Position Control of IT-Robot manipulator using Multi–Loop FOPID

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Abstract – *Position control of the manipulator has been noted for its difficulty as the result of the so-called dynamic stability problem, parameter uncertainty and dynamic coupling. This work focused on position control of the first four degree of freedom (DOF) of IT-Robot manipulator using Fractional Order PID (FOPID) controller that can conquer this difficulty. All procedure description to model of the manipulator and control has been detailed and simulated using MATLAB R2015a/Simulink; from the mechanical model generation in SimMechanic where, the manipulator joint is moved using DC motor. Parameters of FOPID controller are optimized using GA. The controller effectiveness is analyzed for set point tracking. By simulation results, it was observed that FOPID controller give better response with minimum error than PID controller for the position control of the IT-robot manipulator.*

Keywords: *IT-Robot manipulator, SimMechanics, PID, Genetic Algorithm (GA) and Fractional Order PID (FOPID) Controller*

Article History
Received 7 December 2018
Received in revised form 7 January 2019
Accepted 8 January 2019

I. Introduction

IT-Robot manipulators are normally utilized robots in surgery applications to deliver fast movement and high precision and repeatable position. It composed of asset of links, connected by joints, which moved rotationally [1].

As a result of time varying dynamic, and highly coupled nonlinear, the robot manipulator position control is one of the, challenging problems. As well as uncertainty in the parameters of both actuating systems, and mechanical part of manipulators, would cause greater complexity. Different control techniques are introduced in the publications for example, proportional, integration, derivative (PID) control [2], feed-forward compensation control [3], adaptive control [4], variable structure control [5], neural networks control [6] and fuzzy control [7].

A generalization of the PID controllers has proposed by Podlubny, namely Fractional Order PID (FOPID) to get more robust controller [8]. Fractional calculus is a region of mathematics that deals with integrals, and derivatives utilizing non-integer orders. FOPID give better flexibility in the design of the controller and less sensitive to changes of the parameters of a controlled system compared with traditional PID controller [9]. The five parameters (k_p, k_d, μ, k_i and λ) of FOPID controller modeling process should be chosen, so there is a need for an efficient way to optimize these parameters. One of evolutionary optimization methods used to optimize the five parameters of the FOPID controller is Genetic algorithm (GA) [10].

The aim of the paper is to apply FOPID for position control of the first four joint angle of IT-Robot arm in order to get the required position with minimum error. The controller should ensure excellent position tracking to a given desired angle with better response, high stability, and small tracking errors. The 4- DOF IT-Robot manipulator model is done in SimMechanics Toolbox which does not require the mathematical modeling. The SimMechanics model is controlled by using the FOPID controller to effectively satisfy the desired angle for each joint and enables possibility to confirm model-based control algorithm.

The organization of this paper: The platform description of IT-Robot manipulator presented in Section II. Section III introduces the principle of FOPID controller. Position control of the of robot manipulator using fractional-order $PI^{\lambda}D^{\mu}$ controller are introduced in Sections IV. Simulation results for both developed controllers (PID, FOPID) are illustrated in Section V, followed by the concluding remarks in Section VI.

II. Robot platform description

IT-Robot manipulator is made by TeraSoft Incas presented in Fig. 1 [12]. It can be seen that IT-Robot manipulator has a serial 6 DOF with revolute joints. The specifications of the manipulator are presented in Table I This manipulator composed of 4 DOF appeared below categorized from base to top: Turntable, Bicep, Forearm and Wrist.

A. Kinematic model

The relationship between the individual joints of the rehabilitation device , the position and orientation of the robot's end-effector is expressed concisely by the four D-H parameters [13] given in Table II. The four parameters αi, a_i, θ_i d_i, are generally known as link twist, the link length, joint angle, and link offset respectively [14].

