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Optimal Fuzzy-FOPID, Fuzzy-PID Control Schemes for Trajectory Tracking of 3DOF Robot Manipulator

Worod Adris Shatnan [a*], *Muhanad D Hashim Almawlawe* [a], *Mustafa Abd AL-Aress Jabur* [b]

a *Electronic &Communication Department, Engineering College, University of Al-Qadisiyah, Al-Diwaniyah, Iraq.*

b *Computer Engineering Department, Imam Al-Kadhum College (IKC), Al- Diwaniyah, Iraq.*

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****Corresponding author:***

Worod Adris Shatnan

Electronic & Communication Department, Engineering College, University of Al-Qadisiyah, Al-Diwaniyah, Iraq.

Abstract: The present study explores the guidance of a robotic arm along a predefined path by implementing an optimal fuzzy fractional order PID controller-based control strategy. This method serves as a means to address the nonlinearity and unpredictability of the robotic manipulator, contingent upon the fuzzy logic controller's specifications and the employment of a clonal selection algorithm. The dynamic equation of the manipulator was considered as an initial point, followed by designing a fuzzy controller for this purpose. To validate the effectiveness of this approach, it was compared to other techniques, such as Fuzzy, Fuzzy-PID, and fuzzy-FOPID controllers, with PID and FOPID controller parameters optimized using clonal selection algorithms. Simulation results reveal that the fuzzy-FOPID variant outperformed other methods under varying load conditions and model uncertainties, using SIMULINK/MATLAB 2014a.

تصميم المسيطر الضبابي الامثل ومسيطرات اخرى لتتبع مسار روبوت

ورود أدريس شطنان [١]**، مهند ضياء هاشم المولوي** [١]**، مصطفى عبد العريس جبر** [٢]
[١] قسم الالكترونيك والاتصالات، كلية الهندسة، جامعة القادسية، العراق.
[٢] قسم هندسة تقنيات الحاسوب، كلية الامام الكاظم(ع)، العراق.

الخلاصة

تستكشف الدراسة الحالية توجيه ذراع روبوتية على طول مسار محدد مسبقا من خلال تنفيذ استراتيجية تحكم مثالية قائمة على وحدة تحكم PID ذات الترتيب الجزئي الغامض. تعمل هذه الطريقة كوسيلة لمعالجة اللاخطية وعدم القدرة على التنبؤ بالمناور الآلي ، بناء على مواصفات وحدة التحكم المنطقية الضبابية واستخدام خوارزمية الاختيار النسيلي. تعتبر المعادلة الديناميكية للمناور نقطة أولية ، تليها تصميم وحدة تحكم غامضة لهذا الغرض. للتحقق من فعالية هذا النهج ، تتم مقارنته بتقنيات أخرى ، مثل وحدات التحكم Fuzzy و Fuzzy-PID و fuzzy-FOPID ، مع معلمات وحدة التحكم PID و FOPID المحسنة باستخدام خوارزميات الاختيار النسيلي. كشفت نتائج المحاكاة أن متغير fuzzy-FOPID يتفوق على الطرق الأخرى في ظل ظروف تحميل مختلفة وشكوك النموذج، باستخدام SIMULINK / MATLAB 2014a.

الكلمات الدالة: نظام الاستدلال العصبي الضبابي التكيفي (ANFIS)، درجة الحرية (DOF)، وحدة التحكم المنطقية الضبابية، وحدة تحكم ضبابية نوع متناسب- مشتق- متكامل، مناور الروبوت.

