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An Optimal Fractional Order $PI^{\lambda}D^{\mu}$ For Robotic Manipulators Control Under Constrained Torque

Baghdadi Rezali[1,2,*], Benaoumeur Ibari[1], Mourad Hebali[1] and Hocine Abdelhak Azzeddine[1]

[1]*Dept. of Electrical Engineering, University Mustapha Stambouli of Mascara, Mascara, Algeria*
[2]*Signal and System Laboratory, Mostaganem University, Mostaganem, Algeria*

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Abstract

In robotic applications, the correct execution of a task can be a challenge for robotics experts. Therefore, it is necessary to implement a robust control structure for trajectory tracking. This paper proposes a robust control design to track the trajectory of an industrial robot via a fractional order PID controller with the Computed Torque Control (CTC) technique based on the Grey Wolf Optimizer (GWO). To examine the proposed robust control, the Fanuc 710ic/70 robot manipulator model is used as a case study. To begin with, the dynamic formulation of the robot is described. Then, with respect to the control design, the CTC controller that helps overcome the nonlinearity problem of the system is designed to improve the tracking performance. It is proposed to combine the fractional order PID with the CTC technique. This hybridization increases the performance of the control strategy and overcomes external disturbances, sensor noise suppression and especially input control constraints. Typically, FOPID controller parameters are set without considering the constraints of the actuator control inputs. Therefore, it affects its performance over time. To solve this problem, the controller parameters are updated online and optimized according to the input constraints using the GWO technique. The effectiveness of the proposed control strategy is demonstrated by the simulation results in terms of stability, trajectory tracking and compliance with limited inputs.

Keywords: Robotic manipulator, Trajectory control, FOPID controller, CTC, GWO optimizer.

1. Introduction

In industrial applications, the robot has become an important element to perform tasks that humans cannot. It is well known that, in order to perform a certain task successfully, the manipulator arm needs a robust control strategy. Most robotic manipulators are equipped with traditional control strategies, such as PD, PID control, as these techniques do not take into account the uncertainties, External disturbances and sensors noises. They are not desirable despite the suggested modified PID controllers in [1, 2]. In recent years, many researchers have introduced advanced techniques in robot control to overcome the above constraints, namely H-infinity theory, Fuzzy logic theory and sliding mode control [3, 4, 5]. These have been successful approaches, but their design and implementation in real time is very complex.

Besides, research has have demonstrated that the fractional calculation can improve the performance of control techniques [6, 7, 8, 9, 10, 11]. In addition, an integer order controller and a fractional order controller are used to track the control of a parallel robot with different desired trajectories; the obtained results proved the power of the fractional order controller over the integer order controller in terms of overshooting and the steady state error values [6]. Similarly, in order to enhance the performance of controllers, in literatures [7, 8, 9], the authors have replaced Integer Orders with Fractional Orders of the Fuzzy-Proportional, Integral and Derivative controller to control a three serial link manipulator, And the results show that FO-Fuzzy-PID is better than IO-Fuzzy-PID especially in terms of response time.

The behaviour of the robot manipulators is represented by a dynamic model, which is composed of non-linear functions of the state variables (positions and velocities of the joints). This characteristic of the dynamic model requires decomposing the control system's model of non-linear functions. The Computed Torque Control (CTC) is a non-linear control dedicated to the highly non-linear coupled manipulator system. Its main idea is the Feedback Linearization (FL) technique, which consists in transforming and decoupling a non-linear system into a suitable linear system by changing the state variables [12].

In [13], Angel and Viola are proposed a combined control strategy between the fractional order PID and computed torque control method to control the trajectory of a parallel robot manipulator, where it showed good results in terms of disturbance, rejection and trajectory tracking accuracy. But the proposed control strategy has major drawbacks, such as the failure to take into account actuator torque constraints, which are important for actuator safety. Furthermore, the author has relied on the frequency analysis define the controller parameters, the frequency analysis method requires a thorough understanding of the dynamic system to determine desired frequency characteristics such as natural frequency and damping ratio. However, absence of an implicit methodology for calculating parameters of controller.

