Optimal Fuzzy-Immune Fractional PID Control Scheme for Path Tracking of Robot manipulator

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Abstract

This paper explains a new control structure based on the artificial immune system, Fuzzy and fractional order PID control schemes. In this paper immune feedback control system, Fuzzy logic and fractional order control schemes will be combined and optimized using clonal selection algorithm. Fuzzy-immune fractional order PID Control schemes will be used as a new controller for path tracking of the robot manipulator. The performance of the proposed control scheme is compared with fuzzy-immune PID control schemes. The parameters of fractional PID and conventional PID controllers are optimized using Clonal Selection Algorithm (CSA). Simulation results state that optimal Fuzzy-immune fractional PID is better than optimal fuzzy-immune PID Control schemes for path tracking problem under the same condition. All control schemes were tested using SIMULINK under MATLAB2014a.

***Index Terms*— Robot Manipulator, Fractional Order PID, Fuzzy Logic Controller, Immune Feedback Theory, Clonal Selection Algorithm.**

I. Introduction

The important uses of robot manipulators are the correct positioning and following. [1]. Artificial intelligence (AI) is a computational philosophy for taking care of the tuning issues in a wide range of supportable applications. De Castro and Timmis introduced AIS algorithm [2]. Immunity refers to the biological state that describes the defence mechanisms and techniques in an organism against bacteria, viruses and other disease-causing organisms, known as antigens. It is the part of the Biological Immune System (BIS), which is made out of numerous associated cells composes [3, 4].

In addition to that, the principal capacity of the Immune framework is to shield the body from outside or hurtful elements, it is used to battle antigens, nature has furnished us with the Immune System. The immune system also has great pattern acknowledgment ability that might be utilized to recognize outside cells entering the body (non-self or antigen) and the body cells (self).The immune system consists of a comprises of countless B cells, and every B cell has an exceptional sort of receptors on its surface. Both the antigen and the receptors of B ceil have complex three-dimensional structures. The more correlative the states of the antigen and the B cell receptors, the higher affinity between the antigen and the B cell [5, 6].

There have been many studies about using the mechanism of the immune system as controller and optimization technique in the literature in recent years. The first study for artificial immune system algorithm was presented by de Castro and Timmis [2]. The immune evolutionary algorithm is introduced in [6]. The algorithm was utilized to tune a neuro-fuzzy control scheme of an inverted pendulum. Fuzzy immune PID control scheme for path tracking of Nonholonomic Mobile Robot is designed in [7]. This controller combines fuzzy control, immune feedback mechanism of an organism with conventional PID control. The parameters of PID were optimized using a genetic algorithm. Authors in [8] designed 3DOF robot manipulator. Classical clonal selection algorithm was used to optimize the movement of links. A comparison study between the performances of PID, fuzzy, immune feedback controllers for three tank liquid levels is introduced in [9]. Parameters of PID controller were optimized using fuzzy self- tuning PID mechanism. Field programmable gate array (FPGA)-based artificial immune system (AIS) algorithm is designed for four-wheeled holonomic mobile robots in [2]. These FPGA-based AIS gave better result compared with the conventional nonoptimal controllers. A modified Artificial Immune System is presented in [10]. This study covered the hole among a hypothetical system, algorithm based on that theory and then its application to explain optimization problems. From immune feedback mechanism and fuzzy inference, a fuzzy immune PID controller was designed to control the nonlinear system in [11]. The genetic algorithm was used to tune proposed controller's parameters. Optimal fuzzy immune PID to control a three tank delay system is designed in [12]. Optimization toolbox of MATLAB is used to resolve optimization problem. Results showed that the proposed controller gave good performances to a three tank delay system. Studying, implementation, testing, and simulation of clonal selection algorithm are presented in [5] to observe good output response. Set of optimal solutions can be found using clonal selection algorithm. Authors in [13] proposed Constraint Immune Multi-objective Optimization Algorithm (CIMOA). The result of this algorithm compared with genetic algorithm (GA) and weighted objective genetic algorithm (WGA), it is cleared that multiple objective methods were better than other algorithms in term of less traveling time and less consuming energy and the trajectory in joint space is much smoother.

In this paper, new control schemes based on fuzzy immune-fractional order PID controller is designed for path tracking of the robot manipulator. The effectiveness of fuzzy immune fractional PID controller is compared with fuzzy immune PID controller. Clonal selection algorithm (CSA) is utilized to tune the parameters of PID and FOPID. Simulation results showed that the effectiveness of fuzzy immune fractional PID is better than of fuzzy immune PID.

This paper is systematized as follows: after detailed literature review in Section I, the mathematical model of a 2-link robot manipulator is presented in Section II. Section III describes the concept of conventional and fractional PID controllers. The design of the fuzzy logic controller is introduced in Section IV. Section V introduces the concepts of the artificial immune system. Section VI gives simulation result. Finally, the conclusions of this work are summarized in Section VII.

II. THE DYNAMIC MODEL OF ROBOT MANIPULATOR

The dynamical equation of motion for n-link robot manipulator is given by [14]:

$$M(q)\ddot{q} + B(q,\dot{q})\dot{q} + G(q) + f(t) = U \qquad (1)$$

Where q is $n*1$ vector, it is joint displacement vector, u is $n*1$ vector, it is applied joint torque vector, $M(q)$ is $n*n$ matrix, it is inertia matrix, is $B(q,\dot{q})\dot{q}$ is $n*1$ vector, it is coriolis and centrifugal vector, $G(q)$ is $n*1$ vector, it is the gravitational vector, and $f(t)$ is $n*1$ vector, it is external disturbance vector.

The dynamic equations for two-link manipulator shown in Fig.1 are:

$$\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix}\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} + \begin{bmatrix} G_1 \\ G_2 \end{bmatrix} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \qquad (2)$$

Where:

$$M_{11} = (m_1 + m_2)l_1^2 + m_2 l_2^2 + 2m_2 l_1 l_2 \cos(q_2) + J_1$$
$$M_{12} = M_{21} = m_2 l_2^2 + m_2 l_1 l_2 \cos(q_2)$$
$$M_{22} = m_2 l_2^2 + J_2$$
$$B_{11} = -2m_2 l_1 l_2 \dot{q}_2 \sin(q_2)$$
$$B_{12} = -m_2 l_1 l_2 \dot{q}_2 \sin(q_2)$$
$$B_{21} = m_2 l_1 l_2 \dot{q}_1 \sin(q_2)$$
$$B_{22} = 0$$
$$G_1 = ((m_1 + m_2)l_1 \cos(q_1) + m_2 l_2 \cos(q_1 + q_2))g$$
$$G_2 = (m_2 l_2 \cos(q_1 + q_2))g$$

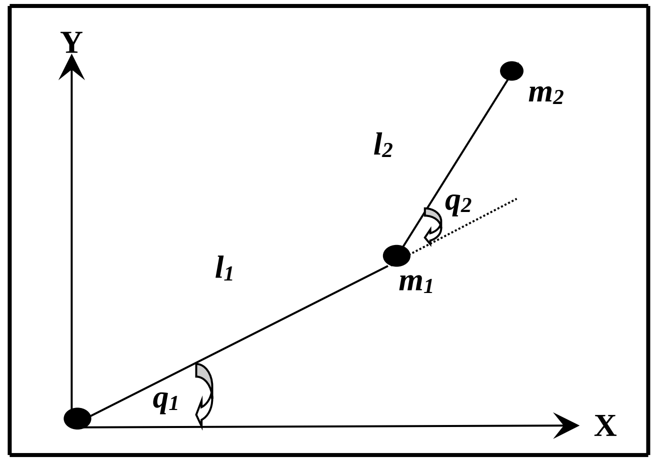

Fig.1 2-link robot manipulator

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Where l_1 and l_2 are lengths of $link_1$ and $link_2$ respectively; m_1 and m_2 are masses of $link_1$ and $link_2$ respectively; q_1 and q_2 are the position of $link_1$ and $link_2$ respectively; l_1 and l_2 are lengths of $link_1$ and $link_2$ respectively; l_1 and l_2 are lengths of $link_1$ and $link_2$ respectively.

The parameters values for 2-link robot manipulator are:
Length of upper link (l_1) = 1m.
Length of lower link (l_2) = 0.8m.
Mass of upper arm (m_1) = 0.5kg.
Mass of lower arm (m_2) = 0.5kg.
The inertia of two joints ($j_1 = j_2$) = 5kg.m^2.

III. CONCEPT OF CLASSICAL AND FRACTIONAL ORDER PID CONTROLLERS

PID controller has been used in process industries. It is so well known because of its simple structure, cost adequacy and straightforwardness in usage [15]. PID controller can be expressed as follows:

$$u(t) = (k_p\, e + k_i \int e(\tau)\, d\tau + k_d \frac{de}{dt}) \qquad (5)$$

Where k_p, k_i, k_d are defined as proportional, integral and differential parts, respectively [16]. Fig.2 shows the block diagram of PID controller.