1.INTRODUCTION

Acquiring a precise mathematical representation for the progression of both classical and contemporary control methodologies proves to be arduous, given that the manipulator could be a multivariable, non-linear, and interconnected dynamic system encompassing certain uncertainties. The fuzzy logic concept was chosen for creating controllers for robotic manipulators due to its successful application in numerous technical projects. As a mathematical description of the system is unnecessary for fuzzy logic control, the formula accounts for environmental variations throughout all operational processes [1, 2]. Numerous studies focused on designing various control schemes beneficial for controlling robot manipulators, such as the method used in Ref. [3,4]. The authors proposed a new robust tracking control scheme utilizing a variable structure compensator for controlling rigid robotic manipulators. The closed-loop control system exhibited exceptional resilience despite significant uncertain dynamics, ensuring that the output tracking error ultimately approached zero. In Ref. [5], Hamdi and Lachiver introduced an innovative fuzzy set control algorithm with simulation outcomes employed to govern a two-link manipulator. In Ref. [6], a fuzzy logic controller was designed for the trajectory tracking of a 2DOF robot manipulator based on integrating conventional control and fuzzy logic. In Ref. [7], an adaptive fuzzy controller was developed for robot manipulators. In Ref. [8], the authors presented an observer-based robust adaptive fuzzy tracking control for rigid robotic systems. This controller proved to be simple and computationally efficient, as it did not require knowledge of either the mathematical model or the parameterization of the robotic dynamics. In Ref. [9], a sophisticated fuzzy control strategy was developed for accurate path tracking in a three-link manipulator system. A new fuzzy terminal sliding mode controller (FTSMC) was designed for robotic manipulators [10]. In Ref. [11], the authors designed a stable adaptive fuzzy-based tracking control for robot systems. A study about an indirect AFNNC scheme and a direct AFNNC strategy for an n-link robot manipulator was presented in [12]. In Ref. [13], the authors designed a Fuzzy proportional integral derivative controller (FPID) for tracking a path of a three-degree of freedom (DOF) robot arm. GA was used to tune the proposed controller. For comparison, study other controllers were designed, such as PD, PID, and Fuzzy PID controls. ANFIS was designed for robot manipulator [14]. In Ref. [15], the authors designed an adaptive fuzzy control algorithm for the path tracking of a robot manipulator. Lyapunov theorem was utilized to investigate the stability condition of the robot manipulator. PID controller was designed and implemented for robotic manipulator in Ref. [16]. PD controller also was implemented for the same system. In Ref. [17], the author presented a thesis that dealt with modeling a six-degree-of-freedom robot manipulator and designing a fuzzy logic controller for path tracking of the robot manipulator. The performance of FLC was then compared with the PID controller. The comparison study proved that the FLC was more efficient than the PID controller. In Ref. [18], the authors designed an ANFIS Controller for a Robot Manipulator. They compared the result with PID and fuzzy controller. It was found that ANFIS was better than PID and fuzzy controller. An Optimal FLC was developed for a robot manipulator in Ref. [19]. In Ref. [20], the authors proposed a sliding mode control strategy based on PSO and ANFIS for path tracking control of a 3-DOF robot manipulator. In this study, an FLC for 3DOF robot manipulator path tracking was developed. For comparison, study fuzzy-PID and fuzzy-FOPID controllers were designed. This paper is structured as follows: Beginning with a brief literature review; Section 2 presents the dynamic model of the robot manipulator. Sections 3, 4, and 5 discuss the trajectory tracking control using fuzzy logic, Fuzzy-PID, and Fuzzy-FOPID controllers, respectively. Section 6 details the Clonal selection algorithm. Simulation results for all proposed controllers are demonstrated in Section 7, and Section 8 concludes the study.

2.THE ADVANCED ALGORITHM FOR ROBOTIC MANIPULATOR DYNAMIC

The dynamic motion equation for an n-link robotic manipulator is presented in Eq. (1) [21] as follows:

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}=U \qquad \textbf{(1)}$$

where q is the joint displacement vector, u is the applied joint torque vector, *M(q)* is the inertia matrix, and *C(q,q)* is the Coriolis and centrifugal vector, each of which was a 3×1 vector given in Eq.(2):

$$M(q)=\begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix};\ U=\begin{bmatrix} U_1 \\ U_2 \\ U_3 \end{bmatrix};\ q=\begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix};\ \dot{q}=\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix};\ \ddot{q}=\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \\ \ddot{q}_3 \end{bmatrix}$$

$$C(q,\dot{q})=\begin{bmatrix} C_{11}(q,\dot{q}) & C_{12}(q,\dot{q}) & C_{13}(q,\dot{q}) \\ C_{21}(q,\dot{q}) & C_{22}(q,\dot{q}) & C_{23}(q,\dot{q}) \\ C_{31}(q,\dot{q}) & C_{32}(q,\dot{q}) & C_{33}(q,\dot{q}) \end{bmatrix} \qquad \textbf{(2)}$$

where:

$$C_{11}=-a_5(\dot{q}_2+\dot{q}_3)\sin(q_2+q_3)-a_3\dot{q}_2\sin(q_2)-a_6\dot{q}_3\sin(q_3);$$
$$C_{12}=-a_5(\dot{q}_1+\dot{q}_2+\dot{q}_3)\sin(q_2+q_3)-a_3(\dot{q}_1+\dot{q}_2)\sin(q_2)-a_6\dot{q}_3\sin(q_3);$$
$$C_{13}=-a_5(\dot{q}_1+\dot{q}_2+\dot{q}_3)\sin(q_2+q_3)-a_6(\dot{q}_1+\dot{q}_2+\dot{q}_3)\sin(q_3);$$
$$C_{21}=a_5\dot{q}_1\sin(q_2+q_3)+a_3\dot{q}_1\sin(q_2)-a_6\dot{q}_3\sin(q_3);$$
$$C_{22}=-a_6\dot{q}_3\sin(q_3);$$
$$C_{23}=-a_6(\dot{q}_1+\dot{q}_2+\dot{q}_3)\sin(q_3);$$
$$C_{31}=a_5\dot{q}_1\sin(q_2+q_3)+a_6(\dot{q}_1+\dot{q}_2)\sin(q_3);$$
$$C_{32}=a_6(\dot{q}_1+\dot{q}_2)\sin(q_3);$$
$$C_{33}=0.$$

$$M_{11}=a_1+a_2+a_4+2a_3\cos(q_2)+2a_5\cos(q_2+q_3)+2a_6\cos(q_3);$$
$$M_{12}=M_{21}=a_2+a_4+a_3\cos(q_2)+a_5\cos(q_2+q_3)+2a_6\cos(q_3);$$
$$M_{13}=M_{31}=a_4+a_5\cos(q_2+q_3)+a_6\cos(q_3);$$
$$M_{22}=a_2+a_4+2a_6\cos(q_3);$$
$$M_{23}=M_{32}=a_4+a_6\cos(q_3);$$
$$M_{33}=a_4.$$

$$a_1=j_1+m_1l_1^2+(m_2+m_3)L_1^2;$$
$$a_2=j_2+m_2l_2^2+m_3L_2^2;$$
$$a_3=(m_3L_2+m_2l_2)L_1;$$
$$a_4=j_3+m_3l_3;$$

$$a_5=m_3l_3L_1;$$
$$a_6=m_3l_3L_2.$$

where $q_1, q_2, and\ q_3$ represent the positions of link₁, link₂, and link₃, respectively, as in Fig.1.

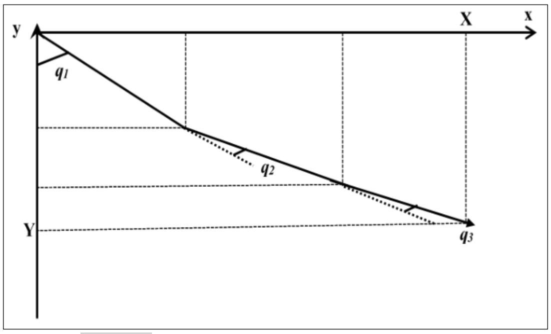


Fig. 1 3 Link Robot Manipulator.

Table 1 shows cases of the parameters associated with the robotic manipulator.

Table 1 Parameters of 3DOF Robot Manipulator

Parameter	Value	Unit
l_1	1	m
l_2	1	m
l_3	1	m
L_1	0.5	m
L_2	0.5	m
L_3	0.5	m
m_1	1	kg
m_2	1	kg
m_3	1	kg
J1	0.0833	Kg.m²
J2	0.833	Kg.m2
J3	0.833	Kg.m2

3.FUZZY LOGIC CONTROLLER DESIGN

The primary framework for the fuzzy logic controller, adept at tackling the nonlinearity and uncertainty within the robotic system, is depicted in Fig. 2. Zadeh first proposed the fuzzy set theory back in 1965, offering an alternative to conventional modeling and control design by providing an effective representation of system knowledge [1]. The four components of an FLC include the fuzzifier, a knowledge base composed of a rule base (RB) and database (DB), a fuzzy inference engine, and a defuzzifier [22].

