Comparative Study on Fractional Order PID and PID Controllers on Noise Suppression for Manipulator Trajectory Control

Vineet Kumar and K.P.S. Rana

Abstract The main contribution of this chapter is to demonstrate the sensor and controller noise suppression capabilities of the best tuned Fractional Order-Proportional plus Integral plus Derivative (FO-PID) and classical PID controllers in closed-loop. A complex non-linear and coupled system, a 2-link rigid planar manipulator was considered for the study as it encounters noise in many forms such as sensor and controller noise during the operation in industry. Uniform White Noise (UWN) and Gaussian White Noise (GWN) were considered both for the sensor and the controller in the closed-loop and a comparative study was performed for FO-PID and PID controllers. Both the controllers were tuned using Genetic Algorithm and all the simulations were performed in LabVIEW environment. The simulation results have revealed that FO-PID controller demonstrates superior sensor and controller noise suppression as compared to conventional PID controller in the closed-loop.

Keywords Fractional order PID controller · PID · Sensor noise · Controller noise · Noise suppression and uncertainty

1 Introduction

Noise is generally an inherent part of every measurement and control system. Noise affects the decision-making capability of the controller in the plant as it introduces uncertainty in the process variable and control action. There are several causes of measurement noise in the process industry such as loose wiring, improper soldering, thermal noise, electromagnetic interference, etc. Furthermore, the execution of control action in a closed-loop control system may be seriously affected due to the

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improper connection of signal line from the controller to the final control element particularly in a vibrating environment. This action may add considerable noise in the control action and may even try to destabilize the process being controlled. Most general nature of sensor and controller noise is likely to be random. Robotic manipulator being a highly non-linear, time-varying and uncertain system noise has adverse effect on the positioning and accuracy of the end-effectors of robotic manipulator. Therefore, it is a challenging task to design such a robust controller which can effectively deal with external noises and uncertainties [5, 7–9, 11, 22, 30, 33, 55, 59].

Conventional PID controller has been the most popular controller in the industries for last sixty years due to its simple structure, low cost, easy design and robust performance. For its implementation it is available in many forms in industry, like pneumatic, hydraulic and electronic etc. Due to these features, it is one of the popular choices of control engineers in robotics as well [1, 3, 6].

The fractional order calculus has a very long mathematical history, but its applications to science and engineering are just recent. One of its popular applications is in fractional order chaotic system [4, 10, 51–53]. Many good works have been reported regarding the control and synchronization of fractional order chaotic system [15, 16, 46–50]. Also, in the last few years, fractional-order calculus has gained extensive attention of researchers and scientists in the area of control engineering to develop fractional order PID (FO-PID) controller [32, 37, 54]. Due to advancements in the electronics now it has become possible to design and realize the FO-PID controllers. It offers additional design Degree of Freedom (DOF) to the control engineers. Advancements also have been observed in the controller tuning methods for customized performance indices. Now-a-days the trend has been the usage of optimization methods such as Genetic Algorithm (GA) and other bio-inspired techniques for tuning the controllers. Therefore, the main goal of this chapter is to demonstrate the capabilities of FO-PID controller to cater the effect of noise in closed loop. In this regard, an intensive simulation studies were performed in closed loop by controlling a complex coupled system i.e. 2-link rigid planar robotic manipulator in presence of sensor and controller noise and using fractional and integer order PID controllers. Uniform White Noise (UWN) and Gaussian White Noise (GWN) were considered for this study. Both the controllers were tuned using GA for minimum Integral of Absolute Error (IAE). The performed comparative study reveals that FO-PID controller with low fractional order derivative term effectively suppress the noise in closed loop. The main contributions of this chapter can be summarized as follows:

- It demonstrates the effect of sensor and controller noise in closed loop for trajectory tracking control of 2-link rigid planar robotic manipulator using fractional and integer order PID controllers.
- It shows that FO-PID controller having low order derivative term effectively suppress the noise effect in closed loop as compared to its counterpart integer order PID controller.

- The performance of fractional and integer order PID controllers tuned with GA were assessed for IAE and it has been found that FO-PID controller outperformed integer order PID controller for sensor as well as controller noise suppression study.

The rest of the chapter is organized as follows: A brief literature review of the related works have been presented in Sect. 2. The implementation of fractional order operator is presented in Sect. 3. In Sect. 4, fractional order PID controller is presented. In Sect. 5, the performance criteria chosen are explained. In Sect. 6, the mathematical model of the 2-link robotic manipulator is described. The detailed description of the performed simulation experiments and obtained results are presented in the Sect. 7. Finally, the conclusions of the present work are drawn in Sect. 8.

2 Literature Survey

Noise in any form may degrade the performance of any controller in closed loop. Therefore, it has drawn attention of various researchers and scientists over the time especially in the field of control system. Many research works have been reported in this regard and presented as follows.

Tsai et al. presented the robustness testing for sensor noise for the fuzzy model-following control applied to a 2-link robotic manipulator [45]. Chaillet et al. investigated the robustness study of PID controller for the external disturbance for a robotic manipulator. A uniform semi-global practical asymptotic stability for PID controller for robotic system with external disturbance was investigated. Simulation was done for the 2-link robotic manipulator with viscous and coulomb friction effects [17]. Song et al. presented a computed torque controller scheme with fuzzy as compensator for the uncertainties in a robotic manipulator. The robustness testing was done with nonlinearities, uncertainties and flexibilities [41]. Tang et al. presented a modified fuzzy PI controller for a flexible–joint robotic manipulator for path tracking performance in handling uncertainty and nonlinearity. The uncertainties used were within 10% tolerance of all nominal system parameter values [42]. Bingul and Karahan investigated the fuzzy logic controller for a 2-link robotic manipulator. The robustness testing was done with model uncertainties, change in used trajectory and white noise addition to the system. White noise with different noise powers were added to each link [12]. Chen presented dynamic structure neural-fuzzy network adaptive controller for robotic manipulator. The robustness was tested with payload variation at second link [18]. Tian and Collins studied the robustness testing of the adaptive neuro-fuzzy control of a flexible manipulator with the tip payload variations [44].