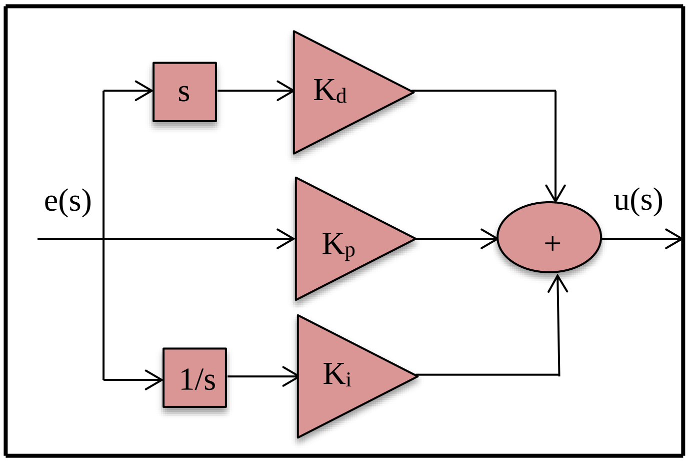


Fig.2 Block diagram of classical PID

$$u(s) = \left(k_p + k_i \frac{1}{s} + k_d\, s\right) e(s) \quad (6)$$

$PI^{\lambda}D^{\mu}$ controller is a generalization form of PID controller. $PI^{\lambda}D^{\mu}$ controller is described as given below [17]:

$$u(s) = \left(k_p + k_i \frac{1}{s^{\lambda}} + k_d\, s^{\mu}\right) e(s) \quad (7)$$

Where k_p ,k_i,k_d are proportional constant, integration constant and differentiation constant respectively. Table I show that the PID controller is a special case of $PI^{\lambda}D^{\mu}$ controller.

Table I PID CONTROLLER IN TERM of λand μ

PID	μ	λ
PI	0	1
PD	1	0
P	0	0
PID	1	1

The block diagram of fractional order PID controller is showed in Fig.3.

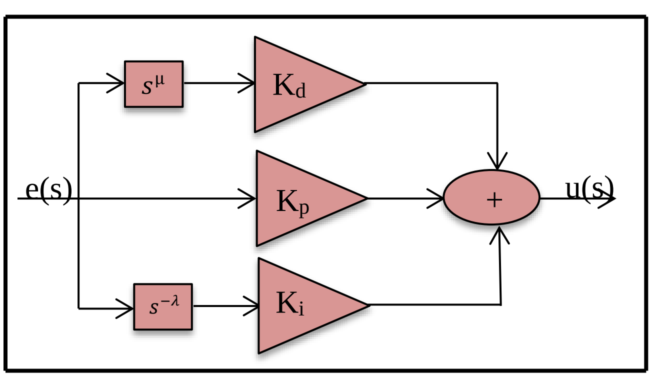


Fig.3 Block diagram of FOPID

IV. Fuzzy logic controller

A fuzzy logic control scheme can be considered as an expert system with an information demonstration based on the usage of fuzzy set explanation [18]. Fuzzy logic controllers are suitable for nonlinear complex systems that have unknown or unmodeled dynamics [19]. Fuzzy controllers can make effective decisions on the basis of imprecise linguistic information [20].

FLC includes four components, which are fuzzifier, knowledge base, fuzzy inference system, and defuzzifier as depicted in Fig.4 [21].

A. Fuzzification

The fuzzifier is the basic element in the FLC that changes crisp inputs into a set of membership values in the corresponding fuzzy sets [8p1].The crisp data translates into equivalent fuzzified data using membership function. The value of membership ranges between [0 1]. The membership function has several forms such as triangular, Gaussian, bell-shaped, trapezoidal, etc [22].

B. Fuzzy Rule Base

Fuzzy rules are set of rules that map fuzzy input to fuzzy output Fuzzy rules can be written as the:

If x is l1 then y is l2

“x is l1 “ is called the antecedent, while “y is l2” is called the consequent [23].

C. Fuzzy Inference System

The inference engine system is the core of FLC. There are three brands of fuzzy logic inference systems: Mamdani type, Sugeno type, and Tsukamoto type, Mamdani type is the most regularly used in FLC. The inference process is used to determine the value of the controller output based on the aids of each rule in the rule base. theMacvicar- Whelan control matrix is one of the methods used for storing the rule base [22, 24].

D. Defuzzification

Defuzzification is a mathematical process utilized to transform fuzzy sets to a real number. It is a requested step because fuzzy sets invented by fuzzy inference in fuzzy rules must be somehow mathematically gathering to come up with one single number as the output of a fuzzy controller or model. After all, actuators for control systems can accept only one value as their input signal, whereas measurement data from physical systems being modeled are always crisp [24].

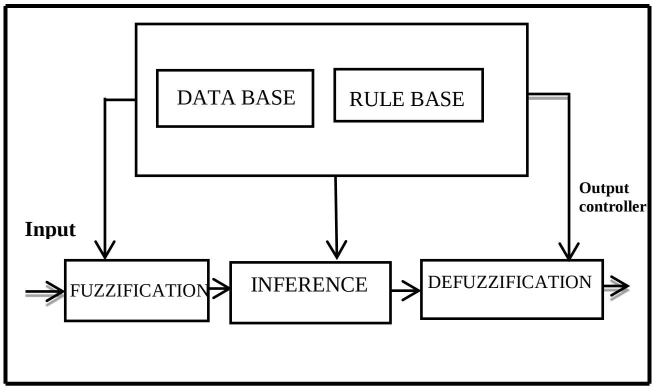


Fig.4 Fuzzy Logic Controller

Because of nonlinear attributes of the fuzzy controller, it can characterize better behavior comparing with classical linear PID controller [25]. The design specifications of the FLC after trial and error for this system are as [26]: no. of input variables =2, no. of output variables = 1, no. of membership function = 7, Fig.5 shows the shape of input and output membership functions.

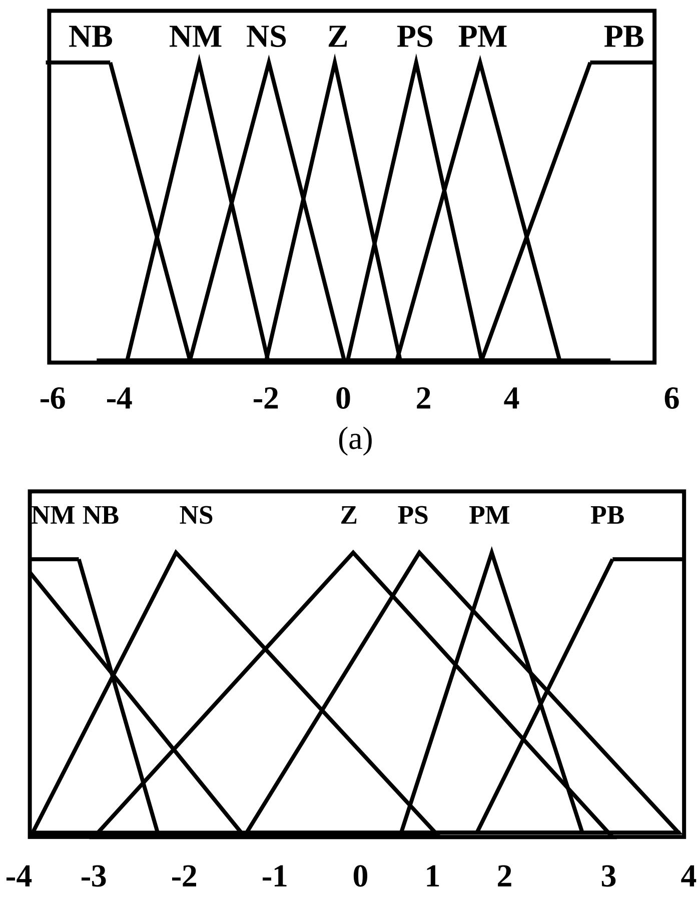


Fig.5 Input and Output membership functions

The fuzzy controller rules, which is given in Table II are represented linguistic values of IF-THEN of rules, the total numbers of rules are 7 × 7 = 49 which are designed heuristically based on the knowledge of the controlled system.