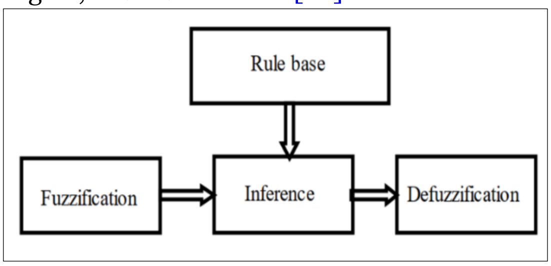


Fig. 2 The Primary Structure of FLC.

a. Fuzzification: The algorithm interprets numerical inputs for linguistic variables and computes the membership values for each input within distinct fuzzy sets, utilizing triangular membership functions.

b. Rule base: guidelines for executing processing are based on input values. Utilizing the IF-THEN-ELSE structure, the rules were established. The rule basis consists of 49 rules, as displayed in Table 2.

Table 2 Fuzzy Logic Controller Rules

U		Fractional Rate of Change of Error						
		NB	NM	NS	Z	PS	PM	PB
e	NB	NM	NS	NS	NS	Z	PS	PM
	NM	NM	NM	NM	NS	PS	PM	PM
	NS	NB	NM	NM	NS	PM	PB	PB
	Z	NB	NB	NM	Z	PM	PB	PB
	PS	NB	NB	NM	PS	PM	PM	PB
	PM	NM	NM	NS	PS	PM	PM	PM
	PB	NM	NS	Z	PS	PS	PS	PM

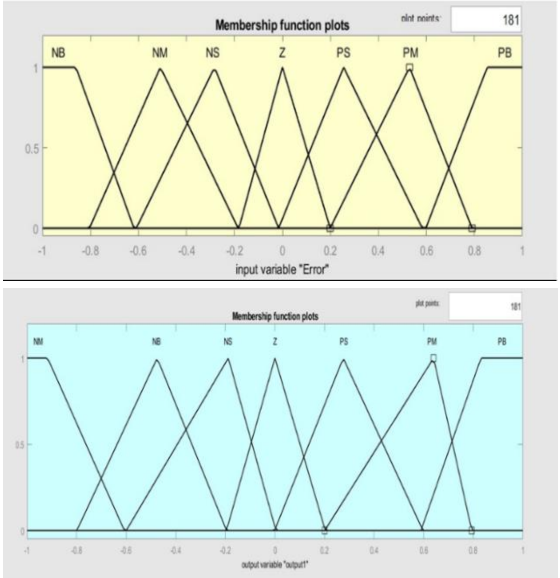


Fig. 3 Input and Output Membership Functions.

c. Inference system: According to the input values, it generated the fuzzy output from the rule basis. The standard techniques are Takagi-Sugeno Kang, Mamdani, Max-min, and Max-dot.

d. Defuzzification: To transform any fuzzy set into a real number, a mathematical process can be used. This process is called defuzzification. It is an important process for gathering fuzzy sets in fuzzy rules mathematically. However, this will make the fuzzy sets come up with the singular output of a fuzzy model or controller. As an input signal, the controller's actuators can accept just one value, while the physical systems data or measurements are normally crisp [23].

4.PRINCIPLES of PID and P I$^{\lambda}$D$^{\mu}$ CONTROLLERS

The primary factor contributing to the widespread usage of PID controllers is their relatively straightforward architecture, which allows for easy comprehension and practical implementation [24]. The transfer function of a PID controller can be expressed as in Eq. (3):

$$u(s)=\left(k_p+k_i\frac{1}{s}+k_d s\right)e(s) \qquad (3)$$

where e is the error signal, kp, ki, and kd are the proportional, integral, and derivative gains, respectively [25]. To enhance the efficacy of the PID controller, fractional-order controllers employing non-integer derivative and integrative components are implemented. This approach offers increased adaptability and the potential to fine-tune the dynamic aspects of the control system more effectively. The fractional-order controller demonstrates considerable robustness, which becomes even more prominent in a non-linear system. The fractional-order PID controller, denoted as PI$^{\lambda}$D$^{\mu}$, can be expressed as in Eq. (4):

$$u(s)=\left(k_p+k_i\frac{1}{s^{\lambda}}+k_d s^{\mu}\right)e(s); \quad (\lambda,\mu>0) \qquad (4)$$

From Eq. (3) and Eq. (4), it can be noticed that the conventional PID controller is a special form of fractional order PID controller by settling [24].