Bingul and Karahan presented a comparative study of fractional PID controllers tuned by Particle Swarm Optimization (PSO) and GA for a 2-link robotic manipulator. The robustness testing included parameter change, trajectory change and addition of white noise. Simulation results, for the robot trajectory experiment, showed that the FO-PID controller tuned by PSO has better performance than the FO-PID controller tuned by the GA [13].

Lin and Huang presented a hierarchical supervisory fuzzy controller for the robot manipulators with oscillatory base. The proposed method had various benefits such as reduced chattering effect, lesser overshoot, faster convergence and lesser online computation time [28]. Peng and Woo investigated a neural-fuzzy controller for the 2-link planar robotic manipulator. In this work, the simulation results suggested that the controller based on online weight adjustment is robust in the presence of uncertainties like friction, unknown disturbance and changing payload [36]. El-Khazali introduces a new design method of FO-PD and FO-PID controllers. A biquadratic approximation of a fractional order differential operator is used to introduce a new structure of finite-order FO-PID controllers. They claimed that using the new FO-PD controller, the controlled system can achieve the desired phase margins without migrating the gain crossover frequency of the uncontrolled system. The proposed FO-PID controller has smaller number of parameters to tune than its existing counterparts. The viability of the design methods is verified using a simple numerical example [21]. Li and Huang presented an adaptive fuzzy terminal sliding mode controller for robotic manipulator. It has several advantages like eliminates chattering, good response with uncertainties and disturbances etc. [27]. Yildirim and Eski presented different neural network implementations as noise analyzer for the robotic manipulator. The performance of Radial Basis Function Neural Network was better than all other networks [56]. Oya et al. investigated a continuous time tracking controller without using velocity measurements of the robotic manipulator. The noise due to quantization error was studied. The proposed controller offered better results than those based on Eular approximation [34]. Zhu and Fang presented a fuzzy neural network algorithm for parallel manipulators. It was designed to cope with external disturbance, payload variation and model uncertainties. The neural network was used to modify the fuzzy rules [58].

Petras presented the hardware implementation of digital FO-PID control for permanent magnet DC motor. The digital and analog realization of proposed controller was done with microprocessor and fractance circuits, respectively [37]. Delavari et al. reported a fractional adaptive PID controller for robotic manipulator in which parameters of PID are updated online and the fractional order parameters are obtained offline [20]. Bingul and Karahan applied a FO-PID controller to a robotic manipulator for trajectory tracking problem using PSO. The simulation results showed that FO-PID controller performed better than that conventional PID [14]. Silva et al. proposed the superiority of fractional order controller over integer order controller for a hexapod robot in which flexibilities and viscous friction were present at the joints of the legs [40]. Sharma et al. presented a comparative performance analysis of fractional order fuzzy PID controller, fuzzy PID, FO-PID and PID controller for a trajectory tracking and disturbance rejection of a 2-link robotic manipulator. Simulation studies revealed that fractional order FPID outperformed rest of the controller [39]. Kumar et al. proposed a robust fractional order Fuzzy

P + Fuzzy I + Fuzzy D controller for nonlinear and uncertain system which offered superior performance as compared to its integer order counterpart fuzzy controller [24].

Pan and Das proposed a FO-PID controller for automatic voltage regulator (AVR) with chaotic multi-objective optimization. In this work, FO-PID controller was not completely superior to PID controller as the simulations results were better for FO-PID for some cases and for conventional PID in other cases [35]. Zamani et al. investigated the performances of FO-PID controllers for AVR systems [57]. Tang et al. developed FO-PID controller for AVR system. The performance of FO-PID was superior to PID controller for the system with or without uncertainties. The Chaotic Ant Swarm algorithm was used for finding optimized parameters [43]. Luo and Chen proposed a systematic tuning procedure for the FO-PD controller for a FO system. The performance of the proposed controller was superior to both FO-PD and integer order PD controller [29]. Monje et al. presented a tuning method of FO-PID controller and ensured the robustness for the noise as well as gain variation. Also, an auto-tuning method using relay test has investigated. Experimental results showed the effectiveness of the proposed tuning methods [32]. Ladaci et al. designed an adaptive internal model controller (AIMC) with a FO system. The robustness of the proposed controller was done against noise. It was superior to conventional AIMC and also, to conventional PID controller [26]. Many other recent applications, such as, binary distillation column control [31] and control of hybrid electric vehicle [25] have also been reported in the literature for making use of fractional order control system.

The literature survey conducted above clearly indicates that several authors have investigated effects of the model uncertainties and external disturbances for the robotic manipulators but the effects of sensor as well as controller noise has not been well explored by the researchers and therefore needs attention.