Table II Fuzzy logic controller rules

U		**ė**						
		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**

V. ARTIFICIAL IMMUNE SYSTEM

1. Immune Feedback Mechanism

The theory was that the immune system maintains a network of interconnected B cells for antigen recognition. These cells both stimulate and suppress each other in certain ways that lead to the stabilization of the network. Two B cells are connected if the affinities they share exceed a certain threshold, and the strength of the connection is directly proportional to the affinity they share [4]. We can see that the immune mechanism acts clearly like a feedback control system. Fig.6 describes the immune processes operating:

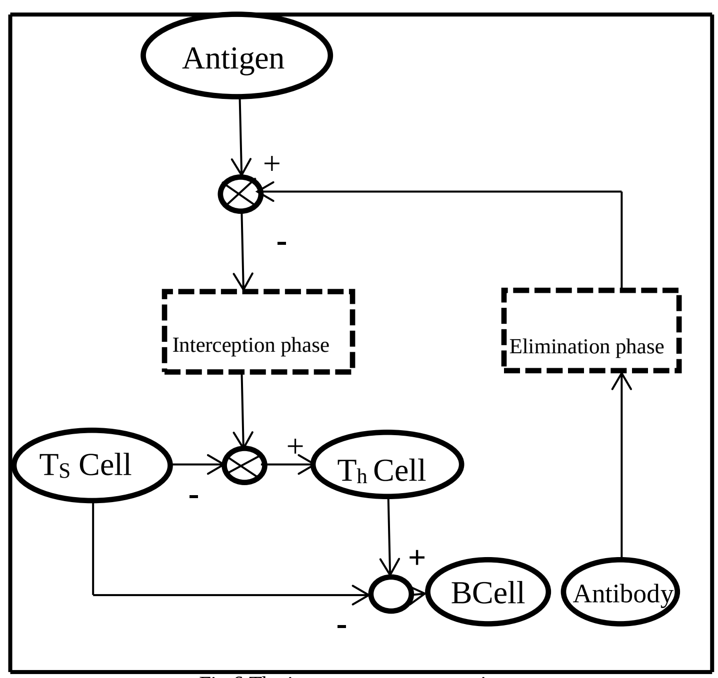


Fig.6 The immune system operation

Immune PID controller is a nonlinear controller designed by immune instrument, which achieves fine and has well robustness Fig.6 explains the standard of feedback instrument. The immune feedback concept can be defined as that the stimulation effect on the B cells equal the difference between the stimulation of TH cells and the inhabitation of TS cells:

$$B(k) = T_h(k) - T_s(k) \quad (7)$$

$$T_h(k) = k_1\, \varepsilon(k) \quad (8)$$

$$T_s(k) = k_2 \{ f[\Delta B(k-d)]\}\varepsilon(k) \quad (9)$$

Where ε(k) is the stability of antigen at the k^th^ generation, k_1 is the inspiration factor, and K_2 is a suppression factor. ΔB (k - d) is the variation of B cell's stability and d is the delay-time of the immune response. f(x) is a nonlinear function that characterizes the interaction between antibody which emerge from B cells and antigen. In this work Fuzzy logic controller is used to realize the nonlinear function f(x).

From (8) and (9) we can find the relationship method about the constancy of B cells and antigen. It is shown as follows:

$$B(k) = k_1\, \varepsilon(k) - k_2 \{ f[\Delta B(k-d)]\}\varepsilon(k) \quad (10)$$

$$= k\,\{1 - \mu\, f[\Delta B(k-d)]\}\varepsilon(k) \quad (11)$$

Where $k=k_1$, $\mu = k_2 / k_1$. The parameter k is utilized to dominate the reply speed, and the parameter μ is utilized to dominate the equilibrium effect. Therefore, the performance of the immune feedback controller importantly depends on the correct selection of these factors [11], while increasing μ contributes to steady the scheme. Equation (11) is similar to the classical proportional control law given by:

$$U(k) = k_p\, e(k) \quad (12)$$

kp is the proportional coefficient, one can remark the analogy between (11) and (12), here the proportional coefficient of the immune controller is nonlinear, from there we can establish the immune inspired proportional control law as follow:

$$U(k) = k_p \{1 - \mu\, f[U(k), \Delta U(k-d)]\}\varepsilon(k) \quad (13)$$

Unluckily, for greatest actual systems, the proportional controller alone could not recover the error from the external perturbation, it seems so clear that a mixture of the immune proportional controller with a classical PID one display a powerful controller called (IMF PID); such controller law can be stated by [12]:

$$U(k) = k_p \{1 - \mu\, f[U(k), \Delta U(k-d)]\} \left(1 + \frac{T_i}{z-1} + T_d\, \frac{z-1}{z}\right)\varepsilon(k) \quad (14)$$

In this work, a fractional order PID controller is s designed with the fuzzy immune controller for path tracking of the robot manipulator. Also, the fractional order PID controller will be optimized using CSA.

2. Clonal Selection algorithm

Clonal selection algorithms effort on the Darwinian's theory in which selection is by reason of the antigen affinity and antibody interactions, alteration are inspired by somatic hypermutation and recreation is inspired by cell division [10]. The clonal selection principle consists of the mechanisms; clonal selection, clonal expansion and maturation via crossover mechanism. The Algorithm is projected with real factors value, not binarily coded factors. This algorithm was used to tune multi-objective problems [5]. Steps of Clonal Selection algorithm can be expressed as in [27]:

Step 1: A specific of antibodies (usually generated in a random manner) are generated which are the current applicant solutions of a problem.

Step 2: The affinity values of each applicant solutions are calculated.

Step 3: The antibodies starting from the lowest affinity are arranged in descending manner. Lowest affinity means that a better identical between antibody and antigen.

Step 4: The better identical antibodies are cloned more with some predefined ratio.

Step 5: The antibodies are mutated with some predefined ratio. This ratio is obtained in a way that better matching clones mutated less and weakly matching clones mutated much more in order to reach the optimal solution.

Step 6: The new affinity values are calculated for each antibody.

Step 7: Repeat Steps 3 through 6 while the minimum error criterion is not met.

VI. Simulation Results and Robustness Test

This section explains the simulation results for trajectory tracking and model uncertainties for CSA-Fuzzy Immune PID and CSA- Fuzzy Immune $PI^{\lambda}D^{\mu}$ controllers. The block diagrams of Fuzzy Immune PID and Fuzzy Immune FOPID for 2-link robot manipulator are shown in Fig.7 and Fig.8

The trajectories chosen are expressed as:

1. $q_{d1} = 1 - \cos t$, $q_{d2} = 1 - \cos 2t$
2. $q_{d1} = \sin t$, $q_{d2} = \sin 2t$
3. $q_{d1} = 1 - e^{-2t^2} \cos t$, $q_{d2} = 1 - e^{-2t^2} \cos 2t$

The fitness function chosen is MSE and can be written as:

$$fitness = \frac{\sum e_1^2}{length(e_1)} + \frac{\sum e_2^2}{length(e_2)}$$

The parameters of PID and $PI^{\lambda}D^{\mu}$ controllers were obtained using clonal selection algorithm optimization techniques. Table II shows the parameters used for initialization of the clonal selection algorithm. The obtained optimized controller parameters are explained in table III for CSA- Fuzzy Immune PID, and CSA- Fuzzy Immune $PI^{\lambda}D^{\mu}$ controllers.

Table II Construction for CSA algorithm

Parameters	Parameter values
Antibody number	40
Clone number	20
Lower boundary	0
Upper boundary	500
Maxgen	50
Mutation factor	80
Remove threshold	1
Clonal selection threshold	0.5

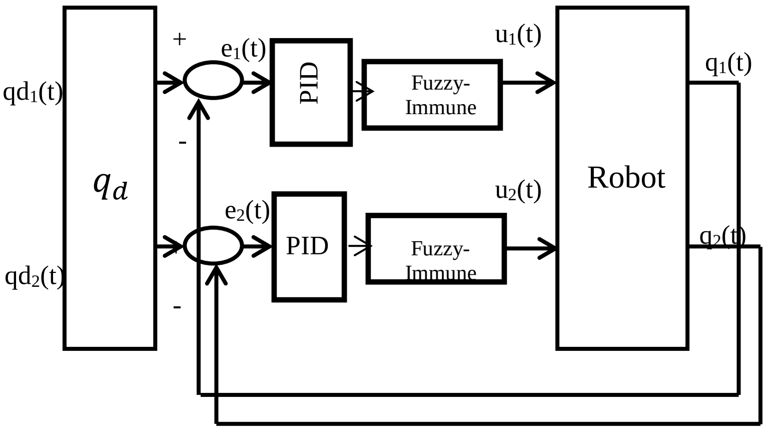


Fig.7 Block diagram of Fuzzy- Immune PID for robot manipulator

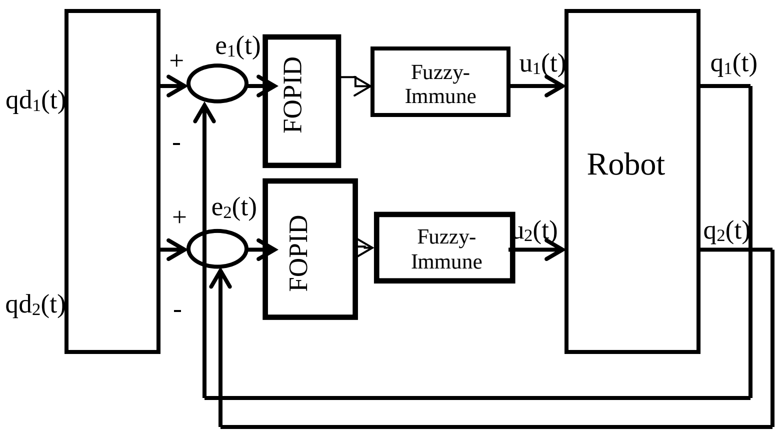


Fig.8 Block diagram of Fuzzy- Immune FOPID for robot manipulator

Table III Parameters values for PID and FOPID controllers in FIPID and FIFOPID control schemes