5.STRUCTURE OF ROBOT ARM BASED ON FUZZY, FUZZY-PID, AND FUZZY FOPID

In Figs. 4-6, block diagrams are displayed for robotic systems governed by Fuzzy, Fuzzy-PID, and Fuzzy-FOPID controllers, respectively. In [26], the authors designed a Fuzzy controller for a Microwave Oven.

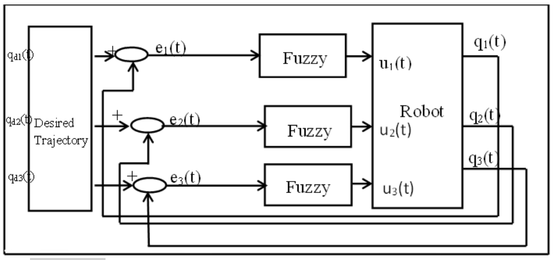


Fig. 4 Fuzzy Control System Diagram for Robotic Arm Manipulation.

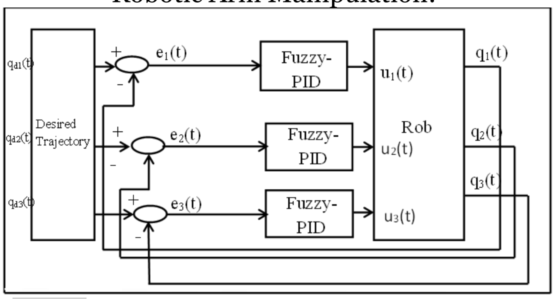


Fig. 5 Fuzzy – PID Control System Diagram for Robotic Arm Manipulation.

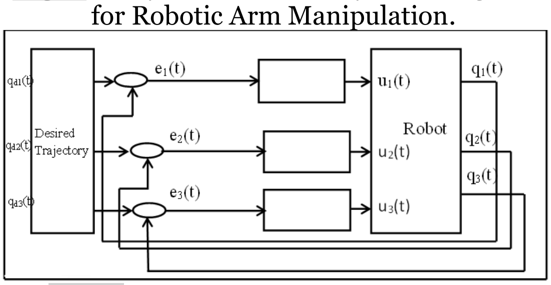


Fig. 6 Fuzzy – FOPID Control System Diagram for Robotic Arm Manipulation.

6.CLONAL SELECTION ALGORITHM

Fundamentally, these algorithms are based on Darwinian concepts, employing antigen affinity and antibody interactions for selection while taking inspiration from somatic hypermutation for modification and imitating cell division for replication. The central idea of clonal selection incorporates three processes: clonal selection itself, clonal expansion, and affinity maturation. Commonly known as the ingenious algorithm, this specific technique employs real parameter values rather than binary-coded parameters. Solely non-dominated individuals and the most viable antibodies are integrated into the memory set, with all members of the memory set undergoing cloning. This algorithm proves particularly beneficial for optimizing multi-objective problems. Fig. 7 depicts the steps involved in this algorithm.

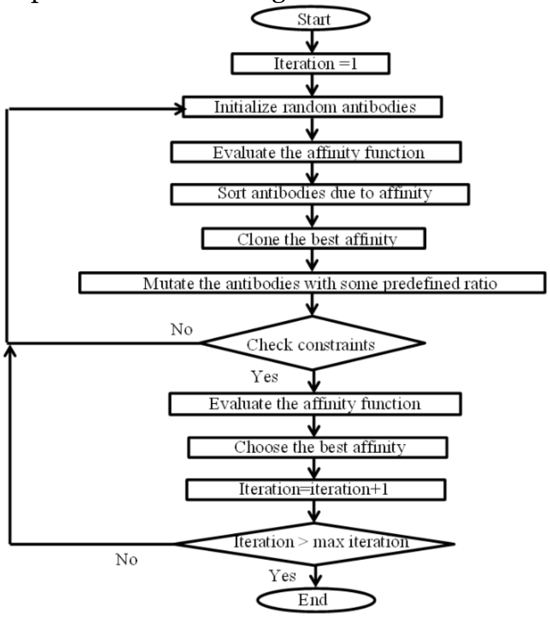


Fig. 7 Flowchart of the Clonal Selection Algorithm.

