

# Fractional order PID controller tuned by bat algorithm for robot trajectory control

Mohammad A. Faraj, Abdulsalam Mohammed Abbood

Department of Electrical Engineering, College of Engineering, University of Anbar, Ramadi, Iraq

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## ABSTRACT

This paper deals with implementing the tuning process of the gains of fractional order proportional integral derivative (FOPID) controller designed for trajectory tracking control for two-link robotic manipulators by using a Bat algorithm. Two objective functions with weight values assigned has been utilized for achieving the minimization operation of errors in joint positions and torque outputs values of robotic manipulators. To show the effectiveness of using a Bat algorithm in tuning FOPID parameters, a comparison has been made with particle swarm optimization algorithm (PSO). The validity of the proposed controllers has been examined in case of presence of disturbance and friction. The results of simulations have clearly explained the efficiency of FOPID controller tuned by Bat algorithm as compared with FOPID controller tuned by PSO algorithm.

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## Corresponding Author:

Mohammad A. Faraj

Department of Electrical Engineering

College of Engineering, University of Anbar, Ramadi, Iraq

Email: Mohammed.faraj@uoanbar.edu.iq

## 1. INTRODUCTION

Robot manipulator has been recently employed in several industrial applications. The existing of Robot manipulators in these industrial applications has been made the designers to make a lot of efforts for solving the problems of controllers' design associated with robot work [1-2]. The complexity in manipulator structure has been made the trajectory tracking control of robotic manipulators is a challenge problem [3]. For treating these problems, many methods have been introduced including computed torque method [4], optimal control [5], variable structure control (VSC) [6], model based adaptive FOPID [7]. The main disadvantages of these types of controllers is the need of deriving complicated mathematical model for the manipulator. The limitations obtained from these methods has been brought bad results and unstable systems. To overcome these limitations, authors present an intelligent control technique which do not need the knowledge of the mathematical model of the manipulator, such as neural network fuzzy logic, wavelet network [8-10]. On the other hand, the various limitations of traditional PID controllers, such as error calculating, noise in the derivative control; simplification, has been made the designers to improve the performance of classical PID controllers depending on some concepts with mathematics background of fractional calculus that deals with integrals and derivatives using non-integer orders. FOPID controllers has been created and named by Podlubny [11]. The performance of FOPID controllers had been tested and implemented in numerous applications such as system identification [12], robotic manipulators [13], thermal systems [14], Induction motors [15], and power systems [16]. The using of FOPID controller enables the designers more degree of freedom for the selection of controller parameters. According to designee criteria, five parameters ( $k_p$ ,  $k_d$ ,  $\mu$ ,  $k_i$  and  $\lambda$ ) need to be tuned. The tuning of these parameters has recently become

possible due to developments of an evolutionary optimization algorithms. Several bio inspired optimization techniques has been tested and implemented as powerful tool for solving an optimization problem for different applications such as : genetic algorithm GA [17], particle swarm optimization PSO [18, 19], ant colony optimization (ACO) [20], differential evolution (DE), artificial bee colony [21], Cuckoo search algorithms (CSA) [22, 23], bat algorithm [24]. Many of these algorithms has been focused on tuning FOPID controller parameters for robotic manipulators [17, 18, 22, 23, 25]. One of these efficient optimization algorithms that is used in tuning FOPID controller parameters is a Bat algorithm. Bat Algorithm has been used as powerful tool in optimization operation for many applications [26-30]. Bat algorithms has become popular among researchers, some of these features is concerned with number of parameter used for initializations where a lower number of parameter used as compared with other types of swarm based algorithms. The other important feature is that bat convergences rate is independent of its parameters [24, 29, 30]. This paper can be constructed as follow: after a brief introduction in Section 1, the deriving of the mathematical model of robot manipulator has been explained in Section 2. In Section 3, the description of FOPID controller structure will be drawn. In Section 4, an explanation of PSO and Bat algorithms are involved. The simulation results have been explained and discussed in detail in Section 5. Finally, the conclusions of the present work and suggestions notes for future works has been drawn in Section 6.