Parameters	CSA-FIPID	CSA-FIFOPID
K_{P1}	323.87	481.69
K_{P2}	408.59	496.92
K_{I1}	283.03	180.74
K_{I2}	471.41	263.58
K_{d1}	475.41	481.92
K_{d2}	256.98	175.38
λ_1	1.0000	0.9569
λ_2	1.0000	0.8728
μ_1	1.0000	0.9802
μ_2	1.0000	0.82216

The fitness value versus generation graphs for both CSA-FIPID and CSA-FIPI$^{\lambda}$D$^{\mu}$ controllers are presented in Fig.9 and Fig.10.

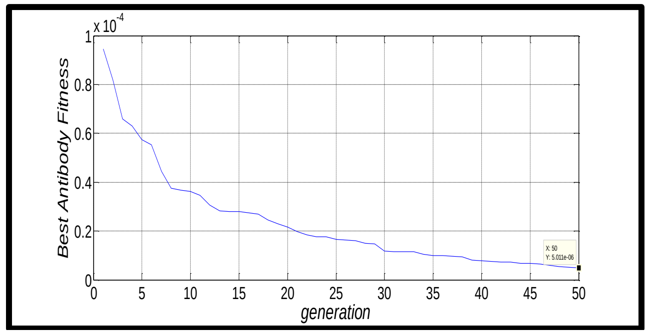


Fig.9 Fitness values versus generation for CSA-FIPID controller

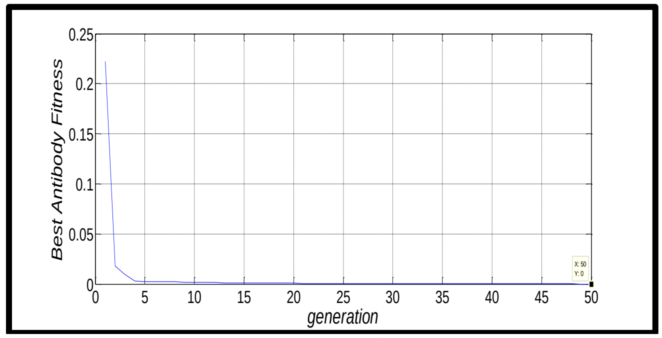
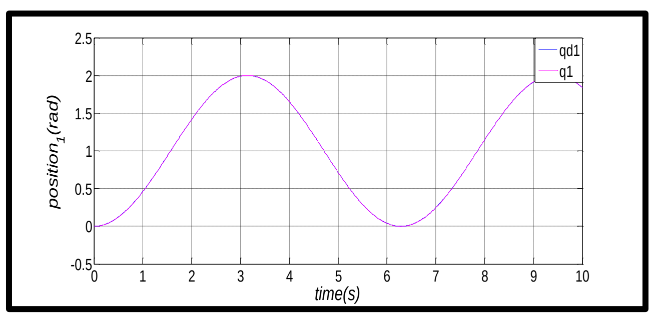


Fig.10 Fitness values versus generation for CSA-FIFOPID controller

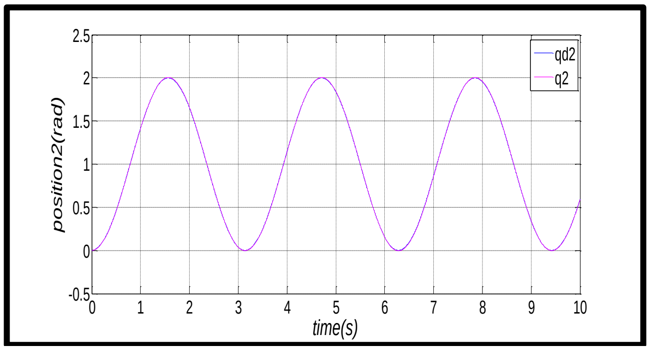
a. Simulation Results

1. The first trajectory

Under no load condition, results for the first trajectory are shown in fig.11 and fig.12. Fig.11 shows the desired and actual position for both links using CSA-FIPID and fig.12 shows the same results using CSA-FIFOPID control schemes. Fig.13 gives a comparison between path tracking by end effector using Fuzzy immune PID and Fuzzy Immune FOPID control schemes. Fig.14 gives complete comparisons between links errors using CSA-FIPID and CSA-FIFOPID.

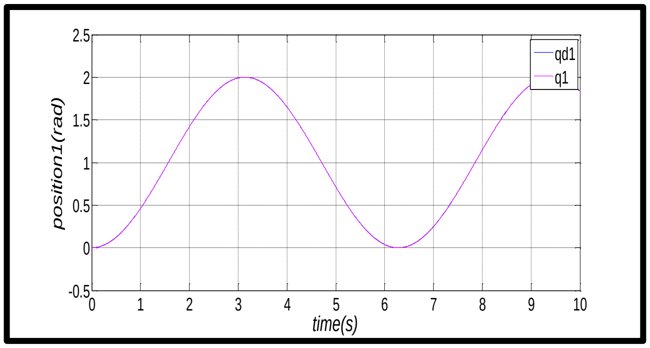


(a) For link$_1$

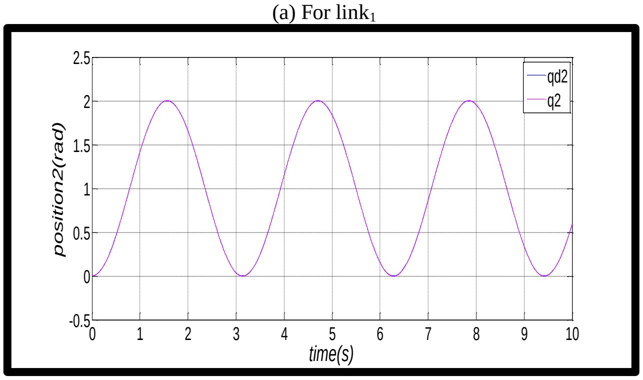


(b) For $link_2$

Fig.11 Desired and actual trajectories for both links using Fuzzy Immune PID



(a) For $link_1$



(b) For $link_2$

Fig.12 Desired and actual trajectories for both links using Fuzzy Immune FOPID

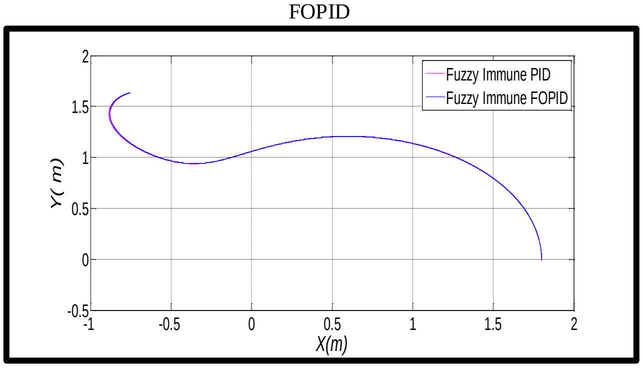
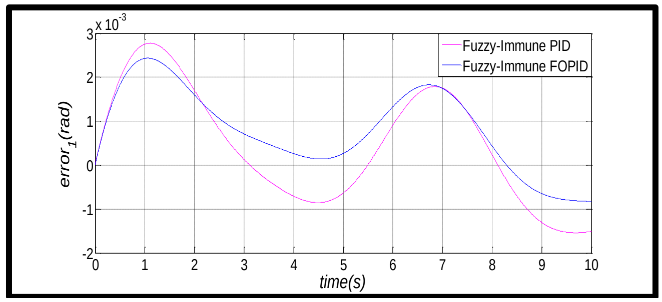
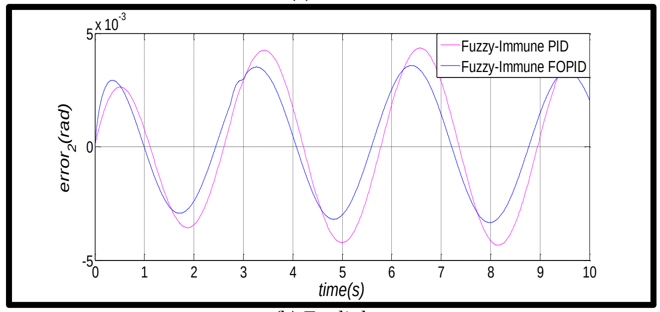


