K^{fuzzy} indicates the constant determined by the fuzzy system. Here, the desired joint angle is determined based the generated control signals from SMC, which get varied. The evaluation of control signal is portrayed in Eq. (8), where ε_{eq} and ε_{sw} specifies the equivalent and continuous part of SMC respectively, expressed in Eq. (9) followed by Eq. (10), s_i indicate the switching boundary.

$$E\Big|_{t=t^{\max}} = \sum_{i=1}^{3} \left|\theta_i^D(t) - \theta^A(t)\right| \tag{6}$$

$$\theta^D = \varepsilon\left(K^{fuzzy}\right) \tag{7}$$

$$\varepsilon = \varepsilon_{eq} + \varepsilon_{sw} \tag{8}$$

$$\varepsilon_{sw} = -K^{fuzzy}\, satf\,(x_i) \tag{9}$$

$$satf\,(x_i) = \begin{cases} +1, & if \quad f(x_i) > s_i \\ \dfrac{f_i}{s_i} & if \quad f(x_i) \le s_i \\ -1, & if \quad f(x_i) < s_i \end{cases} \tag{10}$$

Therefore, the control waveform from SMC is produced dependent on the fuzzy rules as given in Table 1 that further evaluates the optimal joint angle. To the next, it adaptively adjusts the determined joint angle by the SAGWO algorithm. The encircling pattern of grey wolves is indicated in Eq. (11) in which C and H indicates the coefficient vectors, J_P refers to the position vector of prey, J refers to the grey wolves position, and t refers to the present iteration. Furthermore, the formulation of the vectors C and H are expressed in Eq. (13) and Eq. (14) where a denotes a component, that diminished from the value 2 to 0 and r_1 r_2 indicates the random vectors which are uniformly distributed between [0, 1].

$$K = \left| H \cdot J_p(t) - J(t) \right| \tag{11}$$

$$J(t+1) = J_p(t) - C \cdot K \tag{12}$$

$$C = 2a.r_1 - a \tag{13}$$

$$H = 2 \cdot r_2 \tag{14}$$

Furthermore, the adopted SAGWO model adapts the value of *a* dependent on the variation in function. The SAGWO algorithm frames the component a as in Eq. (15), where τ denotes the change in the fitness function. The representation of τ is denoted in Eq. (16) where $f(t-1)$ specifies the previous iteration and $f(t)$ denotes the present iteration. However, during the first iteration, $\tau = 1$.

$$a = \left(2 - 2 \times \frac{1}{Maximum \quad iteration} \right) \times \tau \tag{15}$$

$$\tau = \frac{f(t-1) - f(t)}{f(t-1)} \tag{16}$$

Therefore the hunting characteristics of grey wolves are attained from Eq. (17) to Eq. (22) which provides the respective position to each wolf. Eventually, the Eq. (23) portrays the update position depending on the position of whole wolves.

$$K_\alpha = \left| C_1 \cdot J_\alpha - J \right| \tag{17}$$

$$K_\beta = \left| C_2 \cdot J_\beta - J \right| \tag{18}$$

$$K_\delta = \left| C_3 \cdot J_\delta - J \right| \tag{19}$$

$$J_1 = J_\alpha - C_1 \cdot (K_\alpha) \tag{20}$$

$$J_2 = J_\beta - C_2 \cdot (K_\beta) \tag{21}$$

$$J_3 = J_\delta - C_3 \cdot (K_\delta) \tag{22}$$

$$J(t+1) = \frac{J_1 + J_2 + J_3}{3} \tag{23}$$

5. RESULTS AND DISCUSSION

5.1 Experimental Procedure

The basic Simulink model of the SAGWO-FSMC is shown in fig. 5, where the SAGWO block is broadly modelled in fig. 6. The proposed Adaptive Fuzzy SMC scheme that adopts the fuzzy model to support the SMC to control the robotic manipulator was simulated in MATLAB, and the outcomes were attained. The count of iteration was fixed as 100. To the next of the current experiment implementation, its performance is compared with the conventional experimental models like SMC[16], FSMC[34], and GWO-SMC[32] to validate its effectiveness.

