Design And Experimental Validation Of Adaptive Fuzzy Sliding Mode Controller For Robotic Manipulators

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Abstract: Robotic manipulators are multi-input multi-output (MIMO), 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. Proposed adaptive fuzzy sliding mode controller based on fuzzy logic controller integrated with sliding mode framework is used to provide the adaptation in order to eliminate the high frequency oscillation and adjust the linear sliding surface slope in presence of many different disturbances and to get the best coefficients for the sliding surface. Finally, the proposed methodology can be applied to a three-link robot manipulator including model uncertainty and external disturbances as a case study.

Key words: Sliding Mode Control; Robot manipulators; Controller; Adaptive , Fuzzy, Gray wolf optimization, External Disturbances

Introduction

In general, robotic manipulators are widely applied in the industrial environment for executing dangerous or routine works. Robotic manipulators(RM) have been encounter nonlinearities 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 [1]. The trajectory tracking accuracy is the most important function of an industrial manipulator. Thus, a robot motion tracking control is one of the challenging problem 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 [2]. 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 and link flexibility, actuator dynamics, friction, sensor noise, and unknown loads [3].

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, sliding mode control, and fuzzy control [4]. 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 is a major drawback of sliding mode control. Hence boundary layer is used to avoid chattering phenomenon [5].

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. 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 [6]. 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. 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 [7].

Sliding Mode Controller has been widely applied to various types of non-linear systems. 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. Moreover, in order to achieve the non-chattering SMC, the sign 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 [8]. 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. However it should be noted that sometimes Fuzzy Logic Controller (FLC) is muchmore tranquiller [9]. 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 [10].

2. LITERATURE REVIEW

For Uncertain System, an Artificial Chattering Free on-line FSMC was developed by Sulaiman et al [11] in Robot Manipulator (RM). To project high performance nonlinear controller, an artificial chattering free AFSMC and request to uncertain RM was introduced in this study with the occurrence of hesitations. For robot manipulator, a typical free approximator on-line FSMC is introduced to extent an adequate performance. RM is extremely non-linear and an amount of factors are ambiguous. The main target is to design a typical free controller by means of both systematic and experiential prototypes.

A Strategy and Application of SMC was introduced by Zahra et al [12] for robotic manipulator. In the occurrence of hesitations, an examination of SMC and application to RM was introduced in this study to intend high performance nonlinear controller. An adaptive scheme and FLC is used to enhance the outcomes in SMC. Every single approach has included negative points by means of adding to the previous algorithm. A robot manipulator is nonlinear, and a quantity of factors are indeterminate. This investigation concentrates on relation among SMC which analyzed through several investigator.

Through Torque Control scheme, a Sliding Mode Fuzzy Control was introduced by Khashayar et al [13] for RM. In control science, the occurrence of uncertainties and control signal sliding are two most noteworthy challenges for the robot manipulator. For an n link robots, a new sliding fuzzy mode control scheme is introduced in this study. According to the projected sliding level and approximating part of system dynamics, the preparation of a novel equation for system dynamics has led to the law of sliding mode fuzzy control by means of adaptive fuzzy procedure. Through eliminating control signal sliding and overwhelming uncertainties, the performance of the closed-loop structure is enhanced. Using the Lyapunov's function, the diagonal stability of the projected control law is long-established.

For a two-link robot, the adaptive FSMC was developed by Lin [14]. With unknown nonlinear dynamics, an adaptive fuzzy SMC has been presented in this work for the robust trajectory tracing of MIMO control systems. Robustness is accomplished in this design. By the way of learning algorithm, the fuzzy controller is automatically adapted by the tuning mechanism. Through the Lyapunov stability principle, the global asymptotic stability of the algorithm is recognized.

For robotic manipulators, an adaptive FSMC was developed by Guo and Woo [15]. Through Lyapunov technique, the constancy and the conjunction of the entire structure is verified. In the classical SMC, it is a better solution to the issue of chattering. Moreover, it is considered that the designated components of the controller have influence on the network performance.