**2. DYNAMIC MODEL OF ROBOTIC MANIPULATOR**

For controller design, it is necessary to have a mathematical model of system. The dynamic equations of an n –link robot manipulator can be derived depending on the Lagrangian formulation as [3]:

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) + F(q, \dot{q}) + \tau_d = \tau \tag{1}$$

Where  $M(q) \in R^{n \times n}$  is a symmetric and positive definite inertia matrix,  $C(q, \dot{q})\dot{q}$ , the Coriolis/centripetal vector, and  $G(q)$  is the gravity vector,  $F(q, \dot{q})$  the friction vector contains viscous and coulomb friction, and  $\tau_d$  is a bounded unknown disturbance (including unstructured unmolded dynamics ). A two-link robot manipulator can be can be described as in (2):

$$\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \ddot{q} + \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \dot{q} + \begin{bmatrix} G1 \\ G2 \end{bmatrix} + \begin{bmatrix} D_{istr1} \\ D_{istr1} \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \tag{2}$$

Where:  $M_{11} = (m_1 + m_2)l_1^2 + m_2l_2^2 + 2m_2l_1l_2 \cos(q_2)$ ,  $M_{12} = M_{21} = m_2l_2^2 + m_2l_1l_2 \cos(q_2)$ ,  $M_{22} = m_2l_2^2$ ,  $C_{11} = -m_2m_2l_1l_2 \sin(q_2)\dot{q}_2$ ,  $C_{12} = -m_2m_2l_1l_2 \sin(q_2)\dot{q}_1 - m_2m_2l_1l_2 \sin(q_2)\dot{q}_2$ ,  $C_{21} = m_2m_2l_1l_2 \sin(q_2)\dot{q}_1$ ,  $G_1 = g((m_1 + m_2)l_1 \cos(q_1) + m_2l_2 \cos(q_1 + q_2))$ ,  $G_2 = gm_2l_2 \cos(q_1 + q_2)$ .  $m_1$  and  $m_2$  are masses and  $l_1$   $l_2$  are lengths of link 1 and 2, respectively.  $\tau_1$  and  $\tau_2$  are torque at joints 1 and 2 respectively.  $d_i(t)$  is unknown but bounded external disturbance with:  $|d_i(t)| \leq d_{ui}, i = 1, 2$ .

**3. FRACTIONAL ORDER PID CONTROLLER STRUCTURE**

When an integrator of order  $\lambda$  and a differentiator of order  $\mu$  is added to classical PID controller with real numbers. The transfer function of a controller has the structure shown in (3):

$$U(s) = (K_p + K_I \frac{1}{s^\lambda} + K_D s^\mu)E(s) \tag{3}$$

Where,  $E(s)$  is the error, and  $U(s)$  is controller’s output. The control signal  $u(t)$  can be defined in the time domain as:

$$U(t) = (K_p e(t) + K_I \frac{d^{-\lambda}}{dt^{-\lambda}} e(t) + K_D \frac{d^\mu}{dt^\mu} e(t)) \tag{4}$$

#### 4. FRACTIPONAL ORDERR PID (FOPID) TUNED BY OPTIMAZTION ALGORITHMS

In this work, the five parameters of FOPID controller will be tuned using Bat algorithm (BAT). To show the effectiveness of this algorithm over other optimization algorithms, Bat algorithm will be compared with particle swarm optimization algorithm (PSO). The block diagram of closed loop control system involving FOPID controller is shown in Figure 1.

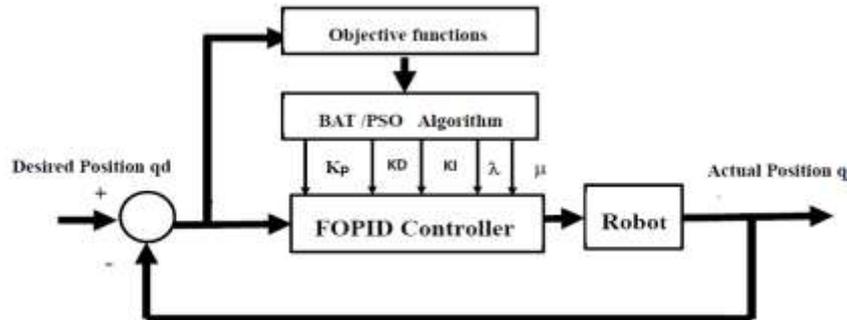


Figure 1. Manipulator position control system using FOPID controller tuned by BAT/PSO algorithms