Fig.13 End effector path using proposed control schemes



(a) For $link_1$

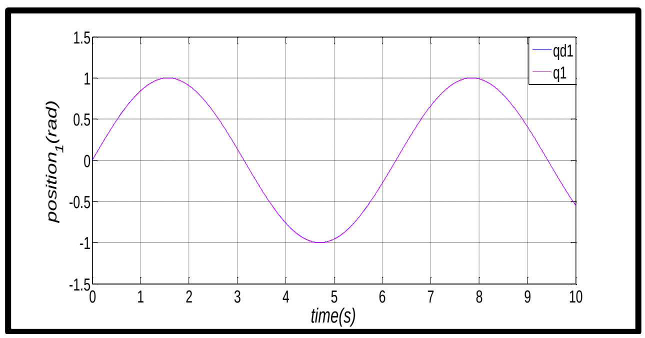


(b) For $link_2$

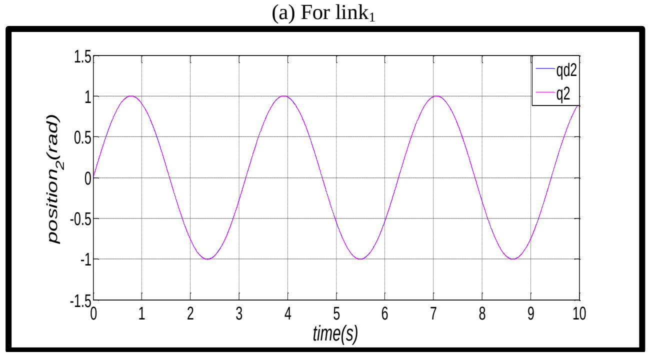
Fig.14 errors in links using proposed control schemes

2. The Second Trajectory

Under no load condition, the desired and actual position for both links of robot manipulator controlled using CSA-FIPID and CSA-FIFOPID are given in Fig. 15 and 16. Fig.17 gives comparison between path tracking by end effector using Fuzzy immune PID and Fuzzy Immune FOPID. Fig.18 gives complete comparisons between links errors using CSA-FIPID and CSA-FIFOPID.

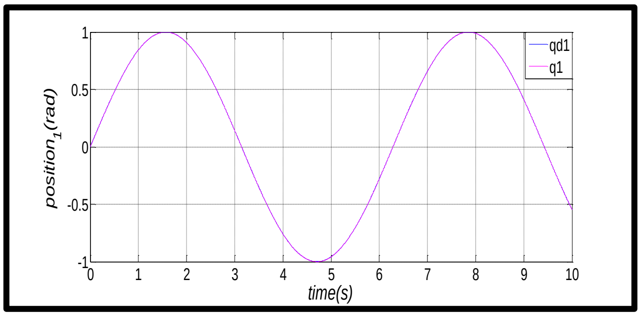


(a) For $link_1$

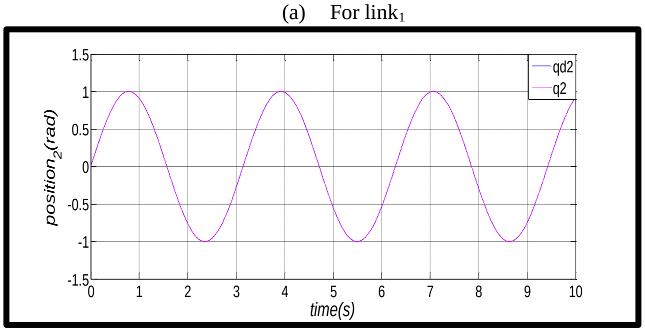


(b) For $link_2$

Fig.15 Desired and actual trajectories for both links using Fuzzy Immune PID



(a) For link$_1$



(b) For link$_2$

Fig.16 Desired and actual trajectories for both links using Fuzzy Immune FOPID

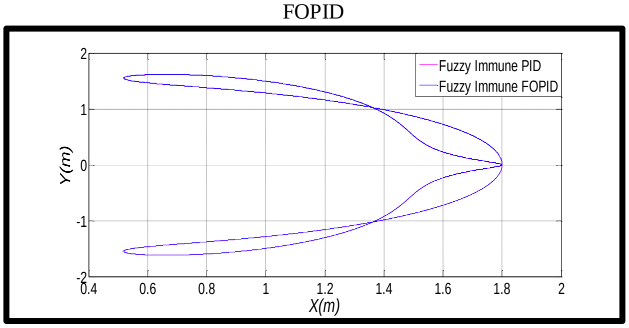
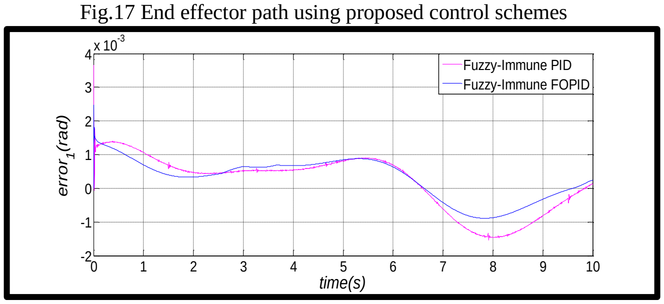
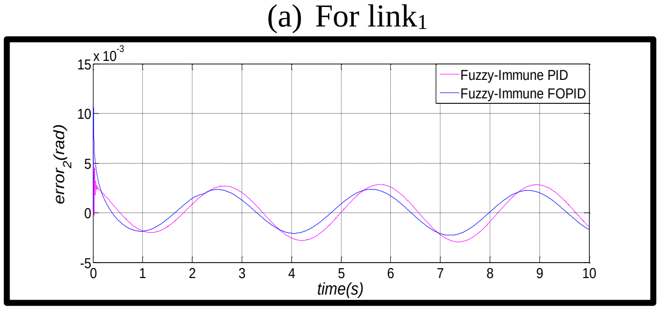


Fig.17 End effector path using proposed control schemes



(a) For link$_1$

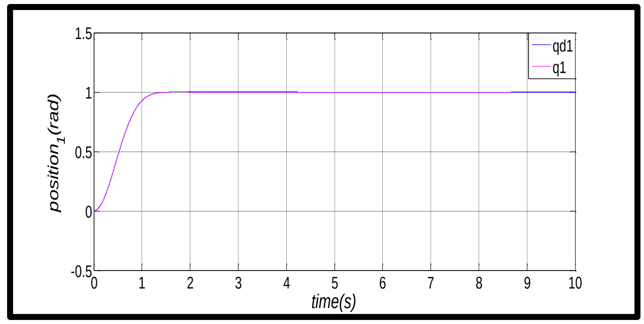


(b) For link$_2$

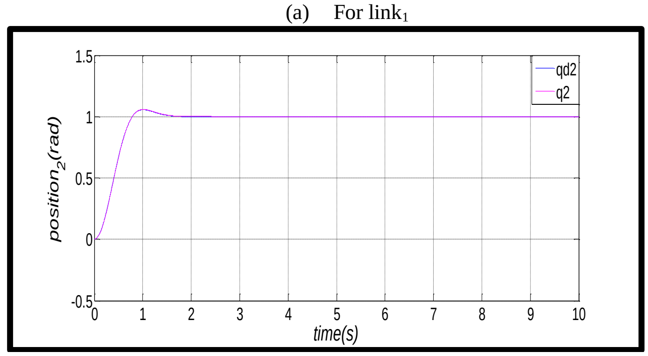
Fig.18 errors in links using proposed control schemes

3. The Third Trajectory

Under no load condition, the desired and actual position for both links of robot manipulator controlled using CSA-FIPID and CSA-FIFOPID are given in Fig. 19 and 20. Fig.21 gives comparison between path tracking by end effector using Fuzzy immune PID and Fuzzy Immune FOPID. Fig.22 gives complete comparisons between links errors using CSA-FIPID and CSA-FIFOPID.