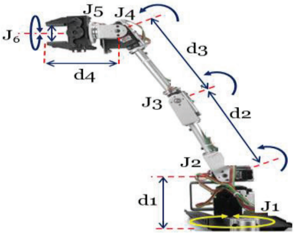


Fig.1. Robot Manipulator Model

TABLE I
THE LINK LENGTH OF MANIPULATOR

joint	*waist*	*shoulder*	*elbow*	*wrist*
symbol	d_1	d_2	d_3	d_4
Link length (MM)	*85*	*155*	*155*	*100*

TABLE II
THE LINK PARAMETER OF THE MANIPULATOR (D-H)

No	$\alpha_{i-1/(°)}$	$a_{i-1/(mm)}$	$d_{i-1/(mm)}$	$\theta_{i-1/(°)}$
1	*90*	*0*	*0*	θ_1
2	*0*	*0*	d_2	θ_2
3	*0*	*0*	d_3	θ_3
4	*-90*	*0*	d_4	θ_4
5	*0*	*0*	*0*	θ_5
6	*0*	*0*	*0*	*End-effector*

Based on these parameters shown in Table II, the transformation matrix T_6^0 includes the overall rotation and translation of tool frame {6} with respect to base frame {0}. The transformation matrix is given by (1):

$$T_6^0 = \begin{bmatrix} C_1.(C_{234}.C_5 - S_{234}.S_5) & C_1.(-C_{234}.S_5 - S_1.C_5) & -C_1.(C_{23}.S_4 + S_{23}.C_4) & C_1.(C_{234}.d_4 + C_{23}.d_3 + C_2.d_2) \\ S_1.(C_{234}.C_5 - C_{234}.S_5) & S_1.(-C_{234}.S_5 + C_1.C_5) & -S_1.(C_{23}.S_4 + S_{23}.C_4) & S_1.(C_{234}.d_4 + C_{23}.d_3 + C_2.d_2) \\ S_{234}.C_5 + C_{234}.C_5 & -S_{234}.S_5 & -S_4.((S_{23}) + C_4.C_{23}) & S_{234}.d_4 + S_{23}.d_3 + S_2.d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

Where:

$$C_i = \cos\theta_i,\ S_i = \sin\theta_i,\ S_{12} = S_1.C_2 + C_1.S_2,\ C_{12} = C_1.C_2 - S_1.S_2,$$

$$C_{234} = C_2.(C_3.C_4 - S_3.S_4) - S_2(S_3.C_4 + C_3.S_4),$$

$$S_{234} = S_2.(C_3.C_4 - S_3.S_4) + C_2.(S_3.C_4 + C_3.S_4)$$

B.Mechanical Model

The first step is to create a model of IT-Robot manipulator for applying the control methods. The mechanical model of the IT-Robot manipulator described with SimMechanic is appeared in Fig.2. Where, SimMechanics does not require the mathematical modeling and aides in mechanical systems simulation and modeling with a suite of tools to indicate bodies and their properties of the mass, systems coordinate, kinematics limitations, and their possible motions.

The mechanical model is composed of four revolute joints and four bodies. The module takes the torques as input and outputs are joint angles. To simply modeling tasks, the masses are considered to be assembled at the end of each connection.

III. Principles of FOPID controller

Fractional-order calculus, (FOC) is a generalization of the traditional integral and differential that incorporates non-integer orders. The most widely recognized type of a fractional order PID controller is the $PI^{\lambda}D^{\mu}$controller. Including a differential order μ and an integral order λ where, μ and λ can be any real numbers [16]. The FOPID transfer function is (2):

$$G_c(s) = \frac{O(s)}{E(s)} = k_p + k_i \frac{1}{s^{\lambda}} + k_d s^{\mu}, (\lambda\,, \mu > 0) \tag{2}$$

Where $G_c(s)$ is the transfer function of the controller, $O(s)$ is controller's output, and $E(s)$ is the error. The control signal $O(t)$ can then be presented as:

$$O(t) = k_p e(t) + k_i D_t^{-\lambda} e(t) + k_d D_t^{\mu} e(t) \tag{3}$$

Fig.3 demonstrates the block-diagram configuration of FOPID. Clearly, selecting $\lambda = 1$ and $\mu = 1$, a traditional PID controller can be recovered. The selections of $\lambda = 1$, $\mu = 0$, and $\lambda = 0$, $\mu = 1$ separately relates traditional & PD controllers. All these traditional sorts of PID controllers are the special cases of the fractional $PI^{\lambda}D^{\mu}$ controller given by [11]:

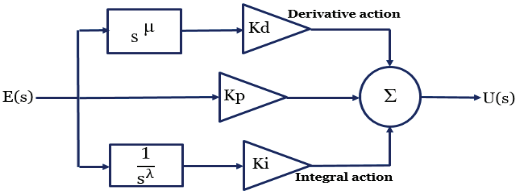


Fig.3. Block Diagram of FOPID Controller

One of the most vital benefits of the $PI^{\lambda}D^{\mu}$controller is its effective control of dynamical system. The fractional order mathematical models may upgrade the system performance. Another benefits, the $PI^{\lambda}D^{\mu}$controllers are less sensitive to changes of the parameters of a controlled system also, FOPID give better flexibility in the design of the controller compared with traditional PID controller [9].

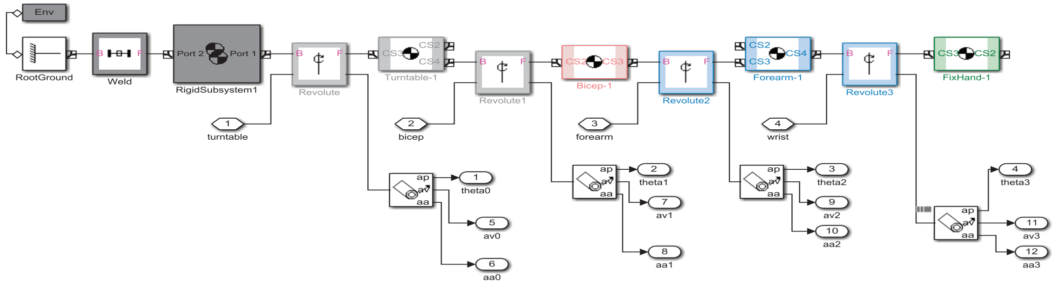


Fig. 2. SimMechanic blocks of IT-Robot manipulator model

IV. IT-Robot Control System Model

DC motor modeling is an important issue; it is common actuator found in numerous mechanical systems and modern applications, for example, industrial and educational robots [15]. Due to its excellent speed and position control characteristic; therefore the actuator is assumed to be an armature-control dc motor. Likewise it is expected that the robot manipulator is connected to the motor through gears.

The overall block diagram for each joint of the IT robot manipulator controlled using FOPID is shown in Fig.4 The manipulator is not influenced by gravity, and rigid. Every joint is driven by a DC motor excepting for the Bicep utilize two DC motors.

Keeping in mind the end goal is to show the effectiveness of the proposed multi loop FOPID controller to acquire an accurate position of every joint. The controller will be verified by simulation on the robot manipulators SimMechanics models.

A. Structure of Robot manipulator Based on FOPID

A simulation has been performed by SimMechanics in MATLAB 2015a. The block structure of the FOPID controller optimized with GA utilizing cost function Integral Square-Error (ISE) to guarantee optimal control performance at nominal working conditions. Since each FOPID controller has 5 parameters, there are a total of 20 parameters to be optimized with GA.

GA is one of the techniques utilized for development in various fields of industrial. It depends on random search and is utilized to solve complex issues in numerous areas particularly when the number of variables is large and hard to get solutions precisely [17]. The significance of this methodology is to eliminate the issue of local search for solutions because the basis of its work is depend on global research for the presence of the best and the most fitting solution for solving the problems. Parts of the fundamental enhancement of this system selection, cross over and mutation respectively [18].