##### 4.1. Particle swarm optimization (PSO)

PSO is an optimization algorithm invented by Kennedy and Eberhart in 1995, inspired from social behavior of animals (birds, fishes, insects) in their swarms when they search to find their foods. PSO has been proven as an effective optimization method for solving optimization problems in many nonlinear systems applications. An initial position and velocity values are assigned in this algorithm. These values moving through the search space and then appreciated according to criteria's of particular objective function [31]. For each iteration, there are two values obtained, the first one is the best local values resulting from particle previous experience for itself and called personal best (Pbest). The second values are coming from having the best position in the swarm and called global best (gbest). In (5) and (6) describe the velocity and position of updating process for each particle in the swarm:

$$v_i^{k+1} = w * v_i^k + c_1 R_1 * (lbest_i - x_i^k) + c_2 R_2 * (gbest_i - x_i^k) \quad (5)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (6)$$

Where:  $x_i^k$  is position of particle  $i$  at iteration  $k$ ;  $v_i^k$  is the velocity of particle  $i$  at iteration  $k$ ;  $w$  is the inertial weight,  $c_1$  and  $c_2$  are the acceleration constants;  $R_1$  and  $R_2$ , are a random variables between 0 and 1 [19-21].

##### 4.2. Bat optimization algorithm (BAT)

In 2010 Xin-She Yang has been developed a population-based metaheuristic optimization technique like PSO and GA. This algorithm simulates the behavior of micro bat animals to take their prey/food by and called it Bat algorithm [24]. The algorithm imitates the echolocation behavior of micro bat by varying its emission pulse rate and loudness. Three general rules developed by Xin-She Yang has been considered as the biases of bat algorithm operations as the following [24]:

- Sensing distance, distinguishing the difference between food/prey and knowing background barriers are achieved by all bats by using echolocation.
- When search on particular prey, bats vary its wavelength  $\lambda$  and loudness  $A_0$  flying randomly with velocity  $v_i$  at position  $x_i$  with a frequency  $f_{min}$ . Wavelength (or frequency) of emitted pulses of bats can be automatically adjusted. Adjusting of the rate of pulse emission  $r \in [0, 1]$  is also accomplished depending on the proximity of their goal.

- c) In spite of the ability of the loudness to vary in many ways, it is assumed that the variations of loudness can be from a large (positive)  $A_0$  to a minimum constant value  $A_{min}$ . Because of the relationship between frequency and wavelength the change can be described in this algorithm either in terms of frequency  $f$  or wavelength  $\lambda$ . Velocity  $v_i^t$  and a location  $x_i^t$  are assigned to each bat at iteration  $t$  for implementing the bat motion in solution space. There exists a current best solution  $x^*$  from all the bats in search space. The rules that describe Bat motion can be formulated as shown in (7-9):

$$f \min = f \min + (f \max - f \min) \beta \tag{7}$$

$$v_i^t = v_i^{t-1} + (x_i^{t-1} - x_{*}) f_i \tag{8}$$

$$x_i^t = x_i^{t-1} + v_i^t \tag{9}$$

Where,  $\beta \in [0, 1]$  is a random vector drawn from a uniform distribution. At the beginning a frequency which is drawn uniformly from  $[fmin, fmax]$  is randomly assigned to each bat therefore, bat algorithm can be considered as an algorithm concerned with using frequency for tuning providing a balanced method between of exploration and exploitation. The loudness and pulse emission rates essentially provide a mechanism for automatic control and auto zooming into the region with effective solutions [21]. During the iterations, the loudness and pulse emission rates must be varied in an effective way such that getting an effective mechanism for controlling the exploration and exploitation. When the prey has been founded by a bat, the loudness will decrease. at the same time the rate of pulse emission increases, therefore we can select the loudness between  $A_{min}$  and  $A_{max}$ , with assumption that  $A_{min}$  goes to zero when a bat has just reach its prey. In this case the bat will stop emitting sounds. According to these assumptions, (10-11) will be considered [29]:

$$A_i^{t+1} = \alpha A_i^t \tag{10}$$

$$r_i^{t+1} = r_i^0 [1 - EXP(-\gamma t)] \tag{11}$$

Where  $\alpha$  and  $\gamma$  are constants. For any  $0 < \alpha < 1$  and  $\gamma > 0$ , we have [27]:

$$A_i^t \rightarrow 0, r_i^t \rightarrow r_i^0 \text{ as } t \rightarrow \infty \tag{12}$$

The procedure for implementing Bat Algorithm used in this paper can be found in [24, 25].