3 Fractional Order Calculus

In the present work, fractional order operators (differ-integral) are implemented using Grünwald-Letnikov (G-L) method [38, 54]. The definition of GL fractional differ-integral can be expressed as follows:

$$ {}_aD_t^{\gamma} g(t) = \lim_{h \to 0} \frac{1}{h^{\gamma}} \sum_{j=0}^{[(t-a)/h]} (-1)^j \binom{\gamma}{j} g(t - jh) \tag{1}$$

where t and a are the limits, γ is the order of the mathematical operation i.e. μ and -λ, D is the differ-integral operator, h is the step size considered to be very small and $\binom{\gamma}{j} = \frac{(\gamma)(\gamma-1)(\gamma-2)\ldots\ldots(\gamma-j+1)}{\Gamma(j-1)}$

In the present study, fractional order calculus was realized in z-domain. Backward difference method i.e. $s = (\frac{1-z^{-1}}{T})$, where T is sampling time, is considered to transform the differentiator operator from s-domain to z-domain. Therefore, fractional differentiator operator 's^{γ}' is transformed into z-domain as follows:

$$s^{\gamma} = \left(\frac{1-z^{-1}}{T}\right)^{\gamma} \tag{2}$$

or

$$s^{\gamma} = T^{-\gamma} \sum_{j=0}^{\infty} (-1)^{j} \frac{(\gamma)(\gamma-1)(\gamma-2)\ldots\ldots(\gamma-j+1)}{\Gamma(j-1)} z^{-j} \tag{3}$$

In terms of discrete time, the differentiator operator 'D' is defined as

$$D^{\gamma} = T^{-\gamma} \sum_{j=0}^{\infty} (-1)^{j} \binom{\gamma}{j} z^{-j} \tag{4}$$

or

$$D^{\gamma} = T^{-\gamma} \sum_{j=0}^{\infty} d_j z^{-j} \tag{5}$$

where, $d_j = (-1)^{j} \binom{\gamma}{j}$ a Binomial coefficient, which can be further arrange in an recursive algorithm.

$$d_j = \left(1 - \frac{1+\gamma}{j}\right) d_{j-1};\ \mathrm{j} = 1, 2, 3, \ldots\ldots\ldots\ldots \tag{6}$$

So, the fractional order operator (differentiator/integrator) of a sequence $g[n]$ can be expressed as follows:

$$D^{\gamma}(g[n]) = T^{-\gamma} \sum_{j=0}^{\infty} d_j g[n-j] \tag{7}$$

Now, it has been clear from the Eq. (8) that in order to realize the fractional order differ-integral operator infinite number of memory is required which seems to unrealistic. Therefore, for the implementation of these fractional order operators a short memory concept was introduced. In this regard, only last few samples have to be stored. In the present case, a memory of 1000 was opted for realization of fractional order mathematical order.

$$D^{\gamma}(g[n]) = T^{-\gamma}\sum_{j=0}^{1000} d_j g[n-j] \tag{8}$$

4 Fractional Order PID Controller ($PI^{\lambda}D^{\mu}$)

The PID controller, in general, can be expressed as

$$U_{PID}(t) = K_C e(t) + K_I \int e(t)dt + K_D \frac{de(t)}{dt} \tag{9}$$

In time domain the Fractional Order PID Controller $(PI^{\lambda}D^{\mu})$ can be expressed as follows:

$$U_{FO-PID}(t) = K_C e(t) + K_I \frac{d^{-\lambda}e(t)}{dt^{-\lambda}} + K_D \frac{d^{\mu}e(t)}{dt^{\mu}} \tag{10}$$

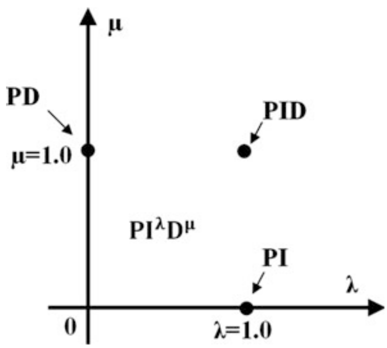
where K_C is proportional constant; K_I is integral constant; K_D is derivative constant; λ is the fractional integral value and μ is the fractional derivative value. $U_{FO-PID}(t)$ is the aggregate output of FO-PID controller and $e(t)$ is the tracking error.

In s-domain, the $PI^{\lambda}D^{\mu}$ controller would become

$$U_{FO-PID}(s) = \left(K_C + K_I \frac{1}{s^{\lambda}} + K_D s^{\mu}\right)E(s) \tag{11}$$

From the Fig. 1, one can clearly understand that the classical PI, PD and PID controllers are unique cases of the FO-PID controller. Particularly, PID can be formed by letting the variables λ and μ as unity. It is due to the selection of values of variables λ and μ, which provides two more DOF to the control engineer in addition to the three controller constants. Hence, for designing a FO-PID controller, five variables need to be tuned in order to get the best desired response.

Fig. 1 FO-PID controller



In the present work, the parameters of FO-PID and PID controllers were optimally determined using GA for a defined performance criterion as described in the following section for a 2-link planar rigid manipulator. With the experiments conducted it can be concluded that the overall control behavior of the FO-PID controller is much superior to the classical PID controller.

5 Performance Criteria

For evaluating the set-point tracking performance of the system in closed-loop the IAE and Integral Square of Change in Controller Output (ISCCO) for each link having equal weight were considered as a performance criteria. The IAE and ISCCO are defined as:

$$IAE = \int_0^t |e(t)| dt \tag{12}$$

$$ISCCO = \int_0^t \Delta u^2(t) dt \tag{13}$$

The above performance indices were used for adjusting the various parameters (K_C, K_I, K_D, λ, μ) of FO-PID and PID controllers.

6 Dynamic Model of 2-Link Manipulator

A 2-link planar rigid manipulator having two DOF is shown in Fig. 2. It has two links having length l_1 and l_2, mass m_1 and m_2, respectively. The angular position of link-1 and link-2 are θ_1 and θ_2, respectively and τ_1 and τ_2 are the respective torque for link-1 and link-2. The dynamic model of 2-link planar rigid manipulator described in [2, 19] has been utilized in this work.