Motivated by the limitations of the existent control strategy, this paper presents an alternative control strategy for trajectory tracking control of the robots. In order to enhancement tracking performance, a fractional order PID is used instead integer PID, and combined with computed

*E-mail address: baghdadi.rezali@univ-mascara.dz
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torque control to overcome nonlinearity of robot manipulator. Further, for overcome the mentioned problems in [13], this technique is provided with an intelligent method for tuning parameters of the controller using the Grey Wolf Optimizer (GWO), which allow update the optimal parameters on line with respect the torque constraints of the manipulator robot actuators. The proposed controller is tested against external disturbances and sensor noise. A comparison of the performance of the fractional controller FOPID-CTC with the full controller IOPID-CTC is performed. Tuning the controller parameters with respect to the torque constraints using GWO approach.

2. Dynamic Model of Fanuc 710ic/70 robot manipulator

To examine the suggested approach, the Fanuc 710ic/70 manipulator robot is chosen as a case study. This strong 6-DoF model has a 70 kg payload and extremely fast axis speeds, making it ideal for a variety of applications, the 3D model of Fanuc 710ic/70 robot is shown in the figure 1.

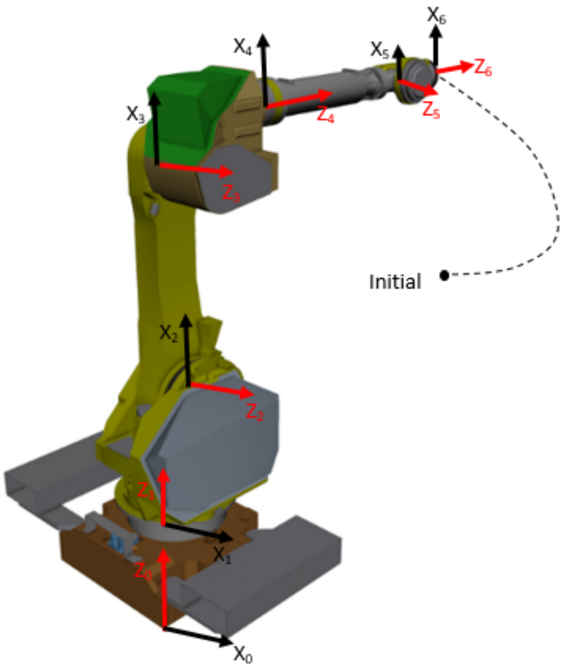

Fig. 1. 3-D model of Fanuc 710iC robot.

A robot manipulator is an open kinematic chain composed of interconnected joints. The dynamic equations describe the relationship between the position, velocity and acceleration, and torque of each manipulator joint. Using the Lagrangian approach, the manipulator model can be described as follows:

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

and can be written as follows:

$$\ddot{q} = M(q)^{-1}\big(\tau + \tau_d - C(q,\dot{q})\dot{q} - G(q) - F(q,\dot{q})\big) \tag{2}$$

where, $q, \dot{q}$and $\ddot{q} \in R^6$are the vectors of the joint position, velocity and acceleration, respectively.$M(q) \in R^{6*6}$ is the inertia matrix,$C(q,\dot{q}) \in R^{6*6}$ is the Coriolis and centrifugal forces matrix, $G(q) \in R^6$ is the gravity vector, $F(q,\dot{q}) \in R^6$ is the friction terms and $\tau, \tau_d \in R^6$ are the torque and the external disturbance vectors, respectively.

3. Controller design and stability

This section consists of two parts, the first being the design of the controller and the second being the stability analysis of the control.

3.1. Controller design

3.1.1. Computed torque control strategy

In trajectory tracking of a robot manipulator, to ensure that the joint variable q follows the desired trajectory q_d, the tracking error is defined as follows:

$$e = q_d - q \tag{3}$$

To show the influence of the torque/force τ on the tracking error, (4) is differentiated twice to find:

$$\dot{e} = \dot{q}_d - \dot{q} \tag{4}$$

$$\ddot{e} = \ddot{q}_d - \ddot{q} \tag{5}$$

By substituting (3) into (6):

$$\ddot{e} = \ddot{q}_d - M(q)^{-1}\big(\tau + \tau_d - N(q,\dot{q})\big) \tag{6}$$

where

$$N(q,\dot{q}) = C(q,\dot{q})\dot{q} + G(q) + F(q,\dot{q}) \tag{7}$$

The (7) can be written in the form of the error state space [14].

$$\frac{d}{dt}\begin{bmatrix} e \\ \dot{e} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} e \\ \dot{e} \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u \tag{8}$$

where

$$u = \ddot{q}_d - M(q)^{-1}\big(\tau + \tau_d - N(q,\dot{q})\big) \tag{9}$$

u represents a control law that will be defined later. According to (9), the general input torque of the robot manipulator becomes:

$$\tau = M(q)(\ddot{q}_d - u) + N(q,\dot{q}) - \tau_d \tag{10}$$

which is called the computed torque control law.