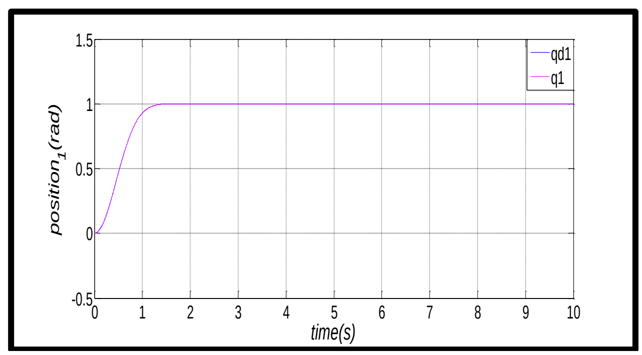


(a) For link$_1$

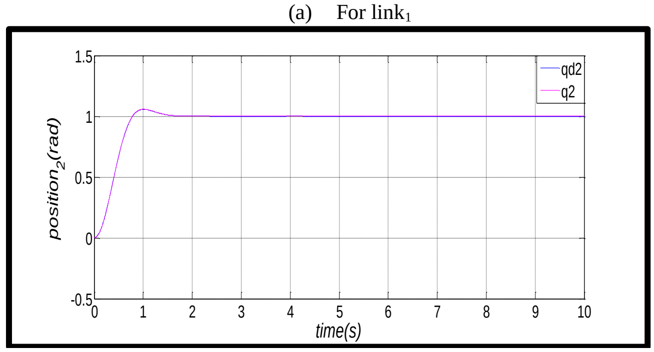


(b) For link$_2$

Fig.19 Desired and actual trajectories for both links using Fuzzy Immune PID



(a) For link$_1$



(b) For link$_2$

Fig.20 Desired and actual trajectories for both links using Fuzzy Immune FOPID

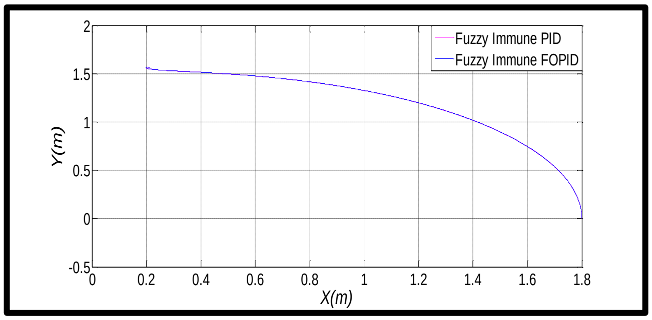
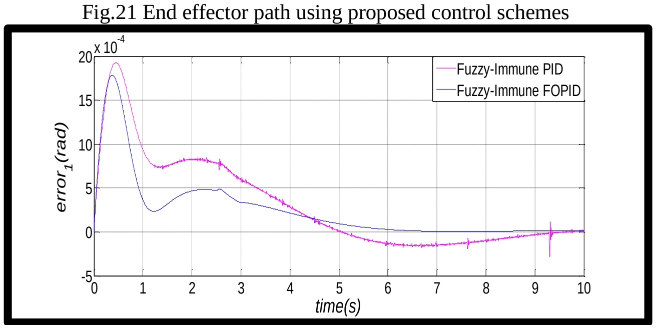
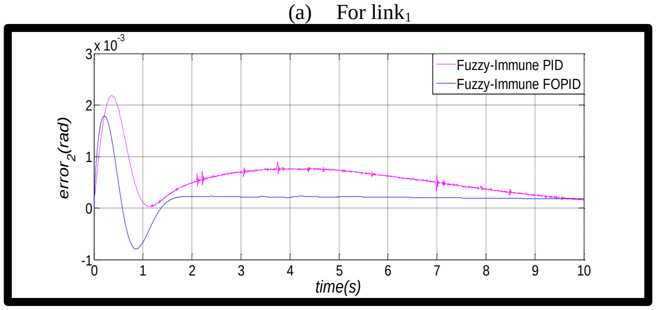


Fig.21 End effector path using proposed control schemes



(a) For link$_1$



(b) For link$_2$

Fig.22 errors in links using proposed control schemes

b. Robustness Test

1. Results for the different load conditions

Robustness test of the proposed controllers is performed for load condition. The values of MSEs for CSA-Fuzzy-Immune PID and CSA- Fuzzy-Immune FOPID controllers for both links under different load conditions are summarized in table IV, V and VI.

a. For First Trajectory

Table IV MSEs for both link using proposed control schemes under different load conditions

Load (kg)	Fuzzy-Immune PID	Fuzzy-Immune FOPID
0	$1.268*10^{-6}$	$8.548*10^{-7}$
	$6.064*10^{-6}$	$3.904*10^{-6}$
0.2	$1.877*10^{-6}$	$1.577*10^{-6}$
	$7.176*10^{-6}$	$4.300*10^{-6}$
0.35	$2.434*10^{-6}$	$2.273*10^{-6}$
	$8.225*10^{-6}$	$4.605*10^{-6}$
0.6	$3.554*10^{-6}$	$3.733*10^{-6}$
	$1.039*10^{-5}$	$5.169*10^{-6}$

From Table IV it can be noticed that the CSA-FIFOPID controller has better MSE value than CSA-FIPID controllers.

b. For Second Trajectory

Table V MSEs for both links using proposed control schemes under different load condition

Load (kg)	Fuzzy-Immune PID	Fuzzy-Immune FOPID
0	$9.611*10^{-7}$	$5.451*10^{-7}$
	$6.745*10^{-6}$	$4.203*10^{-6}$
0.2	$1.390*10^{-6}$	$8.514*10^{-7}$
	$7.947*10^{-6}$	$4.554*10^{-6}$
0.35	$1.784*10^{-6}$	$1.146*10^{-6}$
	$9.173*10^{-6}$	$4.854*10^{-6}$
0.6	$2.617*10^{-6}$	$1.762*10^{-6}$

From Table V it can be noticed that the CSA-FIFOPID controller has better MSE value than CSA-FIPID controllers.

c. For Third Trajectory

Table VI MSEs for both links using proposed control schemes for the different load conditions

Load (kg)	Fuzzy-Immune PID	Fuzzy-Immune FOPID
0	$7.312*10^{-7}$	$1.452*10^{-7}$
	$4.880*10^{-7}$	$2.558*10^{-8}$
0.2	$1.281*10^{-6}$	$2.425*10^{-7}$
	$8.479*10^{-7}$	$3.168*10^{-7}$
0.35	$1.834*10^{-6}$	$3.348*10^{-7}$
	$1.199*10^{-6}$	$3.482*10^{-7}$
0.6	$2.989*10^{-6}$	$5.257*10^{-7}$
	$1.959*10^{-6}$	$4.418*10^{-8}$

From Table VI it can be noticed that the CSA-FIFOPID controller has better MSE value than CSA-FIPID controllers.

2. **Results for Model Uncertainty**

Robustness test for model uncertainty is also performed by increasing the value of inertia from 5kg.m^2 to 5.05kg.m^2.

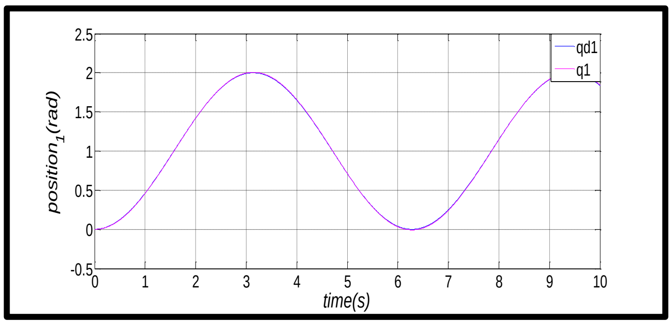
The values of MSE for CSA-Fuzzy-Immune PID and CSA- Fuzzy-Immune FOPID controllers for both links under model uncertainty for three trajectories are summarized in table VII, VIII and IX.

a. The First Trajectory

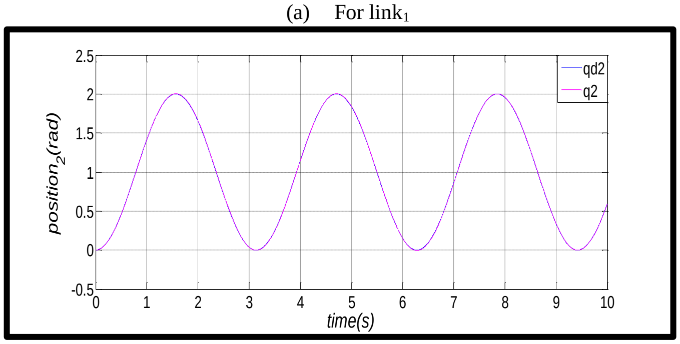
Table VII MSE for both link using proposed control schemes under model uncertainty

J(kg.m^2)	Fuzzy-Immune PID	Fuzzy-Immune FOPID
5	$1.268*10^{-6}$	$8.548*10^{-7}$
	$6.064*10^{-6}$	$3.904*10^{-6}$
5.05	$1.281*10^{-6}$	$8.568*10^{-7}$
	$6.164*10^{-6}$	$4.011*10^{-6}$

The desired and actual position for both links of robot manipulator controlled using CSA-FIPID and CSA-FIFOPID under model uncertainty are given in Fig. 23 and 24. Fig.25 gives a comparison between path tracking by the end effector using Fuzzy immune PID and Fuzzy Immune FOPID under load condition. Fig.26 gives complete comparisons between links errors using CSA-FIPID and CSA-FIFOPID under load condition.