The mathematical model of the 2-link planar rigid manipulator is as follows:

$$\begin{aligned}\tau_1 = {} & m_2 l_2^2\left(\ddot{\theta}_1 + \ddot{\theta}_2\right) + m_2 l_1 l_2 c_2\left(2\ddot{\theta}_1 + \ddot{\theta}_2\right) + (m_1 + m_2) l_1^2 \ddot{\theta}_1 - m_2 l_1 l_2 s_2 \dot{\theta}_2^2 \\ & - 2 m_2 l_1 l_2 s_2 \dot{\theta}_1 \dot{\theta}_2 + m_2 l_2 g c_{12} + (m_1 + m_2) l_1 g c_1\end{aligned} \tag{14}$$

$$\tau_2 = m_2 l_1 l_2 c_2 \ddot{\theta}_1 + m_2 l_1 l_2 s_2 \dot{\theta}_1^2 + m_2 l_2 g c_{12} + m_2 l_2^2\left(\ddot{\theta}_1 + \ddot{\theta}_2\right) \tag{15}$$

where $s_2 = \sin(\theta_2)$, $c_1 = \cos(\theta_1)$, $c_2 = \cos(\theta_2)$, and $c_{12} = \cos(\theta_1 + \theta_2)$.

Fig. 2 A 2-link planar rigid manipulator

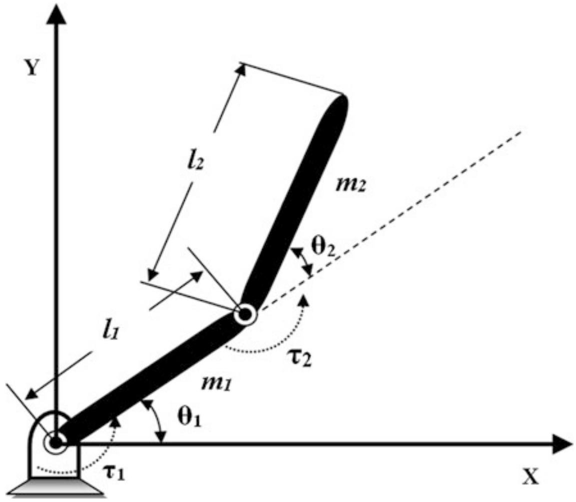


Table 1 Parameters for a 2-link planar rigid robotic manipulator

Parameters	Link-1	Link-2
Mass (kg)	0.1	0.1
Length (m)	0.8	0.4
Acceleration due to gravity (g) (m/s^2)	9.81	9.81

Equations 14 and 15 give the required torques at the actuators as a function of joint positions, velocities, and accelerations. The parameters of the manipulator are listed in Table 1.

7 Experimental Results

The noise suppression investigations were organized as follows. Firstly, sensor noise suppression was investigated followed by the controller's noise suppression as a second case. Both the experiments were simulated in closed-loop for 2-link rigid manipulator trajectory control using FO-PID and PID controllers. The block diagram of closed-loop control system is shown in Fig. 3. Simulations were performed using National Instrument® software, LabVIEW™ 8.5 and its add-ons Simulation and Control Design toolkit. In the simulation loop, 4th order Runge–Kutta method, an ordinary deferential equation (ODE) with a fixed step size of 10 ms was used.

Ayala and Coelho [2] have considered a reference trajectory based on cubic interpolation polynomial nature to be followed by the proposed 2-link manipulator. The same reference trajectory has been taken in this work. It was defined in [2, 19]:

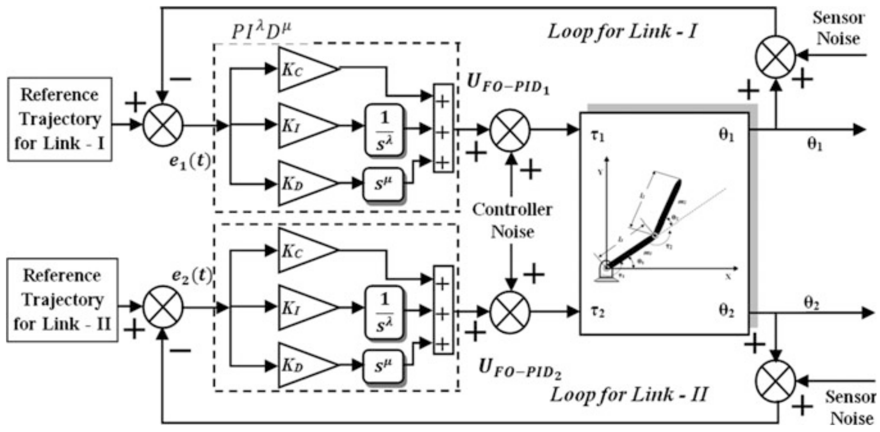


Fig. 3 The block diagram of closed-loop control system

$$\theta_{rt,j}(t) = a_0 + a_1 t + a_2 t^2 + a_0 t^3,\ j = 1, 2 \tag{16}$$

Therefore the joint velocity and acceleration along the reference trajectory becomes

$$\dot{\theta}_{rtf,j}(t) = a_1 + 2a_2 t + 3a_0 t^2,\ j = 1,\ 2 \tag{17}$$

$$\dot{\theta}_{rtf,j}(t) = 2a_2 + 6a_0 t,\ j = 1, 2 \tag{18}$$

where $\theta_{rt,j}(t)$ $[\theta_{rt,1}(t);\ \theta_{rt,2}(t)]$ is the instantaneous desired position for link-1 and link-2, respectively. Also, $\theta_{rtf,j}(t)$ and $\theta_{rtf,j}(t)$ are the final desired values for the position ($\theta_{rtf,1}(t) = 1$ rad and $\theta_{rtf,2}(t) = 2$ rad in $t = 2$ s and $\theta_{rtf,1}(t) = 0.5$ rad and $\theta_{rtf,2}(t) = 4$ rad in final time $t_f = 4$s) and velocity ($\dot{\theta}_{rtf,1}(t) = \dot{\theta}_{rtf,2}(t) = 0$ rad/s in $t = 2$ s and $t_f = 4$ s) of link-1 and link-2 respectively.