3. ADAPTIVE FUZZY SLIDING MODE CONTROLLER FOR PUMA 560 ROBOT

A. 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. In addition, owing to gravity $g(u)$ is produced as the potential energy gradient $U(u)$.

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

Let us consider the joints of the robot are linked together with the revolute joints. Here, u_d represents the required joint positions. Rather, u_d is assumed to be the double differentiable vector function. The actuator torque is approximated by introducing the control issu so that Eq. (2) is accomplished that promotes the suitable control aim.

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

The present simulation regards "DOF PUMA-560 robot", with the set up of six joints[16]. In addition based on dynamical and kinematical features of the arm are introduced. The motors of PUMA are provided with commercially applicable DCservo motors. Therefore, the comparison regarding the power and size of the PUMA motors delivers the electrical parameters of the motors.

B. Proposed System Model

Adaptive fuzzy sliding mode controller (AFSMC) is a controller that controls the uncertainties of non-linear systems without high-frequency switching. AFSMC helps to enhance tracking performance [17]. It is a widely used technique. It adjusts the SMC key parameters, in order to eliminate or minimize the chattering. AFSMC improves the system robustness and get rid of the parameter perturbation [18]. Overall framework of the proposed control scheme is shown in figure 1 and the structure of AFSMC is represented in figure 2 [19].

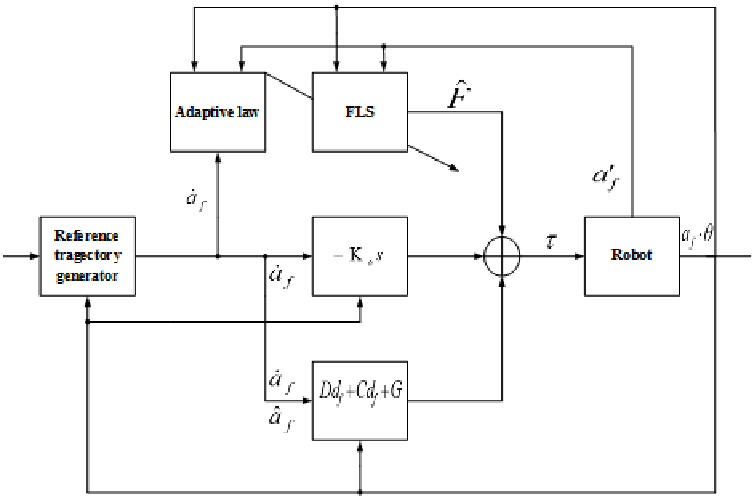

Figure 1. Overall framework of the proposed control scheme

C Design of an AFSMC

C1.1 Design of sliding surface

The error state can be represented as [20],

$$c_i = a_i - b_i \quad (3)$$

Where i =1, 2, 3 …

$$\mathrm{P}(c_1,t) = \mathrm{P}_a(a_1,t) - \mathrm{P}(c_1 + a_1,t) \quad (4)$$

$$\Upsilon() = \Upsilon_a(t,a) - \Upsilon_b(t,b) \quad (5)$$

The equations of error dynamic are:

$$\dot{c}_1 = c_2 \quad (6)$$

$$\dot{c}_2 = c_3 \quad (7)$$

$$\dot{c}_3 = -xc_3 - c_2 + \mathrm{P}(c_1,t) + \Upsilon(\cdot) - v \quad (8)$$

Standardized state space equations of error states can be found as,

$$\dot{c}_1 = c_2 \quad (9)$$

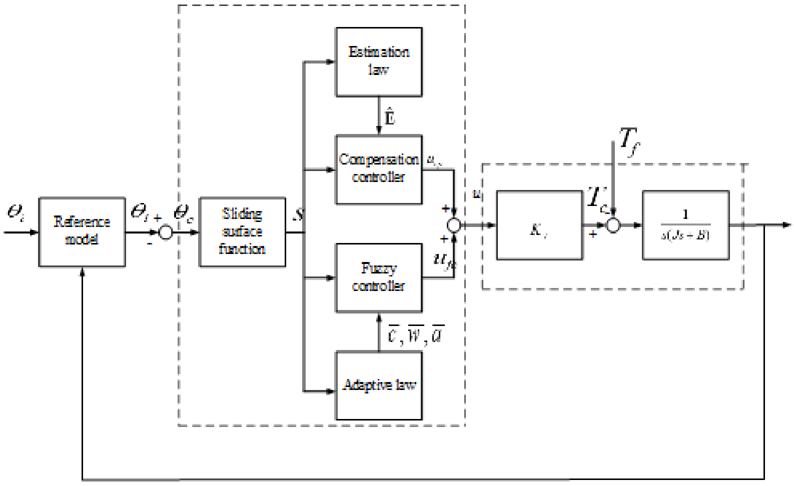

Figure 2. Structure of AFSMC.

$$\dot{c}_2 = c_3 \tag{10}$$

$$\dot{c}_3 = -xc_3 - c_2 + \mathrm{P}(c_1, t) + \mathrm{Y}(\cdot) - v = c_4 \tag{11}$$

$$c_4 = -xc_4 - c_3 + \mathrm{P}(c_1, t) + \dot{\mathrm{Y}}(\cdot) - \dot{v} \tag{12}$$

The sliding surface is given by,

$$u = c_4 - c_4(0) + \int_0^t \sum_{k=1}^{4} e_k c_k dt = 0 \tag{13}$$

Where $c_4(0)$ represents initial state of c_4 . Differential of the equation (13) can be written as,

$$\dot{c}_4 = -\sum_{k=1}^{4} e_k c_k \tag{14}$$

The following is the matrix that defines the error states in equation (14).

$$\dot{\underline{c}} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -e_1 & -e_2 & -e_3 & -e_4 \end{bmatrix} c = \mathrm{M}e \tag{15}$$

Where $\dot{\underline{c}} = [c_1 \quad c_2 \quad c_3 \quad c_4]^T$. c_j can be found by selecting the eigenvalues of M in which the characteristic polynomial

$$\mathrm{H}(c) = \dot{c}_4 + \sum_{k=1}^{4} e_k c_k \tag{16}$$

$H(c)$ is Hurwitz. Speed of the system response and eigen values are relative.

C 1.2 Design of adaptive SMC

The control law is designed as,

$$r = r_{eq} + r_{afz}(t) \tag{17}$$

Where r_{afz} represents the AFSMC and r_{eq} represents hitting control. Sliding surface, u and derivative of sliding function, $\dot{u}$ serves as the input to the fuzzy controller. Overall AFSMC is chosen as,

$$r_{afz} = \hat{\beta} F(\dot{u}, u) \tag{18}$$

Where $F(\dot{u}, u)$ indicates the functional characteristics of fuzzy linguistic decision schemes. $\hat{\beta}$ represents estimated value. The estimated error can be defined as,

$$\tilde{\beta} = \hat{\beta} - \beta \tag{19}$$

Estimation law is designed as,

$$\hat{\beta} = \gamma \left| F(\dot{u}, u) \right| \tag{20}$$

Where γ represents a positive constant. The reaching law can be determined as,

$$\dot{u} = -\hat{\beta} F(\dot{u}, u) \tag{21}$$

From equations (13) and (18),

$$\dot{u} = \dot{c}_4 + \sum_{k=1}^{4} e_k c_k = -\hat{\beta} F(\dot{u}, u) \tag{22}$$

and control input of slave system

$$v = \int_0^t \left[-x c_4 - c_3 + \mathrm{P}(c_1, t) + \Upsilon(\cdot) \right] dt + \int_0^t \left[\sum_{k=1}^{4} e_k c_k + \hat{\beta} F(\dot{u}, u) \right] dt \tag{23}$$