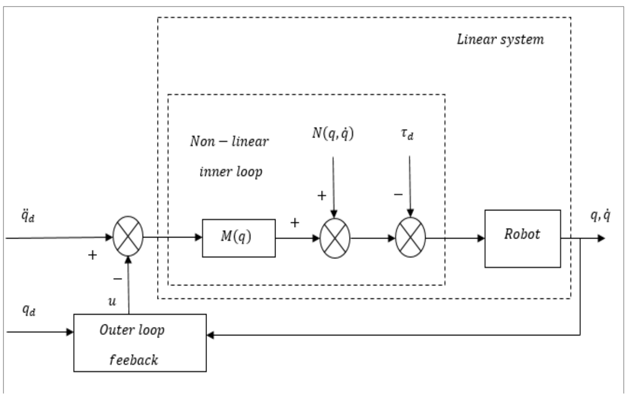

Fig. 2. Computed torque control strategy.

3.1.2. Fractional order PID with CTC

In order to stabilize the error dynamics described in (9), It is necessary to define a control law u. Let us propose a fractional order PID controller, which is given in the following form:

$$u = -k_p e - k_i D^{-\lambda} e - k_d D^{\mu} e \quad (11)$$

where k_p, k_i and $k_d$are the proportional, integral and derivate constants, respectively.
$D^{-\lambda}$, D^{μ} are the fractional integral and fractional derivative, respectively. by substituting (12) into (11), we obtain

$$\tau = M(q)\left(\ddot{q}_d + k_p e + k_i D^{-\lambda} e + k_d D^{\mu} e\right) + N(q, \dot{q}) - \tau_d \quad (12)$$

Figure 3 displays the block diagram of the fractional order PID controller proposed in this study.

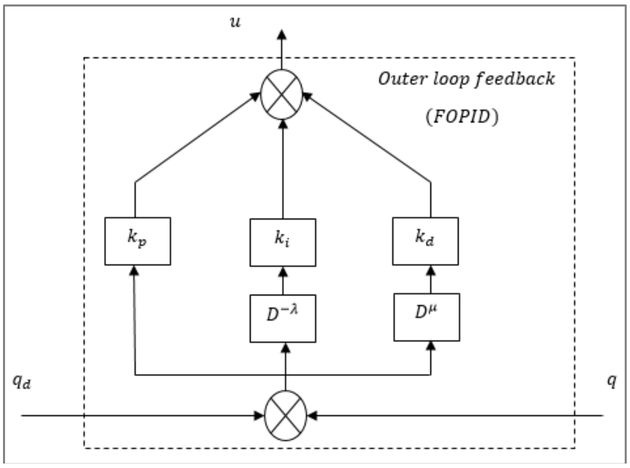

Fig. 3. Block diagram of fractional order PID.

3.2. Stability analysis:

In this section, the Lyapunov approach is used to prove stability of error dynamic. The error dynamic equation is obtained by substituting the control law τ from (12) into manipulator model (1) yielding:

$$M(q)\ddot{q} = M(q)\left(\ddot{q}_d + k_p e + k_i D^{-\lambda} e + k_d D^{\mu} e\right) \quad (13)$$

and

$$\ddot{e} + + k_p e + k_i D^{-\lambda} e + k_d D^{\mu} e = 0 \quad (14)$$

which can be written as the following state space model

$$\dot{X} = AX \quad (15)$$

where

$$X = \begin{bmatrix} \int e \\ e \\ \dot{e} \end{bmatrix}; A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -k_i & -k_p & -k_d \end{bmatrix}$$

Theorem 01:*The equilibrium point $x = 0$ of $\dot{x} = Ax$ is stable if and only if all eigenvalues of A satisfy $Re\lambda_i \leq 0$ and for every eigenvalues with $Re\lambda_i = 0$ and algebraic multiplicity $r_i \geq 2$, $rank(A - \lambda_i I) = n - r_i$, where n is the dimension of x. The equilibrium point $x = 0$is (globally) asymptotic stable if and only if all eigenvalues of A satisfy $Re < 0$* [11].