The various parameters of FO-PID and PID controllers, in the absence of noise, were tuned using GA, developed in the used LabVIEW environment [23]. The population size was considered to be 20 and the tolerance level was kept as 10^{-6} and the maximum numbers of iterations were kept as 100. The used cost function (J), to be minimized, was the weighted sum of the IAE and ISCCO as defined below.

$$J = \int_0^\infty [w_1^1 * |e_1(t)| + w_1^2 * |e_2(t)| + w_2^1 * \Delta u_1^2(t) + w_2^2 * \Delta u_2^2(t)]dt \tag{19}$$

In the present work, equal weights i.e., $w_1^1 = w_2^1 = w_1^2 = w_2^2 = 0.25$ were assigned to IAE and ISCCO while optimizing the parameters of FO-PID and PID controllers. Figure 4 shows cost function versus generation plot for both the controllers.

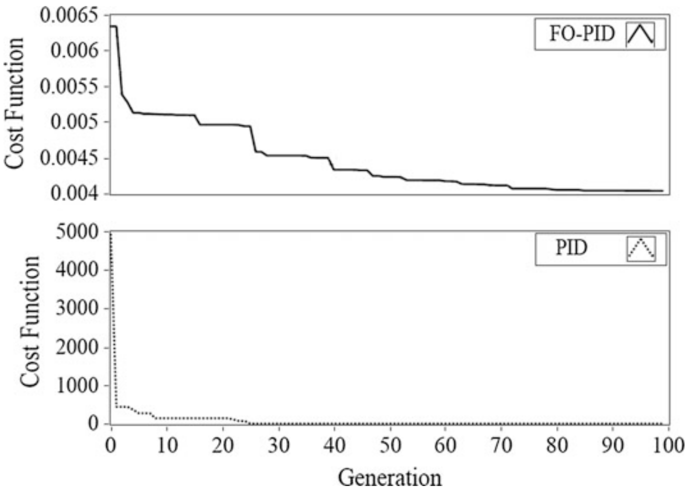


Fig. 4 Cost function versus generation curve for FO-PID and PID controllers

The tuned parameters values for both the controllers are given in Table 2 along with the cost function values. For these gains the obtained values of IAE are tabulated in Table 3. The complete set-point tracking response of 2-link rigid manipulator without sensor and controller noise in closed-loop with FO-PID and PID controllers is shown in Fig. 5. It can be observed that set-point tracking performance of FO-PID controller is better than PID controller. Also, lower variations in the torque of link-1 and link-2 were observed for FO-PID controller as compared to PID controller.

In the present work, point by point UWN and GWN were considered for measurement/sensor and controller noise study. Sensor and controller noise were introduced in the closed-loop control system in both the links of manipulator as shown in the Fig. 3. Noise suppression study, of FO-PID and PID controllers, for sensor and controller noise in closed-loop, is presented in the following section.

7.1 Sensor Noise Suppression

All control systems, in practical cases, are subject to some kind of noise during their operation. Thus, in addition to responding to the input signal, the system should also be able to reject and suppress noise and unwanted signals. There are many forms and sources of noise but the sensor noise play significant impact on the performance of the system. Such noise is typically dominated by high frequencies. Measurement noise usually sets an upper limit on the bandwidth of the loop. Also, it introduces uncertainty in the system. In the subsequent section the sensor noise suppression of FO-PID and PID controllers in the closed-loop is presented.

Table 2 Optimal parameters of FO – PID and PID controller

Controller type	Manipulator link	Performance index	Minimum cost function	Controller parameters				
				K_C	K_I	K_D	λ	μ
$PI^{\lambda}D^{\mu}$	Link-1	IAE and ISCCO	0.0079360	507.102	1035.55	430.616	0.997709	0.17498
	Link-2			10.517	1019.06	312.083	0.894167	0.603051
PID	Link-1	IAE and ISCCO	0.0177892	449.895	0.524	5.550	1	1
	Link-2			238.338	7.755	22.342	1	1

Table 3 Performance index

Controller type	Manipulator link	Performance index
		IAE
$PI^{\lambda}D^{\mu}$	Link-1	0.00215675
	Link-2	0.00196381
PID	Link-1	0.00902466
	Link-2	0.00951855

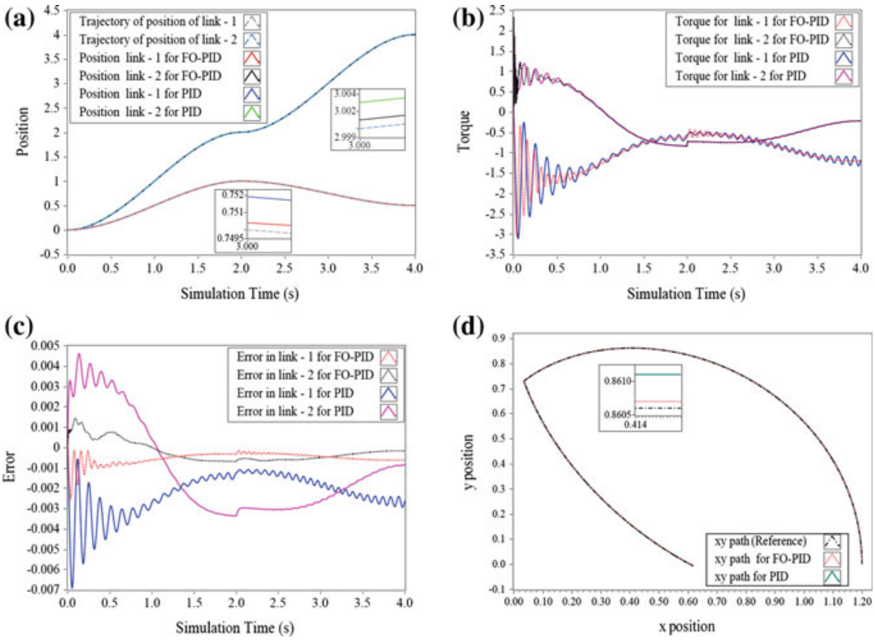


Fig. 5 **Closed**-loop response of link-1 and link-2 of robotic manipulator without sensor and controller noise. **a** Position. **b** Applied torque. **c** Error. **d** xy curve