C. Proposed Controlling Scheme

Overall framework of the proposed control scheme is shown in fig. 1 and Structure of AFSMC is shown in fig. 2. The proposed simulation model is developed to tune the joint angles of the PUMA 560 robot arm[16[. Here, the actual feedback is generated from the real PUMA 560 system, which is connected to the equivalent control law generator. Further, the desired trajectory and the actual feedback are used to compute the error function (E) and the differential error function (DE). 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 self adaptive gray wolf optimization (SAGWO) algorithm[22][23][24], which can further produce the joint angle as in the fixed format with reduced error.

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.

With the above-mentioned input limits, the fuzzy system generates the corresponding rules, which is considered as the sliding mode constants. Therefore, the generated sliding mode constants are completely based on the applied E and DE . Accordingly, table 1 depicts the rules or the sliding mode constants generated by the fuzzy system.

Table 1. Rules OR SMC constants generated by fuzzy systems

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 figure. 3

Meanwhile, the triangular membership function is represented in Eq. (24), 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. (25), 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.

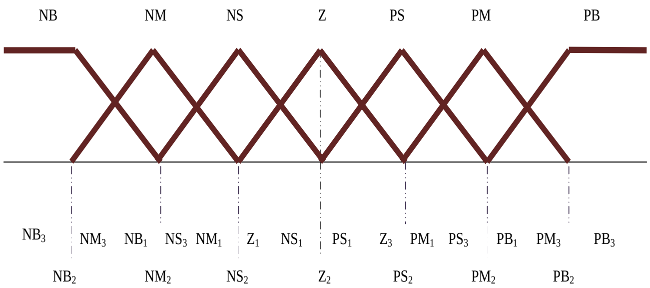

Figure.3 Demonstration of fuzzy membership function

$$\mu_1(x)=\begin{cases}0, & x\le r\\ \dfrac{x-r}{t-r}, & r<x\le t\\ \dfrac{s-x}{s-t}, & t<x<s\\ 0, & x\ge s\end{cases} \qquad (24)$$

$$\mu_2(x)=\begin{cases}0, & (x<r)or(x>s)\\ \dfrac{x-r}{u-r}, & r\le x\le u\\ 1, & u\le x\le v\\ \dfrac{s-x}{s-v}, & v\le x\le s\end{cases} \qquad (25)$$

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. RESULTS AND DISCUSSIONS

A. Experimental Procedure

This paper introduces a fuzzy system model that restores the system model. Mainly the proposed work helps to achieve the objectives. The optimization of each mechanism is used to determine the performance parameters of the proposed controller. This system includes a self-adaptive property into the GWO technique [21]. The SAGWO-FSMC[22][23] scheme helps the fuzzy model to support the SMC model in the robotic manipulator. It is stimulated based on MATLAB, and the output is obtained. To analyze the efficiency of the proposed method, it is compared with the conventional experimental technique such as SMC, FSMC, and GWO-SMC [20].

Figure 4 shows the basic Simulink model of the SAGWO-FSMC technique and the SAGWO block was modeled in figure 5. Simulink is a platform for designing that helps to system level design and verification. In this SAGWO-FSMC system, the required characteristics are acquired based on fuzzy rules. Then obtained fuzzy rules represent in the form of adaptive fuzzy membership functions. During the procedure establishment, the number of iteration assigned for this model is 100. Then the required parameters are set based on the algorithm. Then its performance is compared with known methods.

B. Results and Discussion

B 1.1 Convergence analysis

This Section discusses the results from the experiments on the proposed robotic controller. Fig. 6 shows the convergence analysis. As mentioned earlier, the objective function or the cost function of this experiment is to reduce the error between the actual and the desired value. The analysis compares the converging performance between the conventional GWO and the proposed SAGWO based FSMC approach. Here, the conventional GWO-FSMC [20] initiates from the value of 8×10^{-3} and converged at 4.4×10^{-3}. However, the proposed SAGWO-FSMC initiates from 8×10^{-3} and converged at 4.2×10^{-3}, which is relatively lesser than the GWO-FSMC.