Theorem 02: *A matrix **A**is Hurwitz; $Re\lambda_i < 0$ for all eigenvalues of **A**, if and only if for any given positive definite symmetric matrix Q there exists a positive definite symmetric matrix Pthat satisfies the followed Lyapunov equation* [11].

$$PA + A^T P = -Q \quad (16)$$

To test stability of system (16), a candidate Lyapunov function of quadratic form is considered as follows:

$$V(X) = \frac{1}{2} X^T P X \quad (17)$$

where P is a positive definite matrix.

The derivate of the function $V(X)$ is established as follows:

$$\dot{V}(X) = \frac{1}{2} X^T P \dot{X} + \frac{1}{2} \dot{X}^T P X \quad (18)$$

$$\dot{V}(X) = \frac{1}{2} X^T P A X + \frac{1}{2} X^T A^T P X \quad (19)$$

$$\dot{V}(X) = \frac{1}{2} X^T (PA + A^T P) X \quad (20)$$

Using the theorem 2, we suppose$PA + A^T P = -Q$, where Q is positive definite matrix, then $\dot{V}(X)$ becomes:

$$\dot{V}(X) = -\frac{1}{2} X^T Q X \quad (21)$$

Since the functions $V(X)$ and $\dot{V}(X)$ are positive definite and negative definite respectively as shown in the equations (18-22), then the system (16) is asymptotically stable, therefor the assumption $(PA + A^T P = -Q)$ is validated, according theorem 2 the equilibrium point $(X = e = q_d - q = 0)$ is asymptotically stable.

3.3. Controller tuning strategy:

This subsection deals with the methodology of controller parameters adjustment respectfully to the limited input torque. This strategy is based on the GWO technique, which is a new type of metaheuristic optimisation algorithm suggested by Seyedali Mirjalilia [15]. The mechanism of the GWO algorithm can be summarized in the following table.

Table 1. GWO pseudo code.

Start
Define the objective function$\boldsymbol{f(x)}, \boldsymbol{x} = [\boldsymbol{x_1}, \boldsymbol{x_2}, \dots \dots, \boldsymbol{x_n}]^{\boldsymbol{T}}$.
Initialize population of grey wolf$\boldsymbol{X_i}$, $(\boldsymbol{i} = \boldsymbol{1}, \boldsymbol{2}, \dots . \boldsymbol{p})$.
Fitness function evaluation and find the best solutions ($\boldsymbol{X_\alpha}, \boldsymbol{X_\beta}, \boldsymbol{X_\gamma}$).
While *(the stopping criteria are not met)*
For each grey wolf (solution)
    update the new position of grey wolves
End For
update the parameters a, A and C
Fitness function evaluation
Update the best solutions ($\boldsymbol{X_\alpha}, \boldsymbol{X_\beta}, \boldsymbol{X_\gamma}$).
Iteration=iteration+1
End while
The best solution
End

To obtain the optimal FOPID, the parameter update algorithm works on finding the minimum cost function by adjusting several parameters k_p, k_i, k_d, λ and μ,with respect to the constrained input torque.

The procedure for tuning the controller parameters is shown in Figure 4. First, the desired performance index and input torque constraints are set. Then, the FOPID parameters are initialized and evaluated in the cost function. The next step is to check whether the desired performance is achieved and the input constraints are respected. These parameters are not optimized with the GWO technique until the above conditions are met.

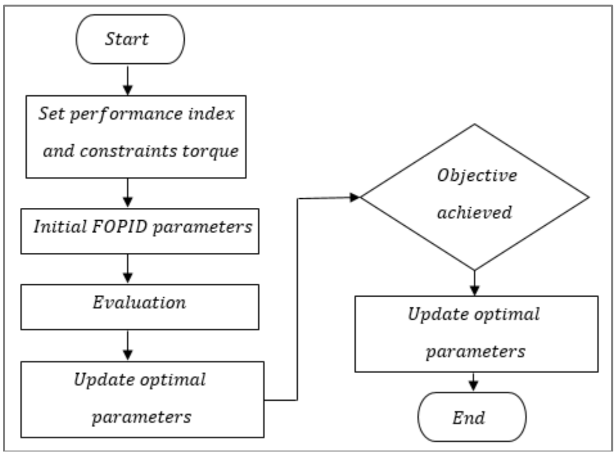

Fig. 4. Flowchart of parameters tuning for FOPID.

In order to find the optimal controller parameters, it is necessary to select the most appropriate performance index that is used to evaluate the capacity of each solution. In this work, a commonly used performance criteria is considered, the ITAE, which is defined as follows:

$$ITAE = \int_0^t t(\sum_{i=1}^{6}|e_i(t)|)dt \quad (22)$$

Where e_i is tracking error of each link $(i = 1,2, \ldots,6)$.