All parameters of the FOPID controllers are updated at every simulation time, where GA parameters $[Kp_1Ki_1Kd_1\ \lambda_1\mu_1Kp_2Ki_2\ Kd_2\ \lambda_2\mu_2Kp_3Ki_3Kd_3\lambda_3\mu_3Kp_4Ki_4Kd_4\lambda_4\mu_4]$ with lower bounds = [0 0 0 0.01 0.01 0 0 0 0.01 0.01 0 0 00.01 0.01] and upper bounds= [400 400 400 1 1 400 400 400 1 1 400 400 400 1 1].

The five gains of FOPID controller after tuning for turntable angle (k_{p1}=100.678, k_{d1}=1.45, k_{i1}= 15.678, λ_1= 0.4 and μ_1= 0.57), for Bicep angle are (k_{p2}=10.12, k_{d2}=25.987, k_{i2}=460.09, λ_2= 0.73 and μ_2= 0.85), for Forearm angle are (k_{p3}=50.067, k_{d3}=25.78, k_{i3}=250.0126, λ_3= 0.34 and μ_3= 0.934)and for Wrist angle are (k_{p3}=120.78, k_{d3}=1.805, k_{i3}=1, λ_3= 0.5 and μ_3= 0.5).

V. Experiments and Simulation Analysis

The techniques portrayed in this paper have been tested in simulations of the IT-ROBOT robot considering the manipulator SimMechanics model from MATLAB Mathworks. Given the original value of joint θ = [0, 0.020, 1.40, –1.60, 1.50, 1.60] and the final value of joint θ = [3.15, 1.5, 1.50, -1.80, 1.50, 1.80]. The end-effector of the robot moves from point A (40, 8, -2) to point B (-15, -8, 29) in Cartesian space. A total of 101 points were sampled between A and B. The sample time was 20 seconds, sampled once every 0.05 seconds.

The end-effector trajectory is determined by the artificial teaching method, as shown in Fig.5, which also indicates the three-dimensional trajectory of the end-effector.

Two controllers examined for position control of the IT- robot manipulator to track the required position with least mistakes. The first is FOPID controller tuned utilizing GA, it is considered as a source of perspective benchmark to compare its results with the second which is PID tuned utilizing GA. Beginning from irregular introduced parameters, GA continuously minimizes different integral performance indices iteratively while finding optimal set of parameters for the FOPID and PID controller. An algorithm ends if the value of the objective function does not change appreciably over some successive iteration.

The desired and actual angle for Turntable, Bicep, Forearm and Wrist angle of IT-Robot manipulator controlled by PID controller tuned using GA are shown in Fig.6(a)-(d) where, GA reaches to the values of the 12 PID parameters after 560 epochs with fitness value 0.00005247.