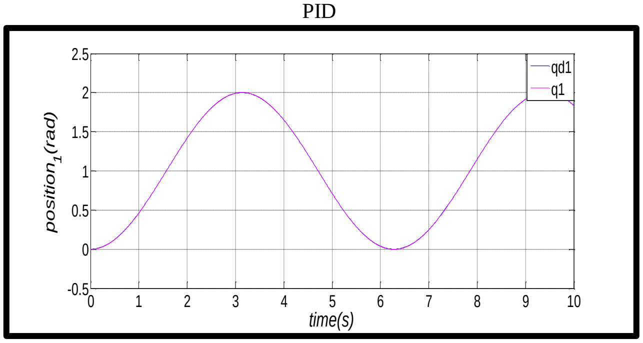


(a) For link$_1$

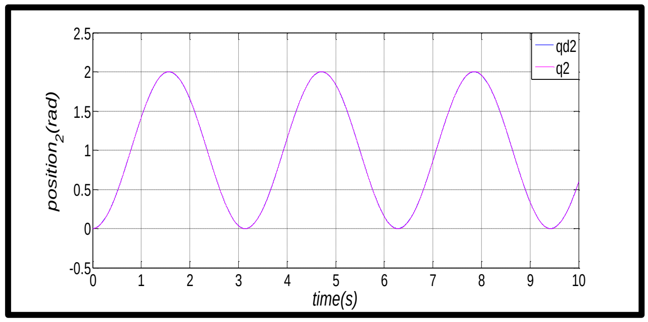


(b) For link$_2$

Fig.23 Desired and actual trajectories for both links using Fuzzy Immune PID



(a) For link$_1$



(b) For link$_2$

Fig.24 Desired and actual trajectories for both links using Fuzzy Immune FOPID

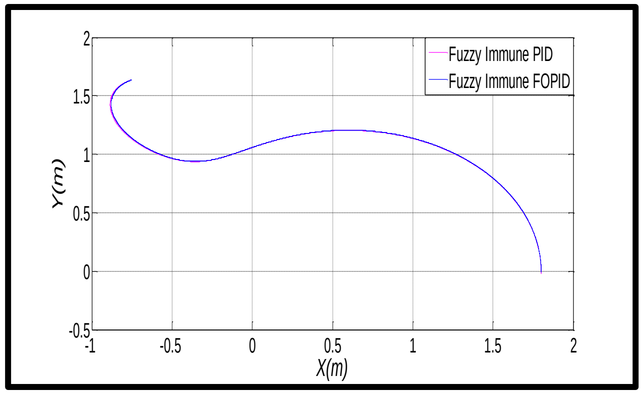
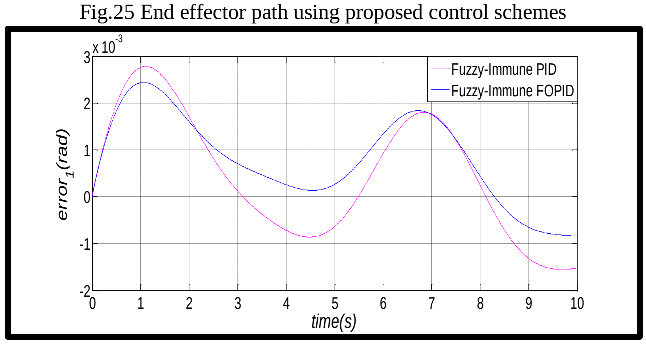
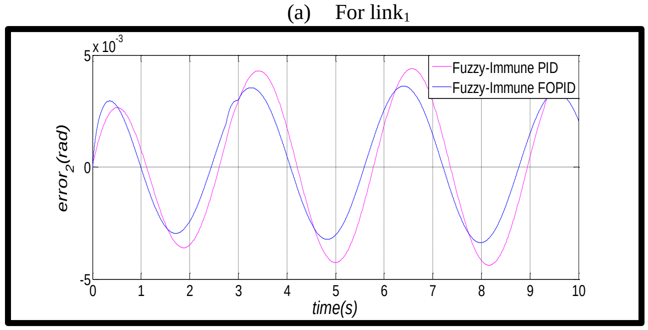


Fig.25 End effector path using proposed control schemes



(a) For link$_1$



(b) For link$_2$

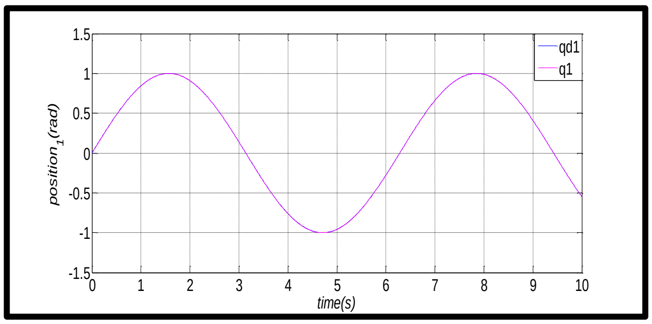
Fig.26 errors in links using proposed control schemes

b. The Second Trajectory

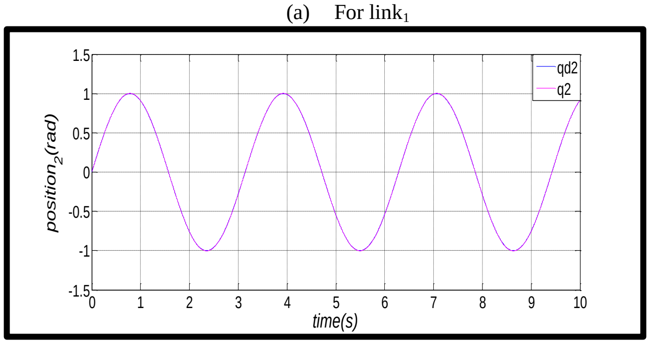
Table VIII MSE for both link using proposed control schemes under model uncertainty

$J(kg.m^2)$	Fuzzy-Immune PID	Fuzzy-Immune FOPID
5	$9.611*10^{-7}$	$5.451*10^{-7}$
	$6.745*10^{-6}$	$4.203*10^{-6}$
5.05	$9.696*10^{-7}$	$5.527*10^{-7}$
	$6.834*10^{-6}$	$4.279*10^{-6}$

From Table VIII it can be noticed that the CSA-FIFOPID controller has better MSE value than CSA-FIPID controllers. The desired and actual position for both links of robot manipulator controlled using CSA-FIPID and CSA-FIFOPID are given in Fig. 27 and 28. Fig.29 gives comparison between path tracking by end effector using Fuzzy immune PID and Fuzzy Immune FOPID. Fig.30 gives complete comparisons between links errors using CSA-FIPID and CSA-FIFOPID.