For the input constraints, the bounded torque of each link is set as following:

$$\begin{cases} |\tau_1| < 1000\ (N.m) \\ |\tau_2| < 800\ (N.m) \\ |\tau_3| < 500\ (N.m) \\ |\tau_4| < 500\ (N.m) \\ |\tau_5| < 100\ (N.m) \\ |\tau_6| < 100\ (N.m) \end{cases} \quad (23)$$

4. Results and discussion:

In order to generate the desired trajectory in the joint space, an initial configuration q_{init} and a final configuration q_{fin} are defined to follow a polynomial function of degree five given by equation (24).

$$q_{init} = [-\frac{\pi}{2}, 0, -\frac{\pi}{2}, -\frac{\pi}{2}, -\frac{\pi}{2}, -\frac{\pi}{2}]^T rad.$$

$$q_{fin} = \left[0, \frac{\pi}{4}, 0, \frac{\pi}{2}, \frac{\pi}{2}, \frac{\pi}{2}\right]^T rad.$$

$$p(t) = 10\left(\frac{t}{T_f}\right)^3 - 15\left(\frac{t}{T_f}\right)^4 + 6\left(\frac{t}{T_f}\right)^5 \quad (24)$$

where $T_f = 10s$ is the minimum time for the joint to reach the final configuration.

Table 2 shows the different optimal parameters of the FOPID-CTC controller developed in this study. According to the results obtained, these optimal parameters allowed to obtain the best tracking of the Fanuc 710ic/70 robot.

Table 2. Optimal parameters obtained

FOPID parameters	K_p	K_i	K_d	λ	μ
	131.1	155	200	0.106	0.99

4.1. Performance comparison between IOPID and FOPID:

To evaluate the performance of the proposed controller in this work, a comparison was made between the IOPID and the fractional order PID optimised by the GWO technique under the input torque constraints. The initial conditions q_0 have set a difference from the initial configuration q_{init} to see the ability of the current trajectory to converge to the desired trajectory. Figure 5 shows the fast response of the FOPID controller in following the desired trajectory, where after 2s the controller shows a similar behaviour to the desired trajectory. On the other hand, the IOPID response time is almost 6s, which is equivalent to three times the first controller. Figure 6 shows the evolution of the robot articulation error resulting from the IOPID and FOPID controllers. It can be observed that the FOPID controller has less error variation in each trajectory compared to the IOPID controller. Moreover, this error disappears in only 2 seconds only for our controller, unlike the IOPID controller, in which the steady state error appears for up to 9 seconds. This represents a smooth joints control of the robot, which translates into better performance for tracking tasks.

Figure 7 shows the torque applied to each joint. There is a clear variation in the torque produced in both cases, the traditional PID controller requires more force to bring the joint into the desired position, whereas the FOPID has a smoother control torque than the IOPID. This implies that the proposed FOPID consumes less energy. Additionally, the fast response of the FOPID controller leads to a reduction in the operating time of the robot's motors, which inevitably leads to lower energy consumption. According to the different results obtained, the FOPID controller proposed in this study is characterized by high performance compared to the IOPID controller, especially with regard to fast response, articulation error and energy consumption of the robot, and this is consistent with the literature [13]. The high performance of the FOPID controller can be attributed to the fractional integral ($D^{-\lambda}$) and fractional derivative (D^{μ}) of this technique, which contribute to the stability and improvement of the robot's behaviour. Fractional computed torque control has five parameters for setting, this give us an extra degree of freedom in parameters.