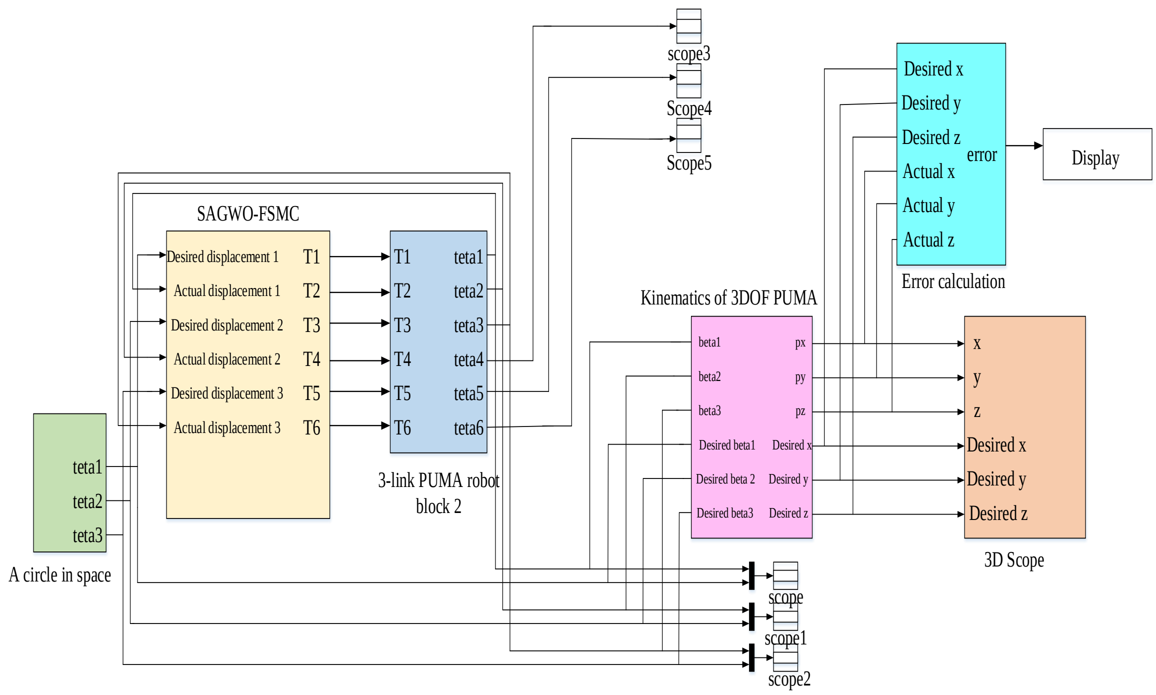

Figure 4: Simulink model of SAGWO-FSMC

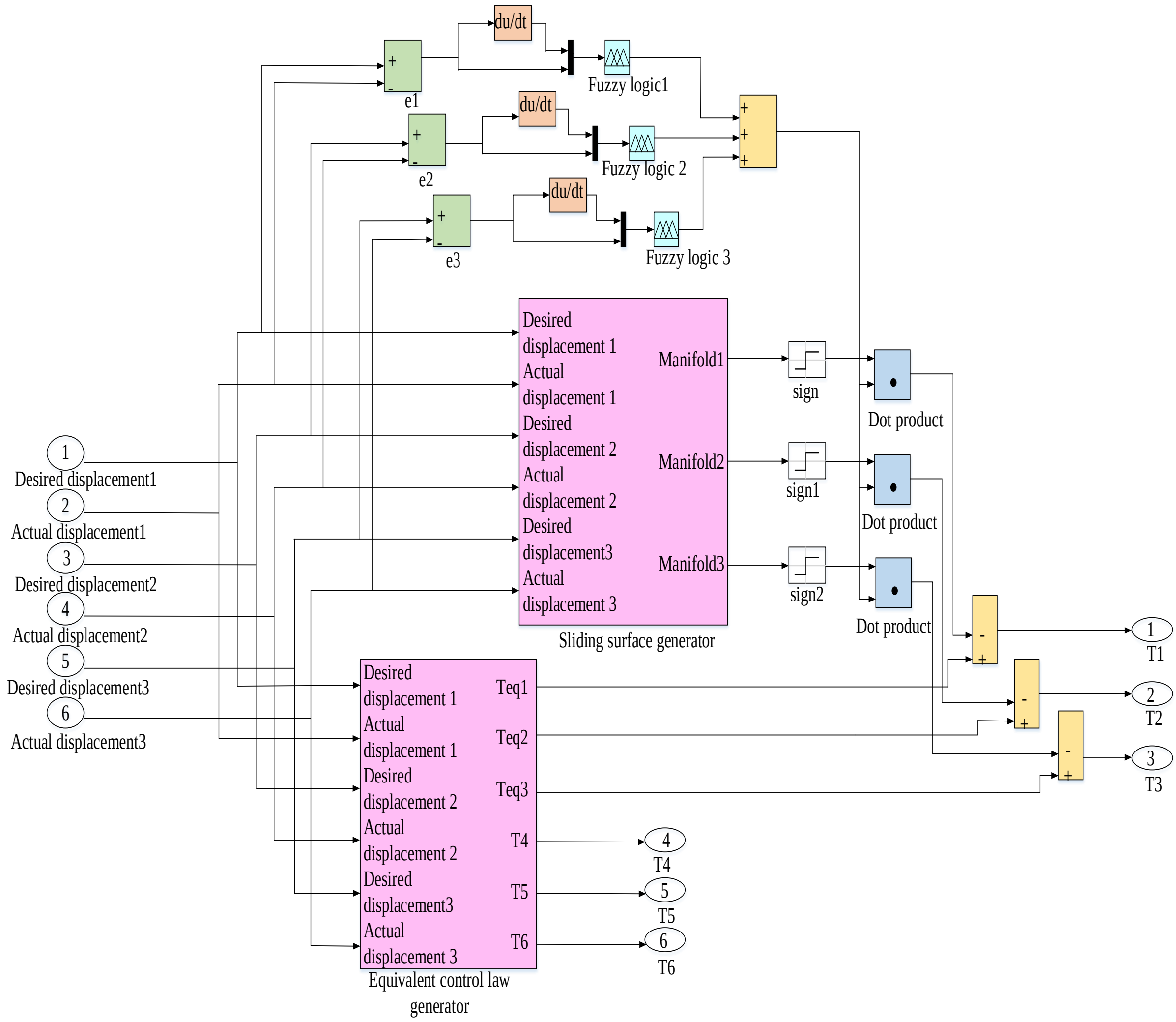

Figure 5: Simulink model of SAGWO block

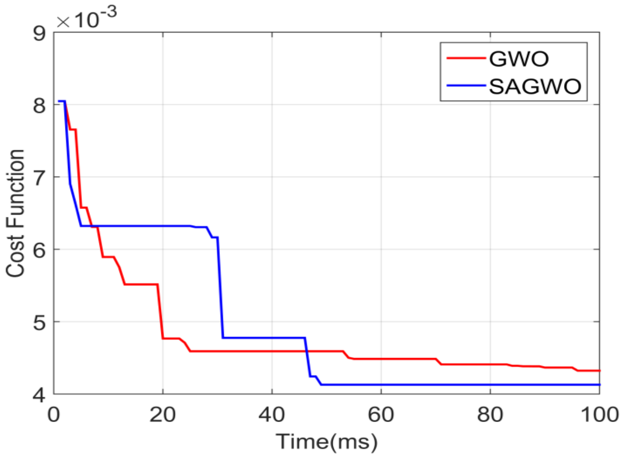

Figure 6.Convergence analysis

B 1.2 Computational Time Analysis:

The computational time analysis for the implemented SAGWO-FSMC based controller is given in table 3. Computational time is the length of time taken to perform the computational process. It is also called 'running time'.