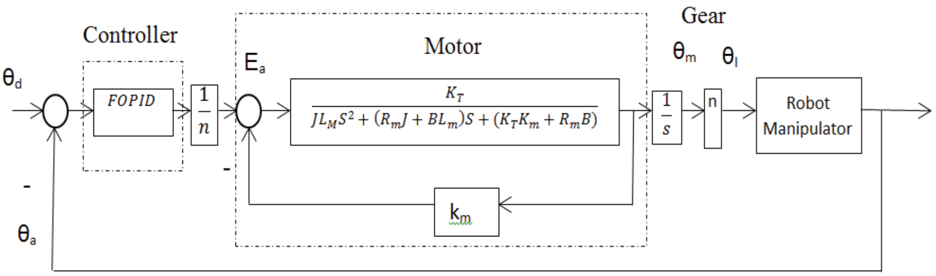


Fig. 4. Robot joint control system

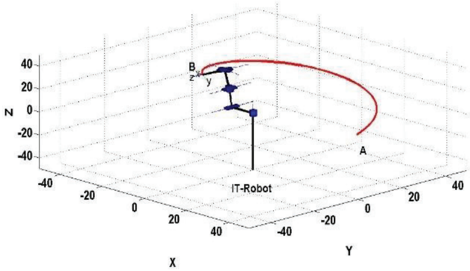
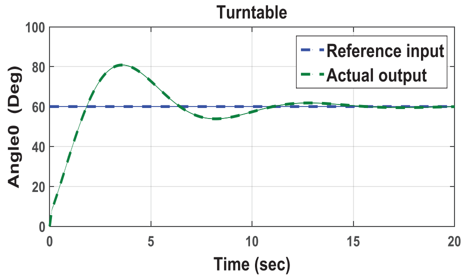
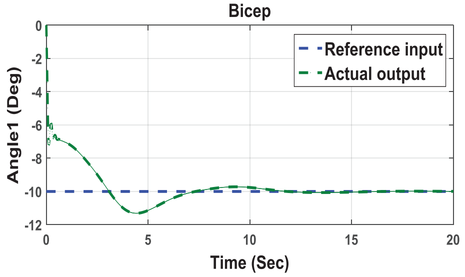


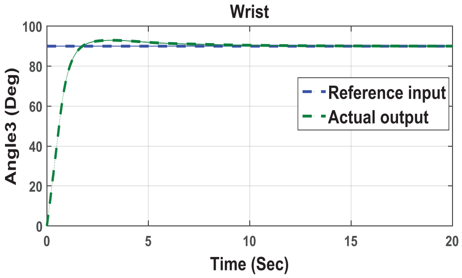
Fig. 5. End-effector Orientation



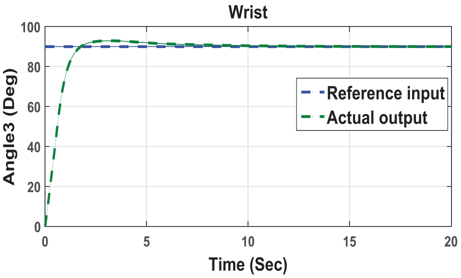
(a) Turntable angle



(b) Bicep angle



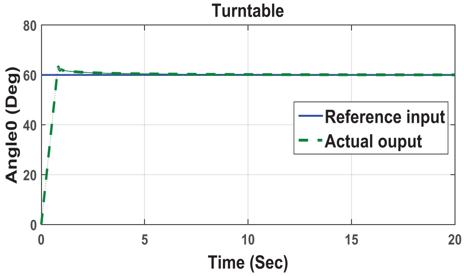
(c) Forearm angle



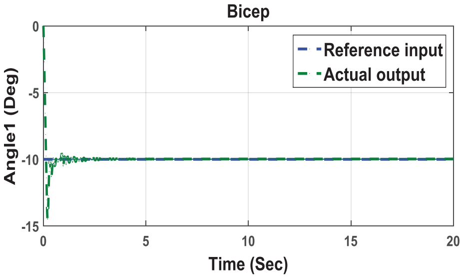
(d) Wrist angle

Fig.6. Desired and actual position using PID Controller

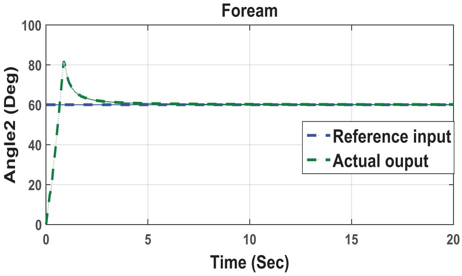
The desired and actual position for Turntable, Bicep, Forearm and Wrist angle of IT-Robot manipulator controlled using FOPID controller are given in Fig.7(a)-(d) where GA reaches to the values of the 20 FOPID parameters after 934 epochs with fitness 1.507×10^{-4}.