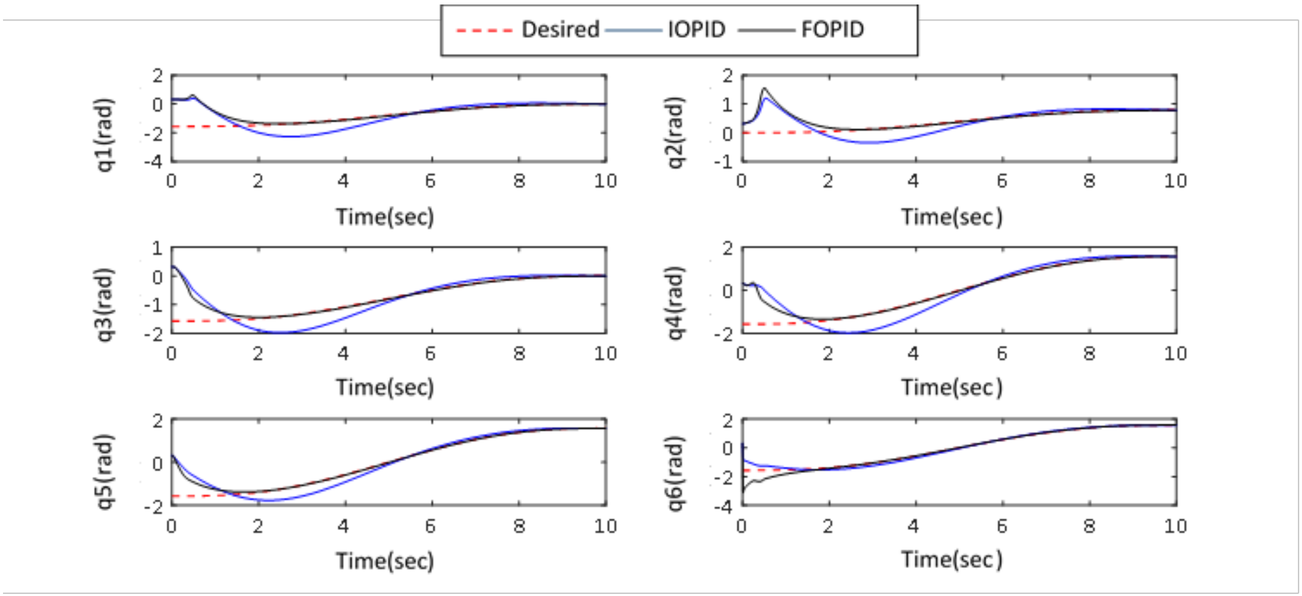

Fig. 5. Position tracking of each link of manipulator.

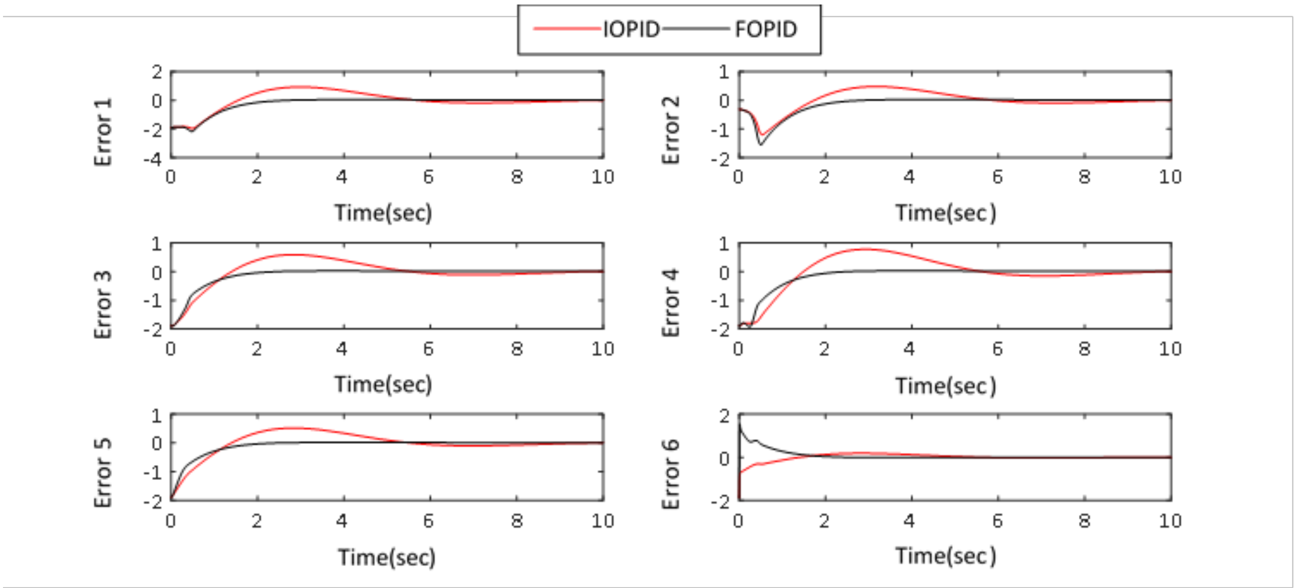

Fig. 6. Steady state error of the joints.