**4.3. Objective functions**

Reducing the errors in control system is considered as the main goal of solving the control problem. The assigning and choosing the appropriate objective function for control problems enable us to improve the performance of the system. In this work, the integral absolute error (IAE) and integral absolute change in control output (IACCO) represented in (13) and (14) has been chosen as objective functions in order to make an error reduction between desired and actual positions as well as minimizing the changing in control output.

$$J_1 = \int |e_1(t)| dt + \int |e_2(t)| dt \tag{13}$$

$$J_2 = \int |\Delta \tau_1| dt + \int |\Delta \tau_2| dt \tag{14}$$

$$J = w_1 J_1 + w_2 J_2$$

where  $e_1(t)$  and  $e_2(t)$  represent the errors in link one and two respectively;  $\Delta \tau_1$  and  $\Delta \tau_2$  indicate the controller output changing obtained in Link1 and Link2 respectively. ( $w_1=0.8$ ) and ( $w_2=0.6$ ) are the weights assigned to  $J_1$  and  $J_2$  respectively.

## 5. SIMULATION AND RESULTS

### 5.1. Trajectory tracking performance of robotic manipulators using BAT- FOPID controller

The results that obtained from tracking reference position trajectory for robot manipulator has been indicated and discussed in this section. The simulation is done using MATLAB program. Bat and PSO algorithms are used to tune the parameters of FOPID controllers. PSO algorithms used as comparative method for showing the effectiveness of BAT algorithms. The value of dynamical parameters of robot has been chosen as following :  $m_1=0.8 \text{ kg}$ ,  $m_2=2 \text{ kg}$ ,  $\ell_1=\ell_2=1 \text{ m}$ . The trajectory chosen:  $q_{d1}(t)=\pi/4-\pi/4\cos\pi t$ ,  $q_{d2}(t)=\pi/4-\pi/4\cos\pi^2/1.66t$ . The initial conditions are:  $q_d(0)=[0 \ 0]^T$ ,  $\dot{q}_d(0)=[0 \ 0]^T$ .

Figure 2 illustrates the values of fitness versus generation in case of using BAT and PSO algorithms in tuning FOPID controllers. Table 1 indicates the parameters values used in initialization of the BAT and PSO algorithms. FOPID gains and IAE values obtained from using BAT and PSO algorithms are presented in Table 2. The graphs of position response, control signals and errors in position are illustrated in Figure 3. It is obvious from the Table 2 and Figure 3 the superiority of FOPID controllers that used BAT algorithm over than of those used PSO algorithm.

Table 1. Parameters of PSO, BAT algorithms

PSO Algorithm BAT			
parameter	Parameter values	Parameter	Parameter values
Population size	10	Population size	10
Generations	10	Generations	10
Acceleration c1	2	a=g	0.9
Acceleration c2	2	$A_i^0$	0.7
Inertia weigh, $w_{min}$	0.9	$r_i^0$	0.8
Inertia weight, $w_{max}$	0.4	$f_{max, min}$	0.1
Iterations	80	Iterations	

Table 2. IAE and controller parameter for PSO-FOPID and BAT-FOPID controllers

Parameter	1 <sup>st</sup> link		Parameter	2 <sup>nd</sup> link	
	FOPID with PSO	FOPID with BAT		FOPID with PSO	FOPID with BAT
$K_P$	56.8	33.7	$K_P$	11.2	18.9
$K_I$	93.2	330.1	$K_I$	88.7	441.6
$K_D$	0.956	1.35	$K_D$	0.876	0.78
$\mu$	0.2888	0.41	$\mu$	0.3111	0.74
$\lambda$	0.9765	0.95555	$\lambda$	0.077	0.876
IAE	0.0411	0.0165	IAE	0.0507	0.0187