7.SIMULATION RESULTS

The performance of the suggested Fuzzy, Fuzzy-PID, and Fuzzy-FOPID control schemes for a 3-link robot manipulator using MATLAB 2014a was compared through simulation with MSE as a performance index in the CSA technique. The CSA technique was used to obtain the parameters for PID and FOPID controllers. The parameter values for CSA and the optimal values of parameters for PID and FOPID using proposed control schemes are given in Table 3 and Table 4, respectively. The desired trajectories for the robot manipulator were expressed as well.

$$q_{d1} = 1 - \cos(0.25t); \quad q_{d2} = 1 - \cos(0.5t);$$

Fitness values computed from the adjusted parameters in control systems are illustrated in Fig. 8 and Fig. 9, respectively.

Table 3 Parameters of the CSA Algorithm

Parameters	Values
Antibody number	40
Number of Clone	20
Inferior limit	0
Superior limit	900
Max. gen.	50
Mutation factor	80
Eliminate threshold	1
Selection of Clones	0.5

Table 4 Parameters of CSA-PID and CSA-FOPID

Parameters	PID	FOPID
K_{p1}	371.9470	617.8548
K_{p2}	50.1138	721.0983
K_{p3}	120.5647	585.9285
K_{i1}	729.7155	373.9397
K_{i2}	290.7868	486.30987
K_{i3}	312.8392	382.0161
K_{d1}	508.2494	484.9478
K_{d2}	840.2532	271.7069
K_{d3}	511.8657	247.9364
λ_1	1	0.9917
λ_2	1	0.3539
λ_3	1	0.62606
μ_1	1	0.6292
μ_2	1	0.6246
μ_3	1	0.65856

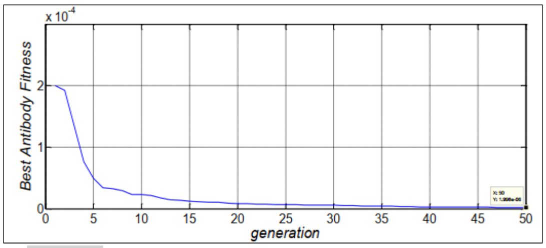


Fig. 8 The Fitness Values of the CSA-PID Controller, as a Function of the Generation.

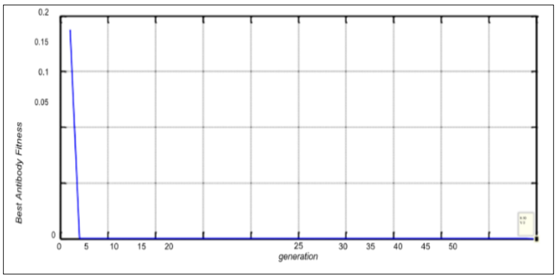
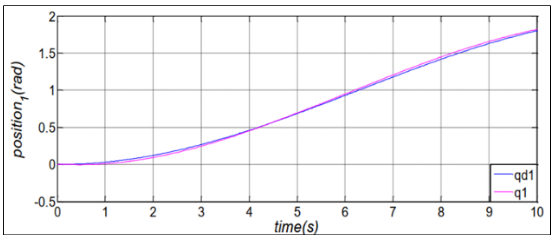


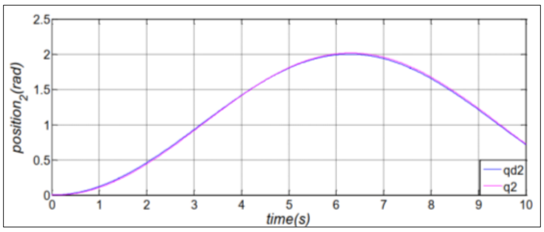
Fig. 9 The Fitness Values of the CSA-FOPID Controller, as a Function of the Generation.

7.1. Fuzzy Control Scheme (No Load Condition)

Fig. 10 illustrates the link's precise and effective positioning using a proficient fuzzy control method while operating under no-load conditions.



Link 1



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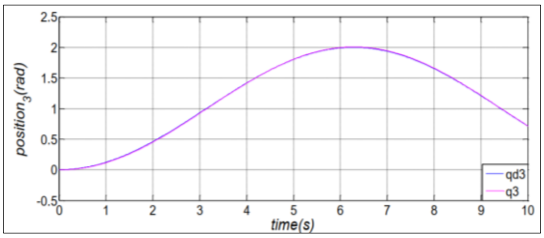
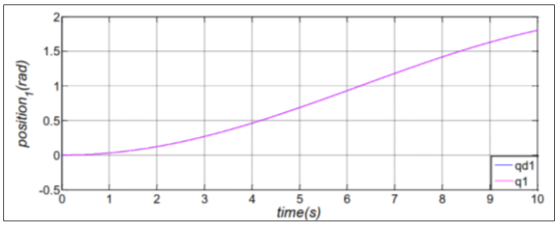


Link 3

Fig. 10 Actual and Desired Paths Utilizing a Fuzzy Control Strategy.