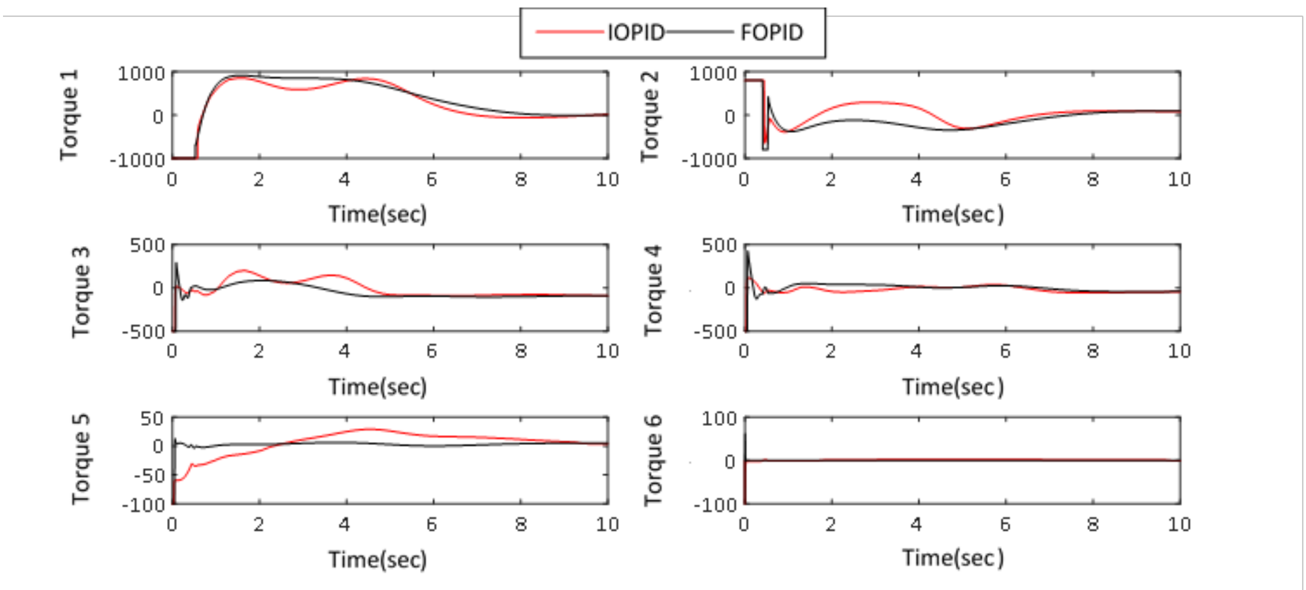

Fig. 7. Torque provided by each actuator.

4.2. Robustness analysis against disturbance and noise

In this subsection, the ability of the suggested controller to adapt with external influences on the system in terms of disturbances and noise will be examined.

4.2.1. External disturbances:

An external disturbance τ_{ext} is applied on the input of robot as shown in Figure 8. The external perturbation applied is in the form of an impulse function at $t = 5s$.The related error signal is shown in Figure 9. It can be seen that during a disturbance, the error deviates from zero. This means that the joint is deflected and then returned to the desired position. This proves that the proposed controller adapts to external disturbances in order to maintain the best tracking of the Fanuc 710ic/70 robot.

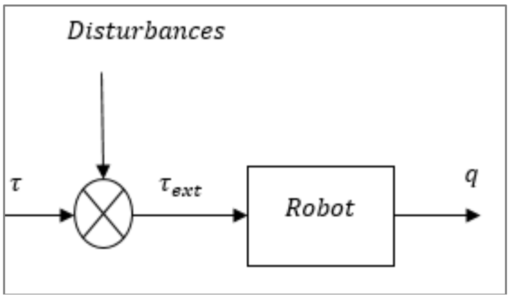

Fig. 8. Effect of external disturbances on robot inputs.

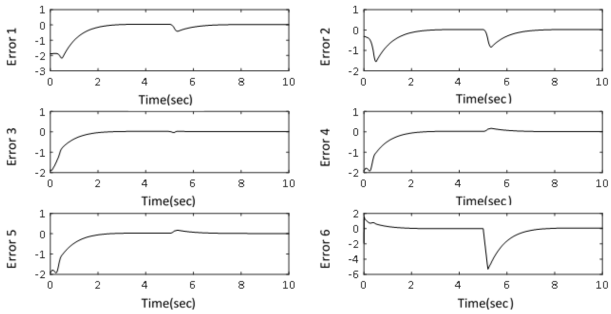

Fig. 9. Error in the presence of disturbances.