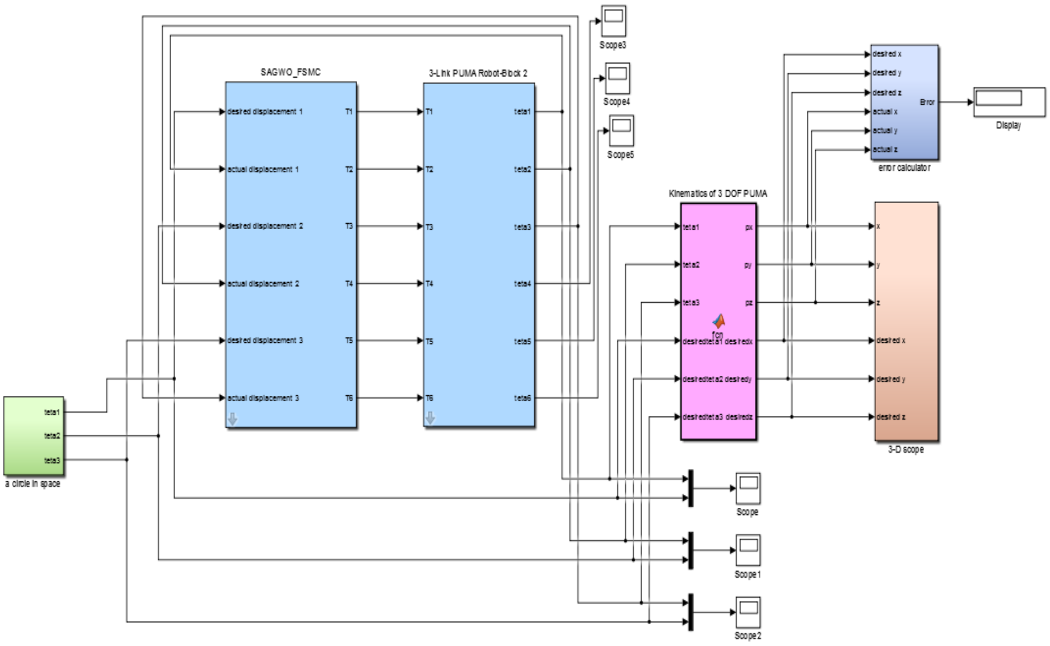


Figure 5. **Simulink model of SAGWO-FSMC**

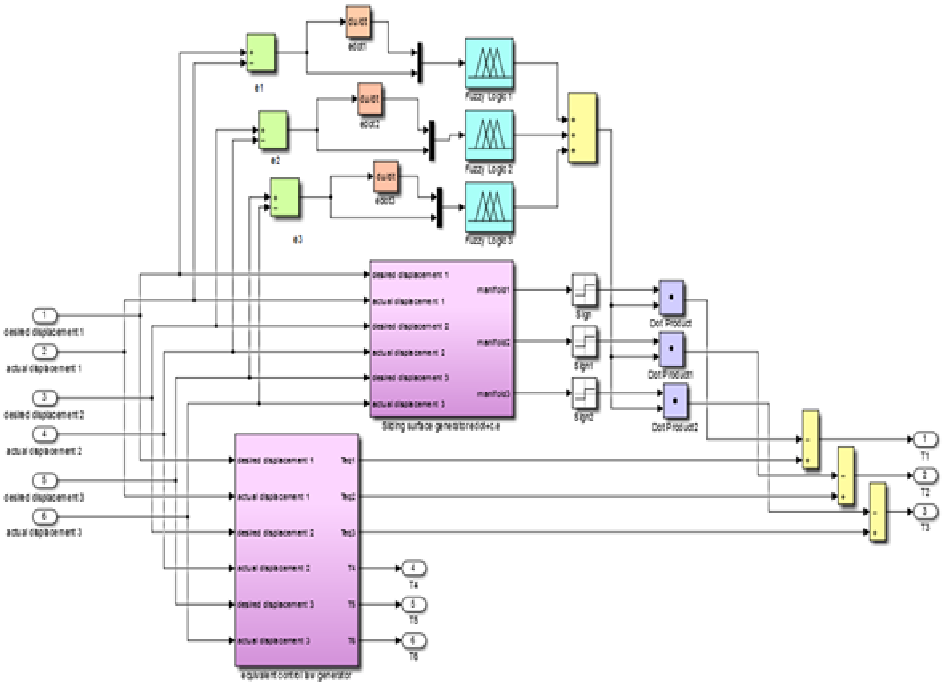
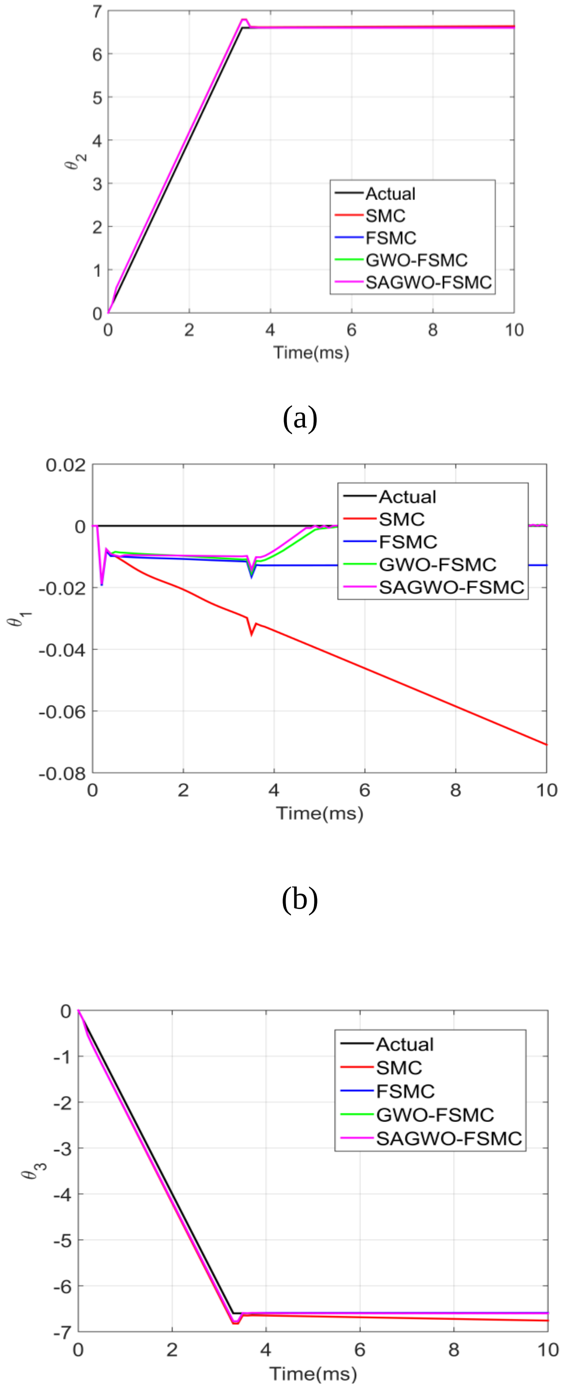


Figure 6. **Simulink model of SAGWO block**

5.2 Analysis on Angles

The analysis was limited to 10 ms and the movement of joint angles to be controlled were observed. On comparing the actual joint angle θ_1 with the desired θ_1 as shown in Fig. 7(a), the performance of SAGWO-FSMC is 1%, SMC is 3%, FSMC and GWO-FSMC is 1.9% varied from the desired angle θ_1. Thus SAGWO-FSMC model resembles the desired model than the conventional GWO-FSMC in controlling θ_1. Likewise, from the analysis on joint angle θ_2 as shown in Fig. 7(b), the actual θ_2 of SAGWO-FSMC is 4.41% deviated from the desired θ_2, which is better than the other models. Furthermore, the actual θ_3 of SAGWO-FSMC is 4.41% deviated from the desired θ_3, as given in Fig. 7(c). Therefore, the proposed SAGWO-FSMC controls the joint angles that exhibit high correlation with the desired joint angles and so it records the superiority over the conventional SMC methods.



(a)