7.2. Fuzzy-PID Control Scheme (No Load Condition)

In Fig. 11, the desired and actual positions of links under a no-load situation are illustrated, utilizing a fuzzy proportional integral derivative control method.



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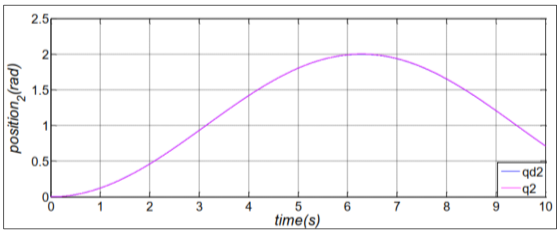

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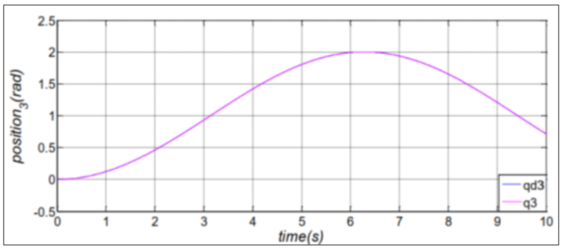
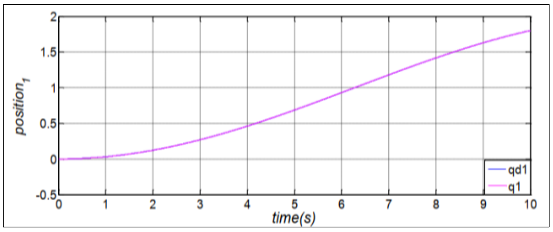


Link 3

Fig. 11 Actual and Desired Paths Utilizing a Fuzzy-PID Control Strategy.

7.3. Fuzzy-FOPID Control Scheme (No Load Condition)

In Fig. 12, the desired and actual positions of links under a no-load situation are illustrated, utilizing a fuzzy -FOPID method.



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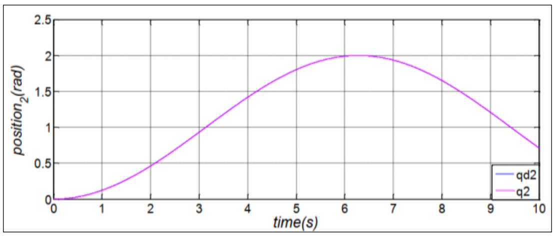

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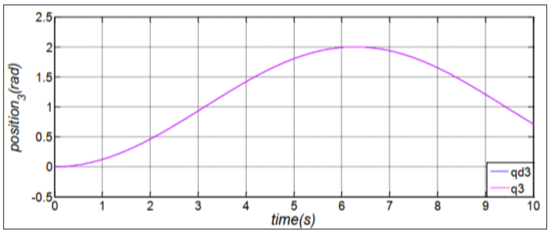
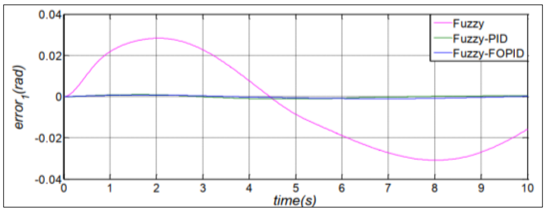


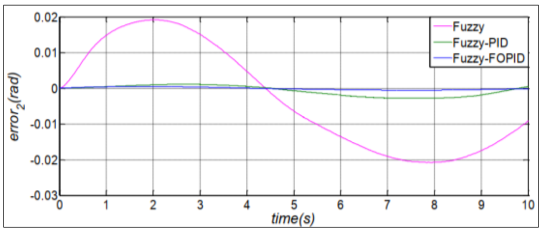
Link 3

Fig. 12 Actual and Desired Paths Utilizing a Fuzzy-FOPID Control Strategy.