7.1.1 Uniform White Noise

UWN was introduced as sensor noise in link-1 then in link-2 and finally it was injected in both links together. For this study, in all the cases, amplitude of UWN was varied and the corresponding IAE of FO-PID and PID controllers in closed-loop were recorded. The variation of IAE of FO-PID and PID controllers in closed-loop and amplitude of UWN are plotted in Fig. 6. It can be noted that PID controller fails to suppress the sensor noise even for very small amplitude of UWN while FO-PID controller is able to suppress even the large amplitude UWN sensor noise effectively. This outcome clearly shows the superiority of FO-PID controller over PID controller. To further elaborate a typical case the time response of robotic manipulator in closed-loop with FO-PID and PID controllers and with UWN sensor noise of amplitude 0.002 in both links was shown in Fig. 7. It clearly demonstrates

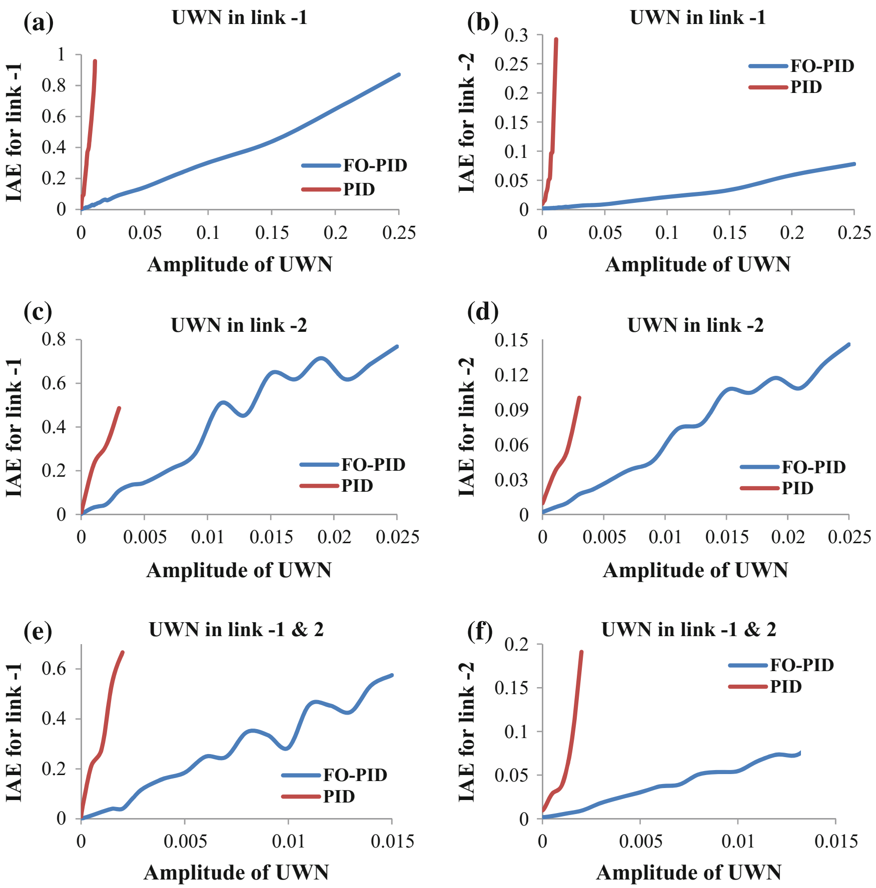


Fig. 6 Effect of sensor noise (UWN) in closed-loop. **a** and **b** in link-1. **c** and **d** in link-2. **e** and **f** in link-1 and link-2

that when sensor noise is present in the both links of robotic manipulator, PID controller fails to track the trajectory and start oscillating around the reference trajectory with increasing amplitude in comparison to FO-PID controller which sticks to the trajectory and follow it without any deviation. In Fig. 7 (d) the resulting xy curve shows it effectively.

7.1.2 Gaussian White Noise

Further, in line with the above, GWN was added as a measurement noise in the link-1, link-2 and link-1 and 2. Figure 8 shows the variation in IAE values for FO-PID and PID controllers as the standard deviation of GWN increases. Again, it can be observed that conventional PID controller fails to suppress this measurement