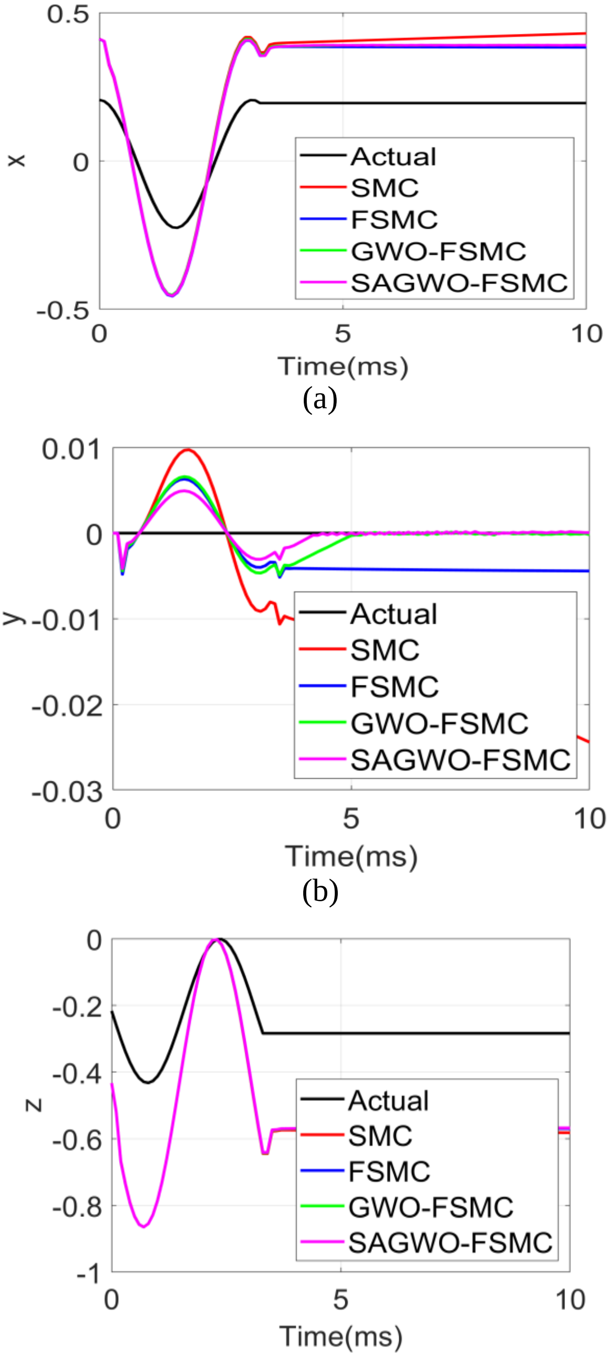
(b)

(c)

Figure 7. **Analysis on three angles of joints such as (a) θ_1 (b) θ_2 and (c) θ_3 with time**

5. 3 Impact of External Disturbance

The graphical demonstration of the examination on three displacements namely, *x y z* with time when applying external disturbance, is revealed in Fig. 8. From Fig. 8(a), at 10ms, the actual value of displacement *x* is 0.23, while the SMC has attained a displacement of 0.4, FSMC has attained a displacement of 0.3, and GWO-FSMC has attained a displacement of 0.3 and the proposed SAGWO-FSMC has attained a displacement of 0.29. Likewise, from Fig. 8(b), at 2ms, the actual value of displacement *y* is 0, while the SMC has attained a displacement of 0.01, FSMC has attained a displacement of 0.005, and GWO-FSMC has attained a displacement of 0.005 and the proposed SAGWOFSMC has attained a displacement of 0.004. In addition, from Fig. 8(c), at 2ms, actual value of displacement *z* is 0, while the SMC has attained a displacement of 0.01, FSMC has attained a displacement of 0.005, and GWO-FSMC has attained a displacement of 0.005 and the proposed SAGWOFSMC has attained a displacement of 0.004. Therefore, the proposed SAGWO-FSMC is found to be adjacent to the actual value, thus showing the superiority of the presented scheme.



(a)

(b)

(c)

Figure 8. Impact of external disturbance on three displacements namely, (a)X, (b)Y and (c) Z

6. CONCLUSION

This paper proposes an adaptive fuzzy sliding mode control method of robotic manipulator like PUMA 560 robotic arm. Here, adaptive SMC was executed for the robotic manipulator on concerning the external disturbances. In general, a system model was not possible to combine with the operation of SMC every time. Therefore, FIS was deployed in this research work to substitute the system model. Here, the experiment was performed based on two stages. The accurate features from the system model beneath a variety of samples were attained in the initial phase to indicate the robotic manipulators, while the attained features were allocated as fuzzy rules. On the contrary, adaptive fuzzy membership function was used to determine the derived fuzzy rules in the second stage, using the SAGWO algorithm. On the contrary, adaptive fuzzy membership function was used to determine the derived fuzzy rules in the second stage, using the SAGWO algorithm. To the next, the performance of the SAGWO-FSMC was compared with the desired experimental model and the conventional methods like SMC, Fuzzy SMC (FSMC) and GWO-SMC. Thus the experimental analysis has revealed the superior performance of SAGWO-FSMC, in tuning the optimum joint angles in the robotic manipulator. The sliding mode variables are tuned by the adopted adaptive fuzzy system using an improved meta-heuristic SAGWO algorithm that can further generate the joint angle with minimized error. Thus fine-tuning of the joint angles of the "PUMA 560 robot arm" is achieved. It is a good solution to the chattering problem in the classical sliding mode control. It is also noticed that the chosen parameters of the controller have impact on the system performance.