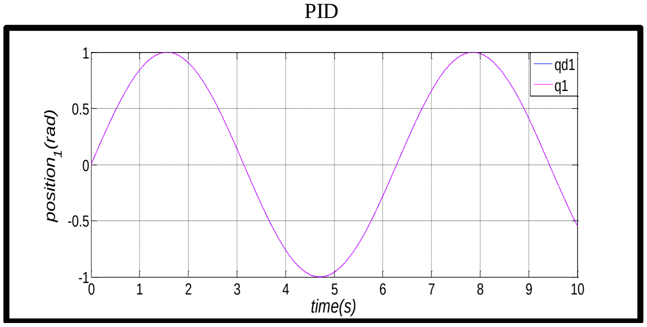


(a) For link$_1$

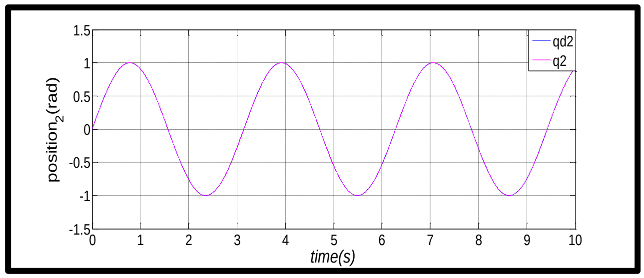


(b) Link$_2$

Fig.27 Desired and actual trajectories for both links using Fuzzy Immune PID



(a) For link$_1$



(b) For link$_2$

Fig.28 Desired and actual trajectories for both links using Fuzzy Immune FOPID

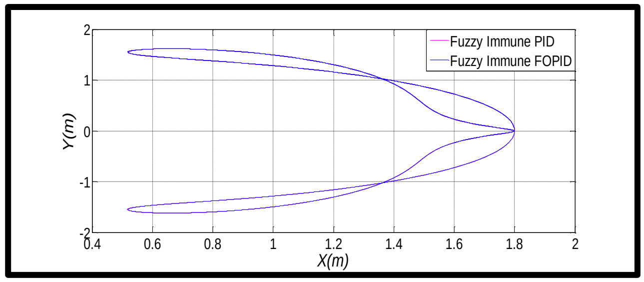
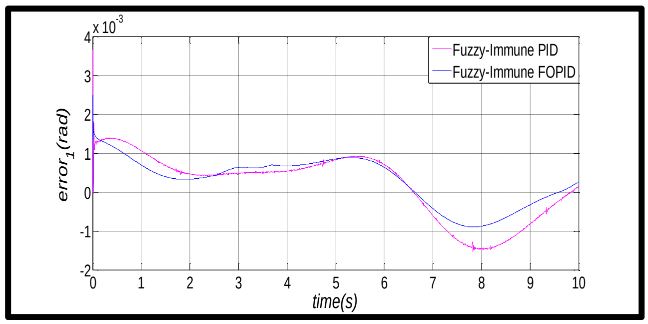
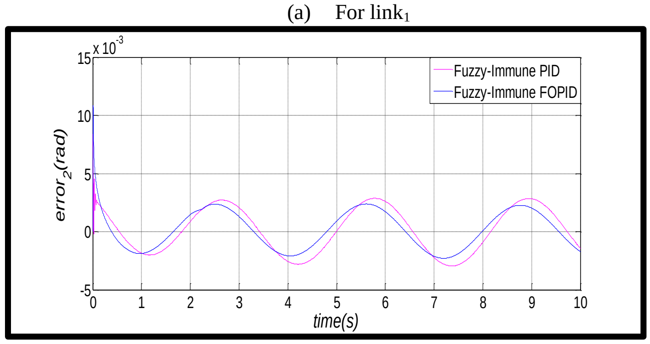


Fig.29 End effector path using proposed control schemes



(a) For link$_1$



(b) For link$_2$

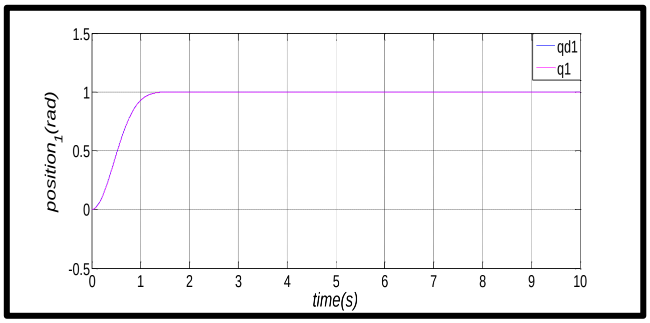
Fig.30 errors in links using proposed control schemes

c. The Third Trajectory

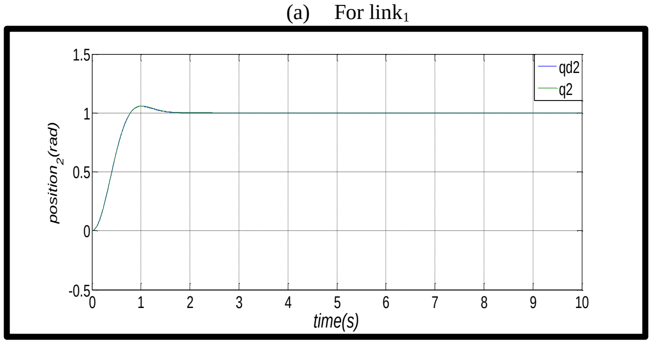
Table IX MSE for both link using proposed control schemes under model uncertainty

$J(kg.m^2)$	Fuzzy-Immune PID	Fuzzy-Immune FOPID
5	$7.312*10^{-7}$	$1.452*10^{-7}$
	$4.880*10^{-7}$	$2.558*10^{-7}$
5.05	$7.412*10^{-7}$	$1.460*10^{-7}$
	$4.933*10^{-7}$	$2.595*10^{-7}$

The desired and actual position for both links of robot manipulator controlled using CSA-FIPID and CSA-FIFOPID under model uncertainty are given in Fig. 31 and 32. Fig.33 gives comparison between path tracking by end effector using Fuzzy immune PID and Fuzzy Immune FOPID under load condition. Fig.34 gives complete comparisons between links errors using CSA-FIPID and CSA-FIFOPID under load condition.

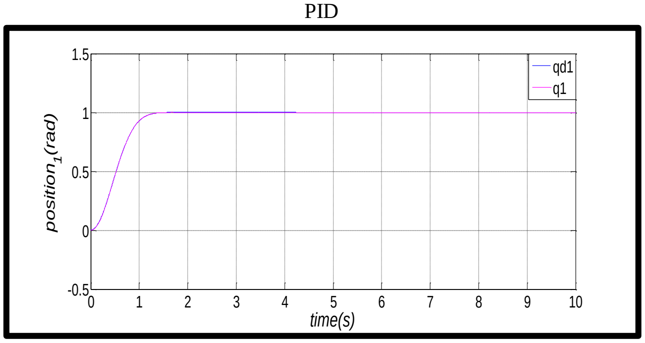


(a) For $link_1$

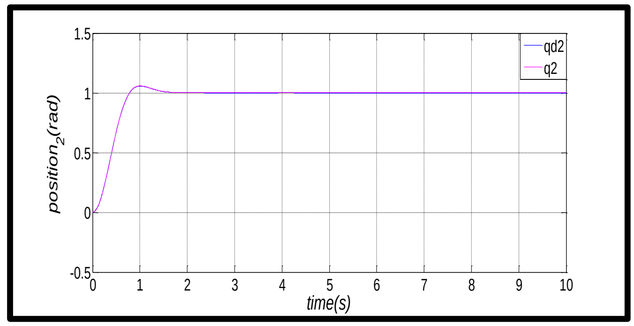


(b) For $link_2$

Fig.31 Desired and actual trajectories for both links using Fuzzy Immune PID



(a) For $link_1$



(b) For $link_2$

Fig.32 Desired and actual trajectories for both links using Fuzzy Immune FOPID

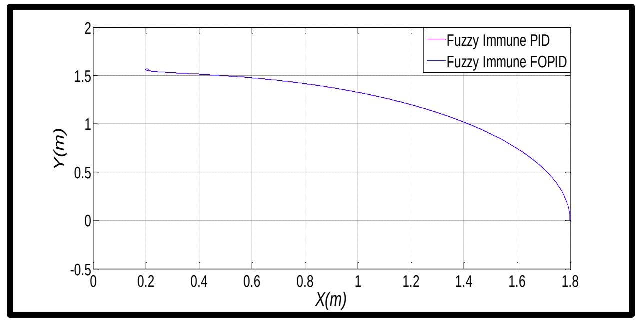
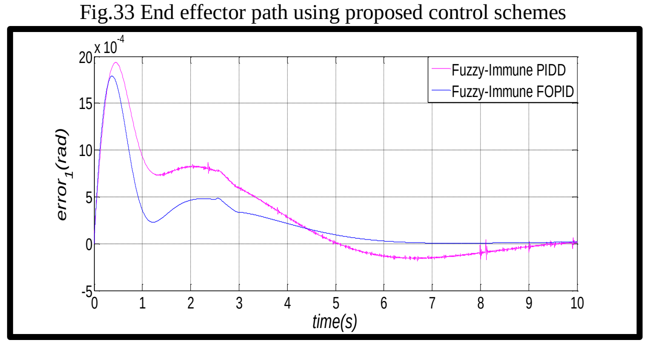
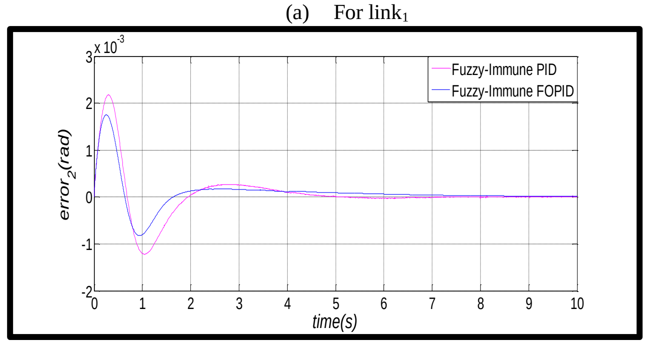


Fig.33 End effector path using proposed control schemes



(a) For $link_1$



(b) For $link_2$

Fig.34 errors in links using proposed control schemes

VII. Conclusion

The FIFOPID controllers are designed for a 2-link robot manipulator for trajectory tracking problem in this paper. The performance of FIFOPID controller is compared with FIPID controller. The tuning techniques namely CSA has been used to adjust the factors of PID and FOPID controllers. From the simulation results, it can be concluded that CSA-FIFOPID controller comes out to be more effective and robust as compared with CSA-FIPID controllers for trajectory tracking problem.

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