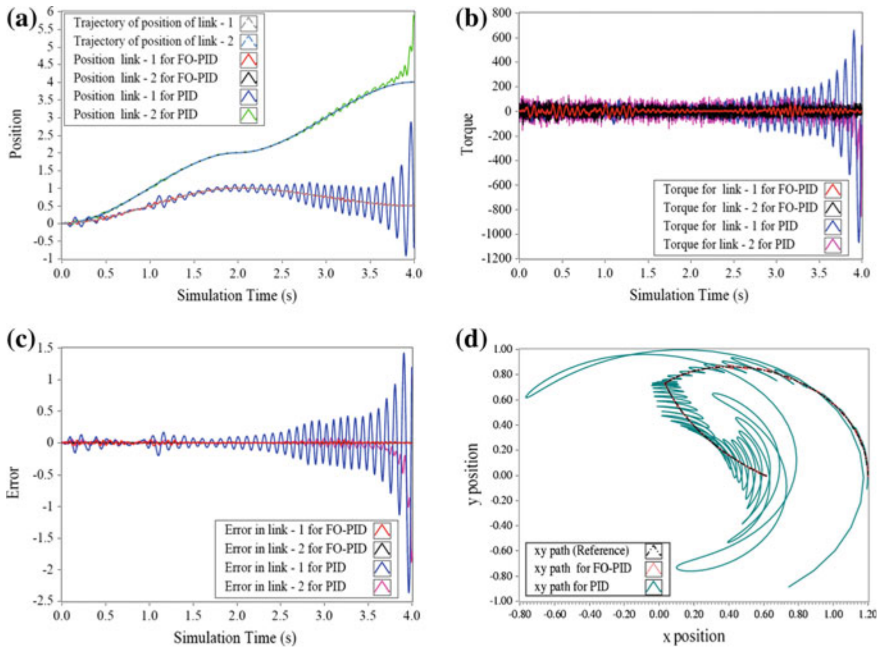


Fig. 7 Closed-loop response of link-1 and link-2 of robotic manipulator with UWN sensor noise of amplitude 0.002 in both links. **a** Position. **b** Applied torque. **c** Error. **d** xy curve

noise as its standard deviation is increased. Also, as the intensity of noise increase manipulator deviates from the desired trajectory and finally become unstable. On the other hand, FO-PID controller effectively handles the sensor noise and eliminates its effect so that robotic manipulator follows the trajectory without any deviation for a sufficient GWN measurement noise as shown in Fig. 8. This investigation clearly demonstrates the superiority of FO-PID controller over PID controller. Figure 9 shows a typical reference trajectory tracking response of manipulator in closed-loop with GWN noise of 0.007 standard deviations, in both links. The time response demonstrates the utility of FO-PID controller over PID controller for sensor noise suppression. From Fig. 9 the trajectory tracking, control action, error and xy curve illustrate it clearly.

7.2 Controller Noise Suppression

Generally, in closed-loop control system the control action is implemented through a manipulate variable. So a control signal is sent from controller to final control element in the plant in order to regulate the manipulate variable to achieve desired set-point. Actually, a physical connection between controller and final control

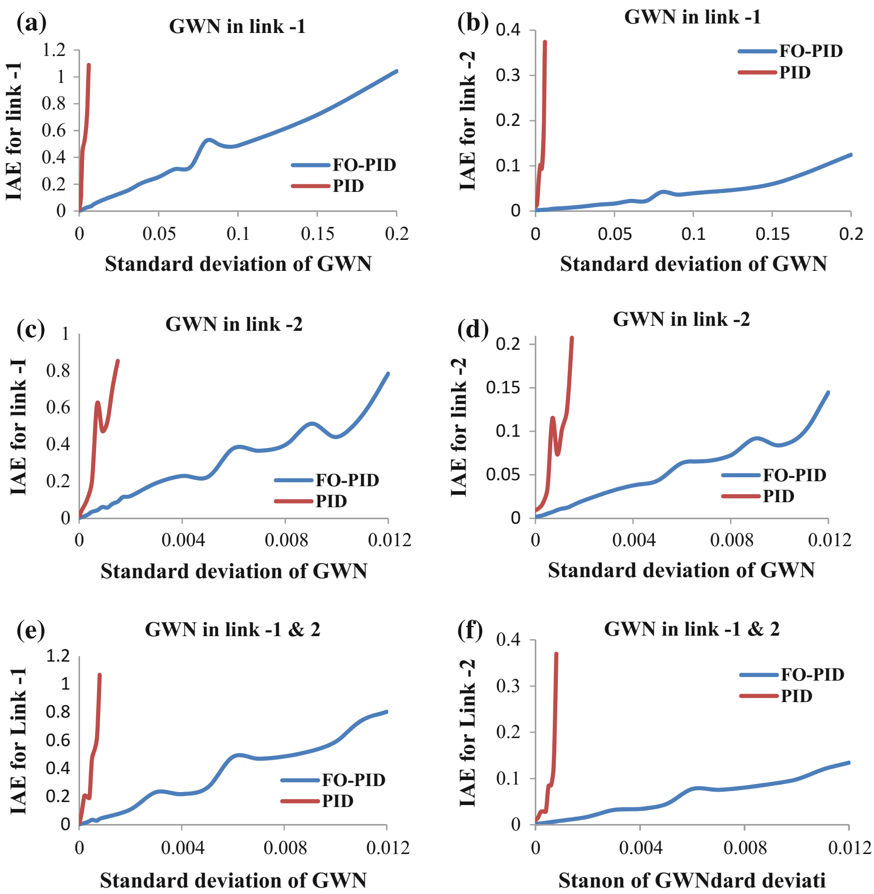


Fig. 8 Effect of sensor noise (GWN) in closed-loop. **a** and **b** in link-1. **c** and **d** in link-2. **e** and **f** in link-1 and link-2

element is required to realize it. In process industry generally the final control elements are placed in the field and due to hazardous area with lots of vibration. Many times connection may become loose and may add additional random noise in the control action. The magnitude of random noise depends upon the environment around the final control element. Also, it has been noted in the industry that many mammals such as mouse cut the wire. In case of partially broken wires, it may pick up the random noise and the magnitude of noise will depend upon the exposure of the conductor to environment and elements around the final control element. Therefore the unexpected noises added in the control signal and corrupt the control action and may try to destabilize the plant or process.