Table 3: Analysis on computational time

Time	SMC	FSMC	GWO-FSMC	SAGWO-FSMC
0	0.33947	0.32275	0.32269	0.32143
1	0.4114	0.41088	0.41006	0.41169
2	0.083813	0.089249	0.085669	0.091279
3	0.32461	0.31499	0.31877	0.31384
4	0.35503	0.34445	0.34458	0.34307
5	0.35938	0.34471	0.34458	0.34283
6	0.36369	0.34469	0.34427	0.34263
7	0.36794	0.34468	0.34473	0.34245
8	0.37214	034465	0.34473	0.34229
9	0.37628	0.34464	0.34477	0.34216
10	0.38037	0.34458	0.34479	0.34204

From the table, the proposed SAGWO-FSMC method is 5.31% superior to SMC, 0.41% superior to FSMC, and 0.39% superior to the GWO-FSMC method at 0ms. Furthermore at 3ms, the proposed SAGWO-FSMC method is 3.32% better than SMC, 0.37% better than FSMC, and 1.55% better than the GWO-FSMC method. At 10ms, the SAGWO-FSMC model is 10.08% superior to SMC, 0.74% superior to FSMC, and 0.79% superior to GWC-FSMC method. Therefore it is proven that the computational time has been maintaining in the SAGWO-FSMC method. Therefore the performance achieved by the SAGWO-FSMC model meets the demand for desired performance.

B 1.2 Error Analysis:

The error analysis of adopted SAGWO-FSMC techniques shown in table 4. It includes the comparison between the proposed method and the conventional methods like SMC, FSMC, and GWO-FSMC. From the analysis, it is found that the proposed system performs well, compared with other techniques. The optimized membership functions are used for the fuzzy system.

Table 4: Error analysis of proposed method

Time (ms)	SMC	FSMC	GWO-FSMC	SAGWO-FSMC
1	0.083907	0.08509	0.085151	0.084797
2	0.082915	0.074572	0.074599	0.074599
3	0.085664	0.078341	0.07845	0.78137
4	0.015349	0.0080468	0.0043225	0.0041288
5	0.020738	0.0080224	0.00036686	0.0005326
6	0.02631	0.0080041	0.0001145	0.00003908
7	0.031954	0.0079878	0.00015332	0.00046102
8	0.037628	0.0079734	0.0002266	0.00039751
9	0.043308	0.0079607	0.00034445	0.00043008
10	0.048986	0.0079494	0.00042725	0.00036425
Mean	0.047676	0.029395	0.024416	0.024389

Conclusion

This paper proposes self adaptive gray wolf optimization fuzzy sliding mode controller for robotic manipulators like PUMA 560. In general, a system model was not possible to combine with the operation of SMC every time. Hence, fuzzy interference system was employed here to replace the system model. The performance of the SAGWO-FSMC was compared with the desired experimental model and the conventional methods like SMC, Fuzzy SMC 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. Finally, the valuable comparative analysis was done by validating the performance of proposed over conventional models while adding external disturbances and noise in the manipulator. Simulation results demonstrate that proposed model has a better performance than SMC and FSMC, because this controller can adapt itself to system parameter's changes and external disturbances. The main advantage of our controller is its ability to eliminate the effect of fluctuations in the transient response with less effort on the control law. Also our result shows that, the tracking error is about 8% whereas it is less than 3 to 4 % in our case. This controller is highly efficient and suppress the chattering effect. Thus, an outstanding performance of the system can achieved by using an adaptive fuzzy sliding mode controller.

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