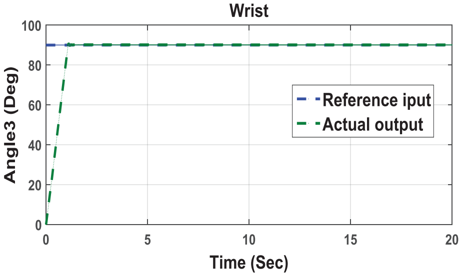
(a) Turntable angle



(b) Bicep angle



(c) Forearm angle

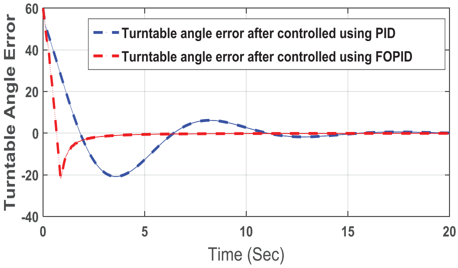


(d) Wrist angle

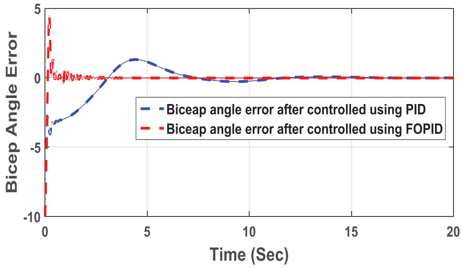
Fig.7. Desired and actual position using FOPID Controller

The position control using FOPID tuned by GA has less steady state error and settling time for the four angles than controlled using classical PID tuned by GA. Where, FOPID controller are less sensitive to changes of the robot manipulator parameters and this give better flexibility in the design of the controller compared with traditional PID controller. Fig.8(a)-(d) give complete comparisons between the two controllers for Turntable, Bicep, Forearm and Wrist angle of IT-Robot manipulator errors respectively.

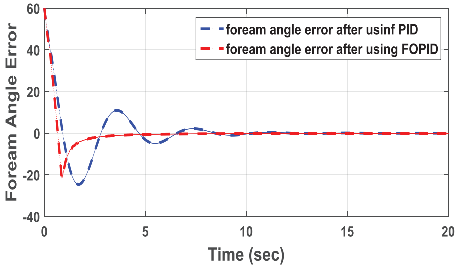
From this comparison, it was observed that the errors of the first four joints converge to zero after the robot is controlled using FOPID. These results show that performances of FOPID are better than traditional PID controller's for the first 4 DOF of the IT robot manipulator. FOPID controller has fast response and small errors for the required trajectory control of robot manipulator.



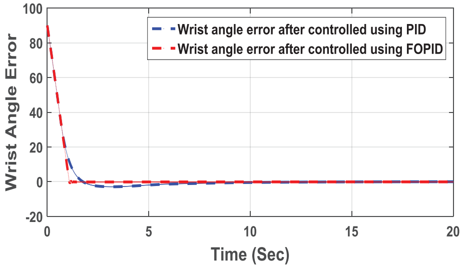
(a) Turntable errors



(b) Bicep errors



(c) Forearm errors



(d) Wrist errors

Fig. 8. Errors comparison using FOPID and PID Controller

Table III shows a comparison of traditional PID and FOPID implemented to control the angle of the first four angles of IT- Robot manipulator.

TABLE III
COMPARISON RESULTS OF PID AND FOPID

	Controller Scheme							
System	**PID Controller tuned using GA**				**FOPID Controller tuned using GA**			
Characteristics	Turntable	Bicep	Forearm	wrist	Turntable	Bicep	Forearm	wrist
Steady State Error	0.1466	-0.01036	0.003447	-0.291	-0.1047	-0.02157	-0.1046	-0.1028
Over shoot	-20.83	1.311	-24.62	-	-21.6	4.49	-0.1046	-
Settling Time	16	12	10	6	2	`0.5	3	5

By comparing the results output (steady state, overshoot and settling time) of the two controllers it was found that the FOPID's are less (steady state error, overshoot and settling time) than PID's results.

VI. Conclusion

In this study, four loop of FOPID controller has been applied to position control of the first four joints angle of the IT- robot manipulator in order to acquire the required position angle with minimum error and better response. Every joint of the manipulator is driven by a DC motor excepting for the Bicep utilize two DC motors. Results have been compared with PID tuned using GA.

From the simulation results it was concluded that:

- By comparing the result output, the position control of the four joints controlled utilizing FOPID has minimum(steady state error, overshoot and settling time)than controlled using PID tuned utilizing GA.
- The system response has showed that FOPID controller has much faster response than conventional PID controllers.

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