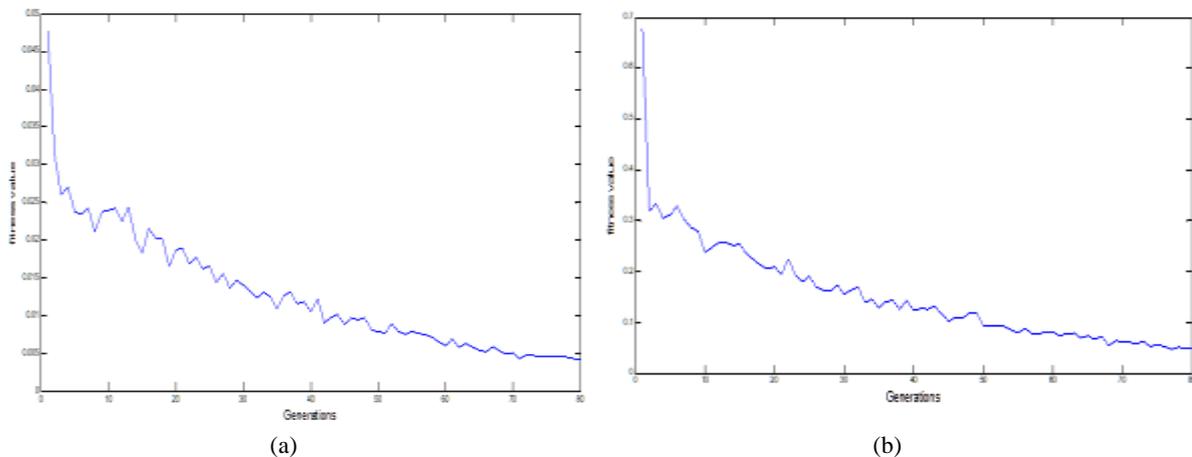


Figure 2. Fitness value versus generations using (a) BAT, (b) PSO

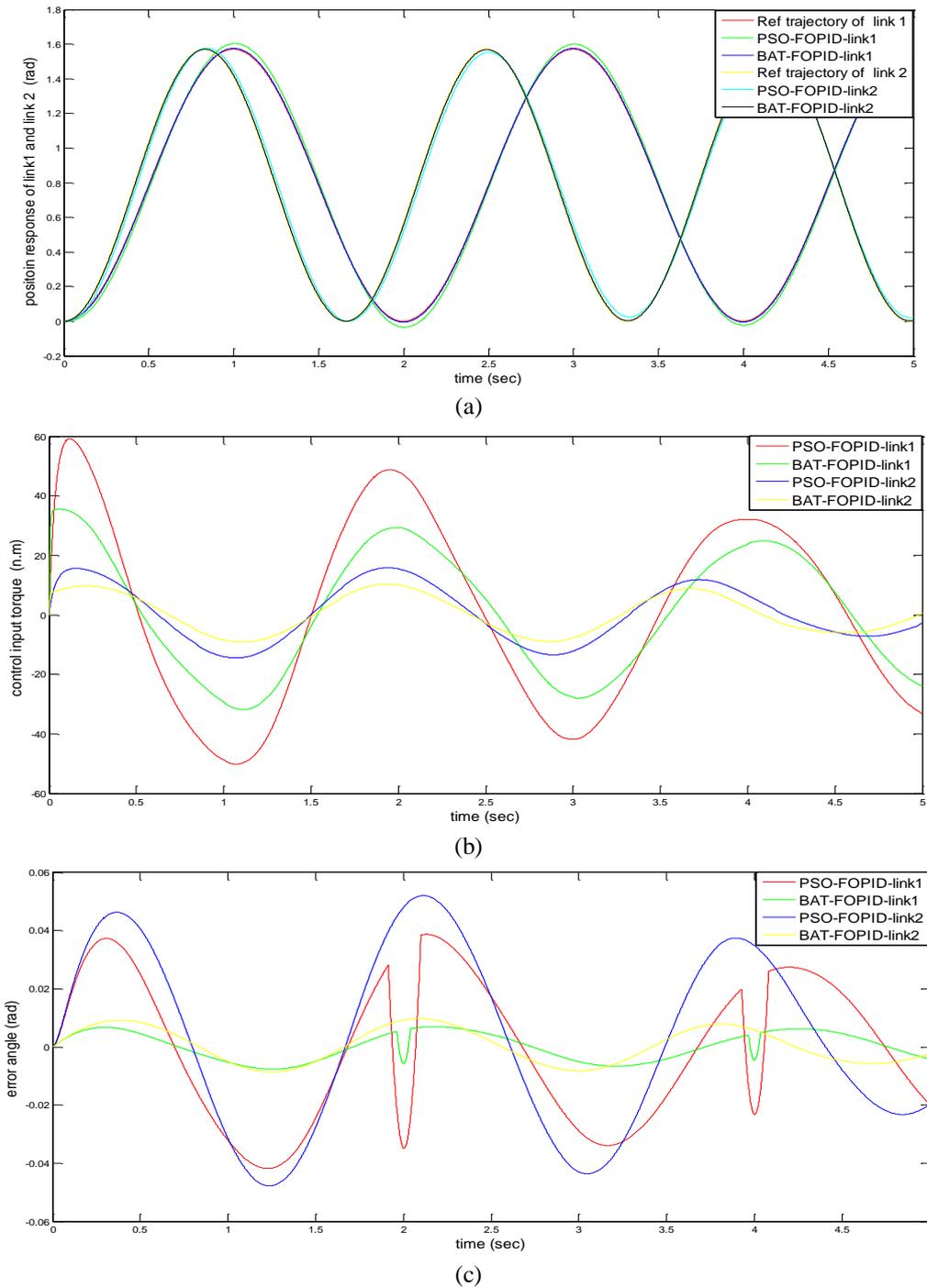


Figure 3. (a) Position response (b) Control signals (c) Errors in position for robotic manipulator links controlled by FOPID controllers tuned by BAT and PSO algorithms

**5.2. Trajectory tracking performance of robotic manipulators using BAT- FOPID controller with sinusoidal disturbances**

In this Section, ability of BAT-FOPID and PSO-FOPID controllers to reject the disturbances existence has been investigated.  $0.2\sin(t)$  N.m has been chosen as a disturbance. This disturbance is applied to the controller output of the first Link, second link and both links for the entire 5 sec. Figure 4 illustrates The position response, control signals and position errors graphs when a sinusoidal disturbance is applied. Table 3 indicates an IAE in case of disturbances rejections. It is obvious from the Table 3 that the IAE values for FOPID controllers that used BAT algorithm are lesser than of those used PSO algorithm.

Table 3. Values of IAE for FOPID controllers tuned by BAT and PSO algorithms in case of rejection of disturbance

	Disturbance (N.m ) FOPID tuned by BAT Algorithm		FOPID tuned by PSO Algorithm	
	1 <sup>st</sup> link	2 <sup>nd</sup> link	1 <sup>st</sup> link	2 <sup>nd</sup> link
1st link	0.0144	0.0199	0.0415	0.0711
2nd link	0.0180	0.0214	0.0439	0.0827
Both links	0.0214	0.0265	0.0612	0.0894