[1]. F.C. Sun, Z.Q. Sun and G Feng," Design of Adaptive Fuzzy Sliding mode controller for robotic manipulator" IEEE, 1996.
[2]. Chung-Chun Kung and Chia-Chang Liao," Fuzzy-Sliding Mode Controller Design For Tracking Control of Non-Linear System" Preceding of American Control Conference Baltimore, Maryland June 1994.
[3]. Chung Chun Kung, Tung-Yun Kao, and Ti-Hung Chen," Adaptive Fuzzy Sliding Mode Controller Design" 2002, IEEE.
[4]. Yuzheng Guo and Peng-Yung Woo, " An Adaptive Fuzzy Sliding Mode Controller for Robotic Manipulators" IEEE Transactions on Systems, and Cybernetics-Part A: Systems and Humans, Vol. 33, No. 2, March 2003
[5]. T. C. Kuo, B. W. Hong, Y. J. Huang, and C. Y. Chen," Adaptive fuzzy controller design for robotic manipulator with sliding mode control." 2008 IEEE
[6]. S. Barghandan and M. A. Badamchizadeh," A New Approach for Designing Robust Adaptive Fuzzy Sliding Mode Controller"2013, IEEE
[7]. Wei-Song Lin, and Chun-Sheng Chen," Adaptive Fuzzy Sliding Mode Controller Design For Nonlinear MPMO Systems" IEEE
[8]. Q. P. Ha, Q. H. Nguyen, D. C. Rye and H. F .Durrant-Whyte," Fuzzy Sliding-Mode Controllers with Applications" IEEE transaction on industrial electronics, volume no 48 February 2001
[9]. Tri V.M. Nguyen, Hung T. Nguyen and Q.P. Ha," Sliding Mode Neural Controller for Nonlinear Systems with Higher-Order and Uncertainties" Proceedings of the 2004 IEEE Conference on Robotics, Automation and Mechatronics Singapore, 1-3 December, 2004
[10]. Chih-Min Lin, Senior Member, IEEE, Te-Yu Chen, Wei-Zhe Fan and Yueh-Feng Lee," Adaptive Fuzzy Sliding Mode Control for a Two-Link Robot", 2005 IEEE International Conference on Robotics and Biomimetics
[11]. Sunil C.Kalshetti, S.K.Dixit,"Self-adaptive grey wolf optimization based adaptive fuzzy aided sliding mode control for robotic manipulator", Control and Cybernetics, Vol.47 2018,
[12]. Feng Qiao Quanmin Zhu, Alan Winfield, Chris Melhuish and Lifeng Zhang," Indirect Fuzzy Adaptive Control of Robotic Manipulator Based on Sliding Mode Scheme" Proceedings of the 2007 IEEE International Conference on Mechatronics and Automation August 5 - 8, 2007, Harbin, China
[13]. Juntao Fei," A Class of Adaptive Sliding Mode Controller with Integral Sliding Surface" Proceedings of the 2009 IEEE International Conference on Mechatronics and Automation August 9 - 12, Changchun, China
[14]. H.J. Shi, L.F. Qian, Y.D. Xu an d L.M. Chen," Fuzzy Moving Fast Terminal Sliding Mode Control for Robotic Manipulator" Proceedings of the 2012 IEEE International Conference on Robotics and Biomimetics December 11-14, 2012, Guangzhou, China
[15]. Sunil C.Kalshetti , S.K.Dixit," Adaptive Fuzzy Sliding Mode Controller for Robot Manipulator: Effect on External Interferences", International Journal of Innovative Technology and Exploring Engineering ,Volume 9, November 2019
[16]. Nabanita Adhikary, Chitralekha Mahanta, "Sliding mode control of position commanded robot manipulators", Control Engineering Practice, vol. 81, pp. 183-198, December 2018.
[17]. Abbas Karamali Ravandi, Esmaeel Khanmirza, Kamran Daneshjou, "Hybrid force/position control of robotic arms manipulating in uncertain environments based on adaptive fuzzy sliding mode control", Applied Soft Computing, vol. 70, pp. 864-874, September 2018.
[18]. M. Vijay, Debashisha Jena, "PSO based neuro fuzzy sliding mode control for a robot manipulator", Journal of Electrical Systems and Information Technology, 11 October, 2016.