In Fig. 13, inaccuracies in connections are depicted utilizing the suggested control strategy.



(a)



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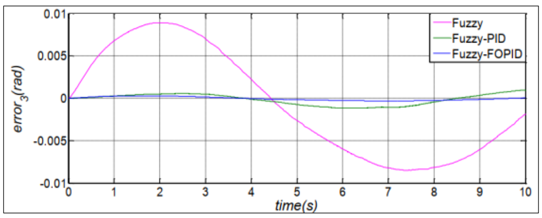

(c)

Fig. 13 Errors in Connections using Suggested Control Methods.

7.4. Results for Different Load Conditions

The suggested controllers' robustness was tested under various load conditions and model uncertainty. The values of MSEs using proposed control schemes under different load conditions are explained in Table 5.

Table 5 MSE for links under different load conditions

Load (kg)	Fuzzy	Fuzzy-PID	Fuzzy-FOPID	MSE
0	$4.787*10^{-4}$	$4.723*10^{-7}$	$4.308*10^{-7}$	MSE_1
	$2.221*10^{-4}$	$2.227*10^{-6}$	$1.442*10^{-7}$	MSE_2
	$4.034*10^{-5}$	$4.458*10^{-7}$	$4.476*10^{-8}$	MSE_3
0.1	$5.560*10^{-4}$	$5.474*10^{-7}$	$4.908*10^{-7}$	MSE_1
	$2.477*10^{-4}$	$2.547*10^{-6}$	$1.602*10^{-7}$	MSE_2
	$4.281*10^{-5}$	$4.482*10^{-7}$	$4.781*10^{-8}$	MSE_3
0.2	$6.589*10^{-4}$	$6.058*10^{-7}$	$5.548*10^{-7}$	MSE_1
	$2.868*10^{-4}$	$2.864*10^{-6}$	$1.722*10^{-7}$	MSE_2
	$4.669*10^{-5}$	$4.797*10^{-6}$	$5.106*10^{-8}$	MSE_3
0.3	$7.504*10^{-4}$	$6.668*10^{-7}$	$6.239*10^{-7}$	MSE_1
	$3.174*10^{-5}$	$3.212*10^{-6}$	$1.948*10^{-7}$	MSE_2
	$4.950*10^{-5}$	$5.121*10^{-7}$	$5.427*10^{-8}$	MSE_3

7.5. Model Uncertainty Results

Moreover, to test the model's stability under uncertainty, 0.01 kg/m² was added to the inertia values of link 3. Table 6 elucidates the MSE values acquired using the recommended control methods for links experiencing model uncertainty.

Table 6 MSE for Links under Model Uncertainty

J3 (kg.m²)	Fuzzy	Fuzzy-PID	Fuzzy-FOPID	MSE
0.8333	$4.787*10^{-4}$	$4.723*10^{-7}$	$4.308*10^{-7}$	MSE_1
	$2.221*10^{-4}$	$2.227*10^{-6}$	$1.442*10^{-7}$	MSE_2
	$4.034*10^{-5}$	$4.458*10^{-7}$	$4.476*10^{-8}$	MSE_3
0.8433	$4.807*10^{-4}$	$4.746*10^{-7}$	$4.319*10^{-7}$	MSE_1
	$2.239*10^{-4}$	$2.251*10^{-6}$	$1.449*10^{-7}$	MSE_2
	$4.118*10^{-5}$	$4.472*10^{-7}$	$4.538*10^{-8}$	MSE_3

8.CONCLUSIONS

The main conclusions of the present paper could be summarized as follows:

1- The issue of trajectory tracking in a 3DOF Robot Manipulator was addressed by employing an optimal fuzzy FOPID controller and compared to a Fuzzy controller and a fuzzy PID controller in terms of varying load conditions and model uncertainties.

2- The CSA method was employed to determine the parameters for both PID and FOPID controllers.

3- Multiple mass parameters and perturbations were considered while assessing the efficiency metric for the three-link robotic manipulator.

4- The SIMULINK/MATLAB 2014a simulation procedure illustrated the fractional order fuzzy controller's superior performance compared to alternative controllers, given varying model weights and uncertainties.

The simulation outcomes revealed that the advanced fractional-order fuzzy PID controller demonstrated exceptional trajectory tracking and resilience when juxtaposed with all other examined controllers.

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