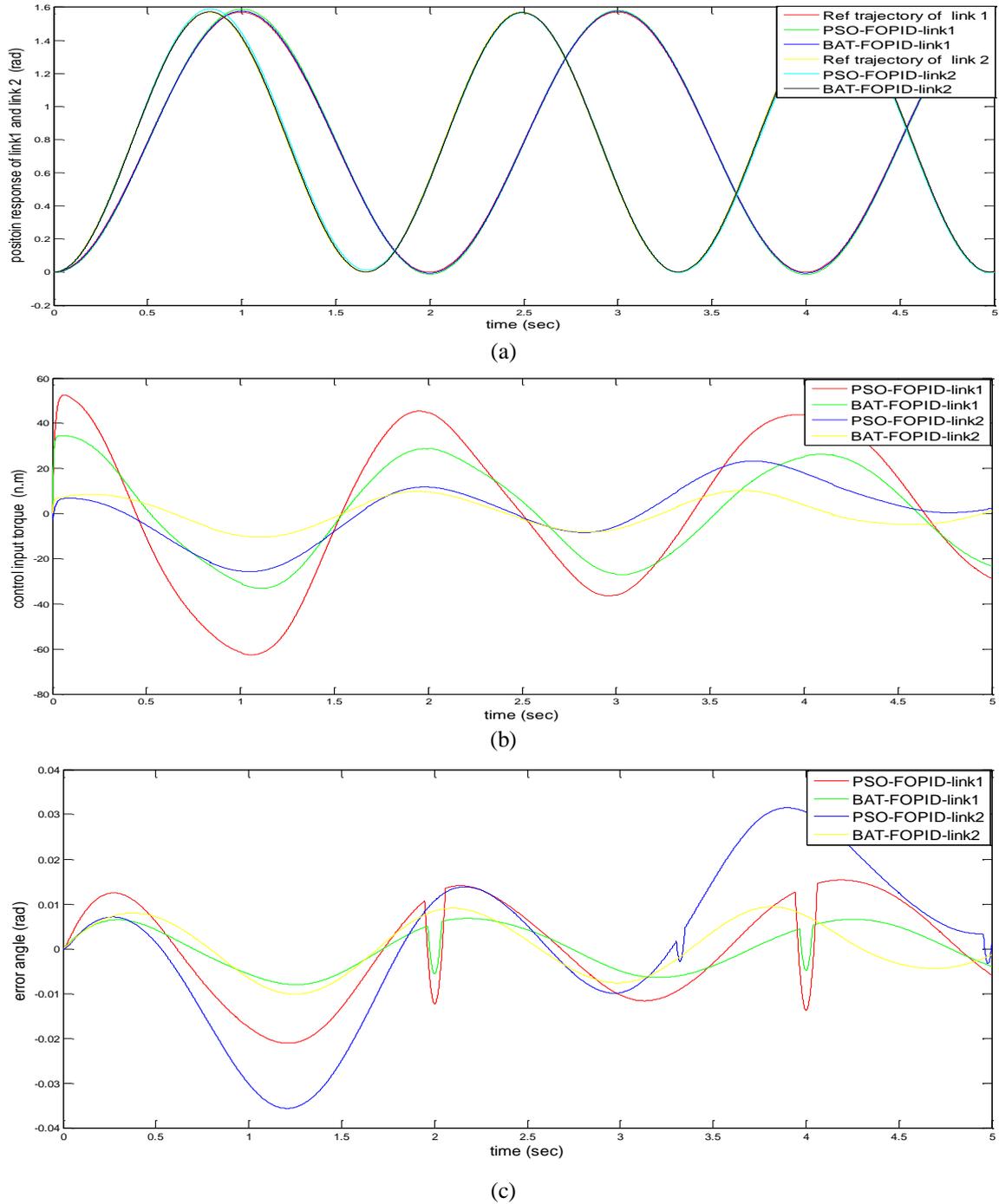


Figure 4. (a) Position response, (b) Control signals, (c) Errors in position for FOPID controllers tuned by BAT and PSO algorithms in case of Disturbance rejection in link1 and link2

**5.3. Trajectory tracking performance of robotic manipulators using BAT- FOPID controller with friction terms**

In this section, friction terms will be applied for two link robotic manipulators. The friction terms  $f_1(\dot{q}_1)$  and  $f_2(\dot{q}_2)$  in (1) can be specified using equations:  $f_1(\dot{q}_1) = c_1 \text{sgn}(\dot{q}_1) + v_1 \dot{q}_1$ ,  $f_2(\dot{q}_2) = c_2 \text{sgn}(\dot{q}_2) + v_2 \dot{q}_2$ , The parameter values are selected as  $c_1 = c_2 = 0.1$   $v_1 = v_2 = 2$ . The position response, control signals and position errors graphs when a friction terms are applied are illustrated in Figure 5. The IAE values in case of friction terms existence has been indicated in Table 4. It is obvious from the Table 4 that the IAE values for FOPID controllers that used BAT algorithm are lesser than of those used PSO algorithm.