[19]. Mondal, Chitralekha Mahanta, "Adaptive second order terminal sliding mode controller for robotic manipulators", Journal of the Franklin Institute, vol. 351, no. 4, pp. 2356-2377, April 2014.
[20]. Kali, Maarouf Saad, Khalid Benjelloun, Abdelilah Fatemi, "Discrete-time second order sliding mode with time delay control for uncertain robot manipulators", Robotics and Autonomous Systems, vol. 94, pp. 53-60, August 2017.
[21]. Mohd Salim Qureshi, Pankaj Swarnkar, Sushma Gupta, "A supervisory on-line tuned fuzzy logic based sliding mode control for robotics: An application to surgical robots", Robotics and Autonomous Systems, vol. 109, pp. 68-85, November 2018.
[22]. Luis Gracia, J. Ernesto Solanes, Pau Muñoz-Benavent, Alicia Esparza, Josep Tornero, "Cooperative transport tasks with robots using adaptive non-conventional sliding mode control", Control Engg. Practice, vol. 78, pp. 35-55, September 2018.
[23]. M. Vijay, Debashisha Jena, "Backstepping terminal sliding mode control of robot manipulator using radial basis functional neural networks", Computers & Electrical Engineering, vol. 67, pp. 690-707, April 2018.
[24]. Manjusha Bhave, S. Janardhanan, L. Dewan, "Configuration Control of Planar Underactuated Robotic Manipulator using Terminal Sliding Mode", IFAC-PapersOnLine, vol. 49, no. 1, pp. 148-153, 2016.
[25]. J. Ernesto Solanes, Luis Gracia, Pau Muñoz-Benavent, Jaime Valls Miro, Josep Tornero, "Human-robot cooperation for robust surface treatment using non-conventional sliding mode control", ISA Transactions, vol. 80, pp. 528-541, Sept. 2018.
[26]. Zhiqiang Ma, Guanghui Sun, "Dual terminal sliding mode control design for rigid robotic manipulator", Journal of theFranklin Institute, 4 February 2017.
[27]. Minh-Duc Tran, Hee-Jun Kang, "Adaptive terminal sliding mode control of uncertain robotic manipulators based on local approximation of a dynamic system", Neurocomputing, vol. 228, pp. 231-240, 8 March 2017.
[28]. Mehran Rahmani, Ahmad Ghanbari, Mir Mohammad Ettefagh, "Hybrid neural network fraction integral terminal sliding mode control of an Inchworm robot manipulator", Mechanical Systems and Signal Processing, vol. 80, pp. 117-136, 1 Dec.2016.
[29]. Magdy M. Abdelhameed, "Enhancement of sliding mode controller by fuzzy logic with application to robotic Mechatronics, vol. 15, no. 4, pp. 439-458, May 2005.
[30]. Seong Ik Han, Jangmyung Lee, "Finite-time sliding surface constrained control for a robot manipulator with an unknown deadzone and disturbance", ISA Transactions, vol. 65, pp. 307-318, November 2016.

[31]. Srinivasan Alavandar and M.J. Nigam, "Fuzzy PD + I control of a six DOF robot Manipulator " Industrial Robot: An International Journal, vol. 35, no.2, pp. 125–132, 2008.
[32]. Seyedali Mirjalili, Seyed Mohammad Mirjalili, and Andrew Lewis, "Grey Wolf Optimizer" Advances in Engineering Software, vol. 69, pp. 46–61, March 2014.
[33]. B. Armstrong, O. Khatib, and J. Burdick, "The explicit dynamic model and inertial parameters of the PUMA 560 arm," Proceedings. 1986 IEEE International Conference on Robotics and Automation, pp. 510-518, 1986.
[34]. Ruey-Jing Lian, "Enhanced adaptive grey-prediction self-organizing fuzzy sliding-mode controller for robotic systems", Information Sciences, vol. 236, pp. 186-204, 1 July, 2013.