4.2.2. Sensor noise suppression

In the real world, there is always random noise affecting the sensors in order for them to give wrong position values as shown in Figure 10, which are reused in the control system. That is why; the controller must be able to suppress the noises and return the trajectory to the desired position.

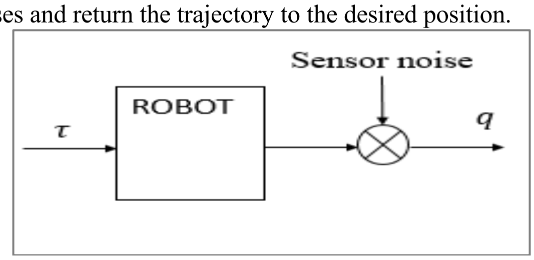

Fig. 10. Effect of noise on measurements sensors.

To examine the controller in relation to sensor noises, we applied noise as a step function to the first joint. Figure 11 clearly shows the extent of the sensor noise effect on the reaction of the controller, especially during the operating period from 5s to 7s. The results clearly show that the FOPID controller deals intelligently with the incorrect measurements of the sensors in order to obtain the desired behaviour of the robot.

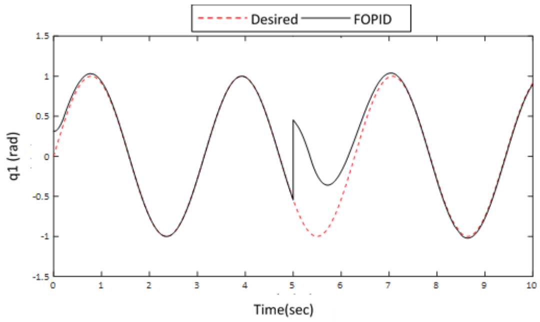

Fig. 11. Sensor noise effect.

4.3. GWO method Performance:

To evaluate the performance of the GWO optimisation technique, it is compared to another traditional optimisation method, such as the genetic algorithm (GA). The comparison is shown in Figure 12, which represents the evolution of the fitness function of the two methods GWO and GA. The fitness function is considered as a performance index which is represented by ITAE. It can be observed that the GWO algorithm has a better optimization of the fitness function and has a shorter execution time.

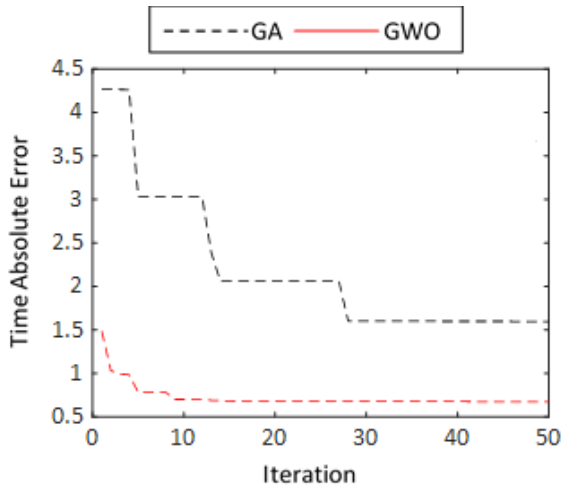

Fig. 12. Fitness function evolution.

5. Conclusion

In this paper, an optimal controller has been designed for a trajectory tracking control of robotic manipulators under constrained torque. The control design is made up of a conjunction between FOPID and CTC controllers with an online optimisation using the GWO technique. A Fanuc 710iC/70 robot is used to test the suggested controller. As for the performance evaluation, FOPID is compared with traditional PID, where the obtained results show that FOPID presents less joint errors and a faster response time. Despite the constraints applied to inputs, FOPID provides a smooth control input compared with IOPID. In addition, the GWO method is employed successfully to find an optimal FOPID controller against constraints inputs, which has better performance compared to the traditional optimization methods as GA. Also, the FOPID is tested in the presence of external influences, which the controller is able to return the trajectory to the desired position after an external disturbance. In addition, FOPID has proven its ability to suppress noise that affects sensors. Finally, the hybrid FOPID-CTC controller with online optimisation (GWO) can be considered a suitable solution for trajectory tracking of a robot manipulator, where it shows good performance in terms of response time, compliance with torque constraints, suppression of external disturbances and sensor noise. In the future work, the performance of the proposed method will be further enhanced by Kalman filter and tested under more stringent operating conditions.

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