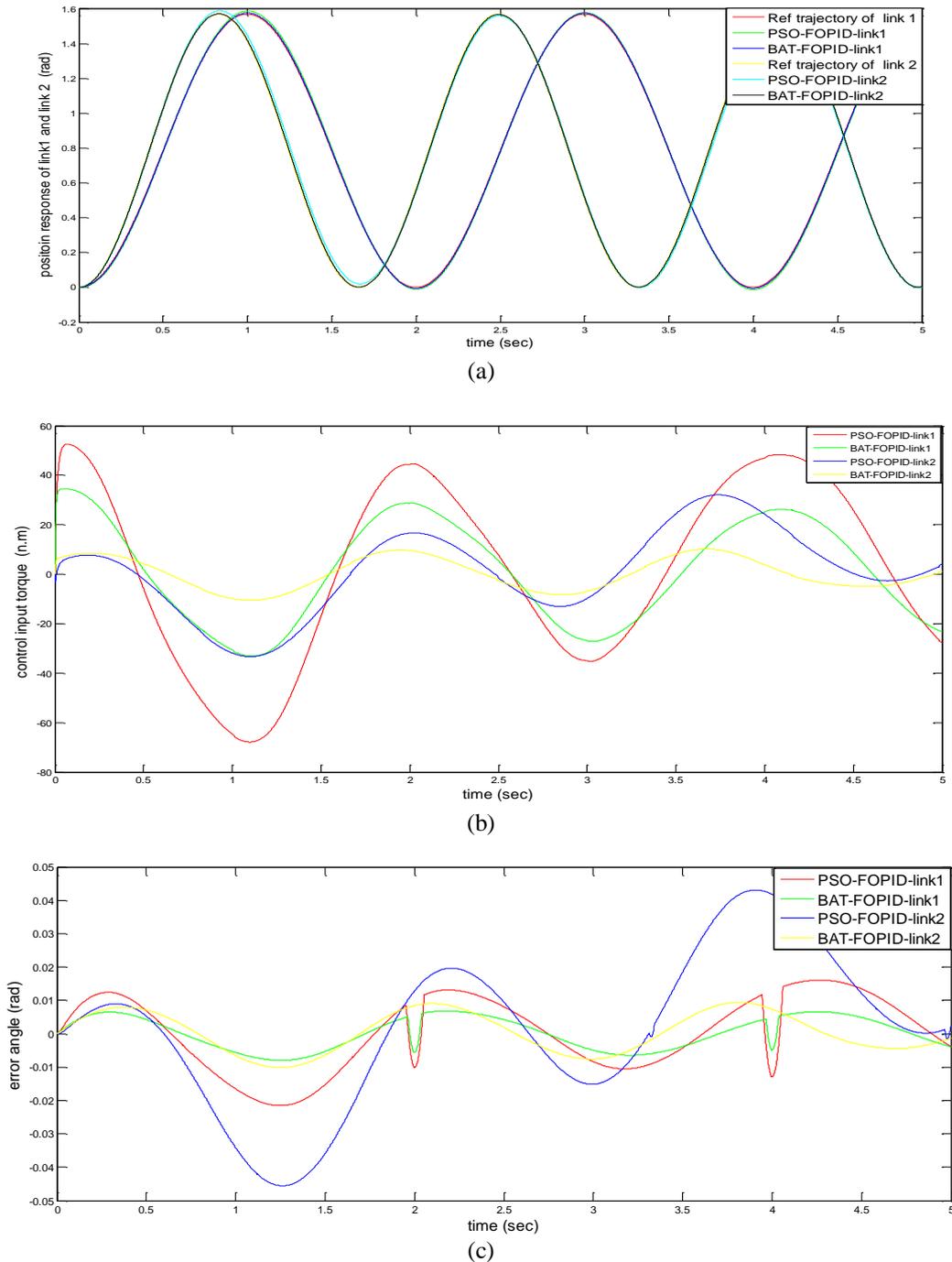


Figure 5. (a) Position response (b) Control signals (c) Errors in position for FOPID controllers tuned by BAT and PSO algorithms in case of friction existence

Table 4. Values of IAE for FOPID controllers tuned by BAT and PSO algorithms in case of friction existence

	Friction FOPID tuned by BAT Algorithm		FOPID tuned by PSO Algorithm	
	1 <sup>st</sup> link	2 <sup>nd</sup> link	1 <sup>st</sup> link	2 <sup>nd</sup> link
Both links	0.0117	0.0199	0.0679	0.0905

## 6. CONCLUSION

In this work, the FOPID controller tuned by one of evolutionary algorithms called a BAT algorithm are employing for trajectory tracking problem in position control system for a 2-link robot manipulator. FOPID controller tuned by BAT algorithm has been compared with PSO-FOPID controller for position response task. To examine the effectiveness of proposed controllers, the disturbance rejection test and friction terms has been applied to first and second links of robotic manipulators. It can be observed from results of simulation that BAT -FOPID controller is more efficient and accurate when compared with FOPID controller tuned by PSO algorithm in case of position tracking, rejection of disturbance and friction existence. In the future, BAT-FOPID controller can be applied for another types of robotic manipulators.

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## BIOGRAPHIES OF AUTHORS



**Mohammad. A. Faraj** was born in Al-anbar, Iraq in 1982. He received the B.Sc. from the university technology, control and systems engineering department. Baghdad, Iraq, in 2004. And he received the M.Sc. degree from University of Technology, control and systems engineering department in 2008, in mechatronics engineering specialization. In 2008, he joined the department of electrical engineering at university of Al-Anbar, Ramadi, in Iraq, as an Asst. Lecturer. Currently he is a lecturer in the department of electrical engineering at university of Al-Anbar, Ramadi, in Iraq. His research interest include adaptive control, control systems, robot manipulator, and mobile robot and optimization algorithms.



**Abdulsalam Mohammed Abbood** was born in babil, Iraq 1958. He received the B.S degree from the university of Sarajevo of Yugoslavia, in 1981 and M.S. degree from the university of Beograd of Yugoslavia, in 1983. Currently he is a lecturer in the department of electrical engineering at university of Al-Anbar, Ramadi, in Iraq. He has published over 4 refereed journal and conference papers in the areas of electronic circuits. and electrical machine