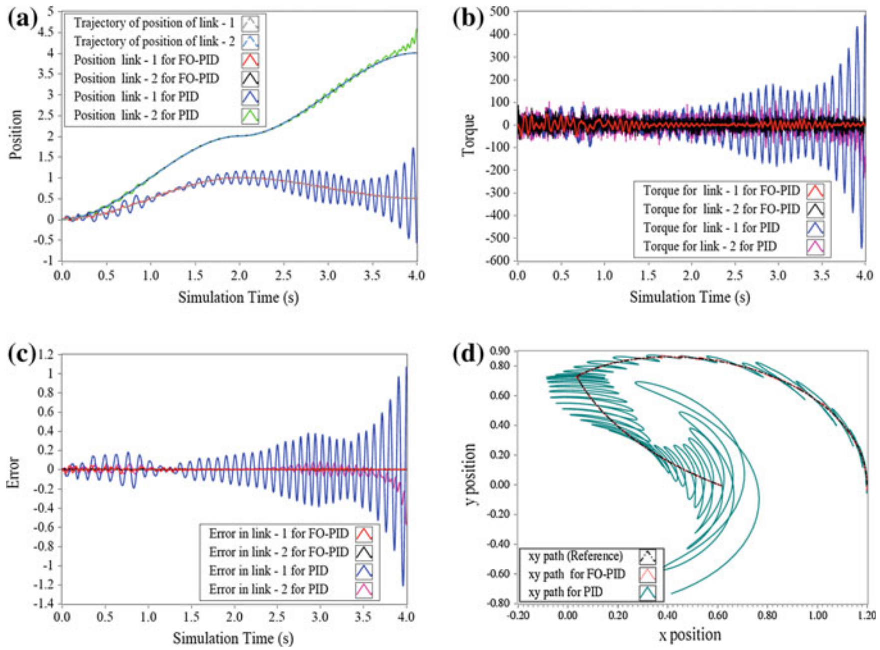


Fig. 9 Closed-loop response of link-1 and link-2 of robotic manipulator with GWN sensor noise of standard deviation of 0.0007 in both links. **a** Position. **b** Applied torque. **c** Error. **d** xy curve

In the present work, UWN and GWN are added in the control action as a controller noise. In the next section, the impacts of both controller noises on the system response are presented.

7.2.1 Uniform White Noise

UWN was added as controller noise in the links independently and then in both links simultaneously. The amplitude of UWN was increased linearly and corresponding IAE for FO-PID and PID controller were recorded. Figure 10 illustrates the variation of the amplitude of UWN and IAE for FO-PID and PID controllers in closed-loop. It can be noted that PID controller acquired considerable IAE and became unstable around the amplitude of UWN has a value 50. While FO-PID controllers have moderate value of IAE and follow trajectory effectively up to the amplitude of UWN having a value 200. The time response curve of the robotic manipulator trajectory control for amplitude of UWN of 24 in both links was shown in Fig. 11. It undoubtedly demonstrates the superiority of FO-PID controller in comparison of PID controller for controller noise suppression.

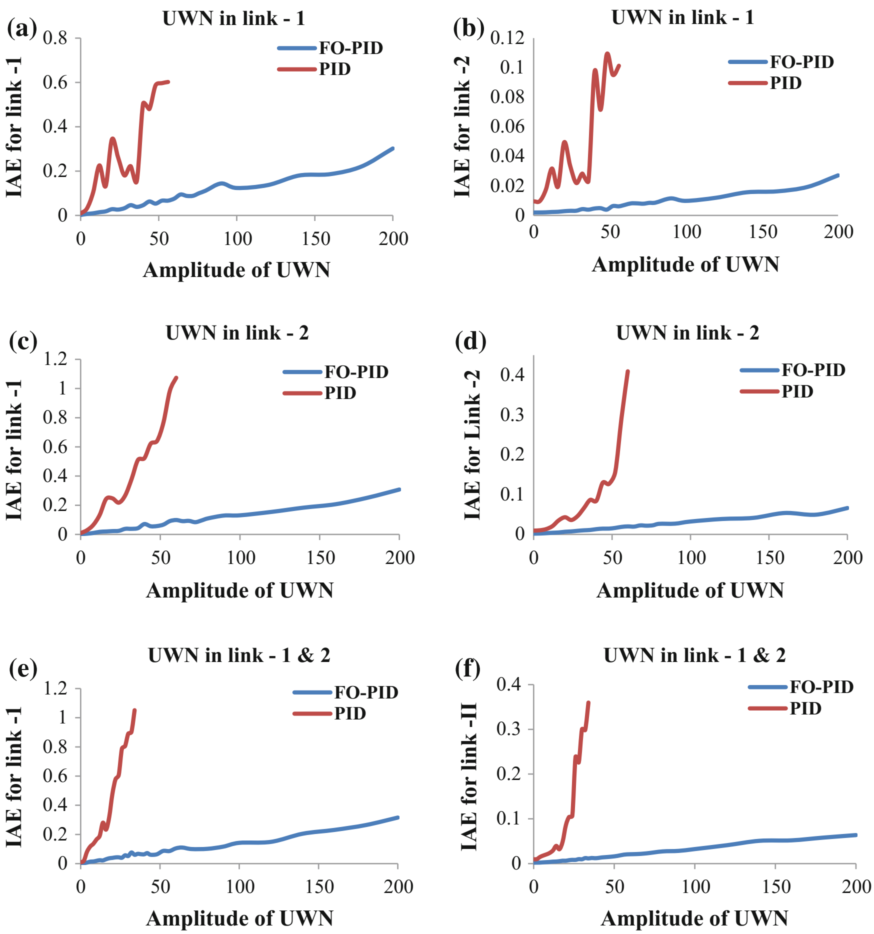


Fig. 10 Effect of controller noise (UWN) in closed-loop. **a** and **b** in link-1. **c** and **d** in link-2. **e** and **f** in link-1 and link-2

7.2.2 Gaussian White Noise

Now, GWN was introduced as a controller noise in closed-loop. The standard deviation of controller noise was varied and the corresponding variation in IAE for FO-PID and PID controller was plotted in Fig. 12. It has been observed that IAE of PID controller increases rapidly and system become unstable around the 40 standard deviation of GWN. In contrast, FO-PID controller keeps its IAE quite small and as the standard deviation of GWN is increased up to 200 and still it has

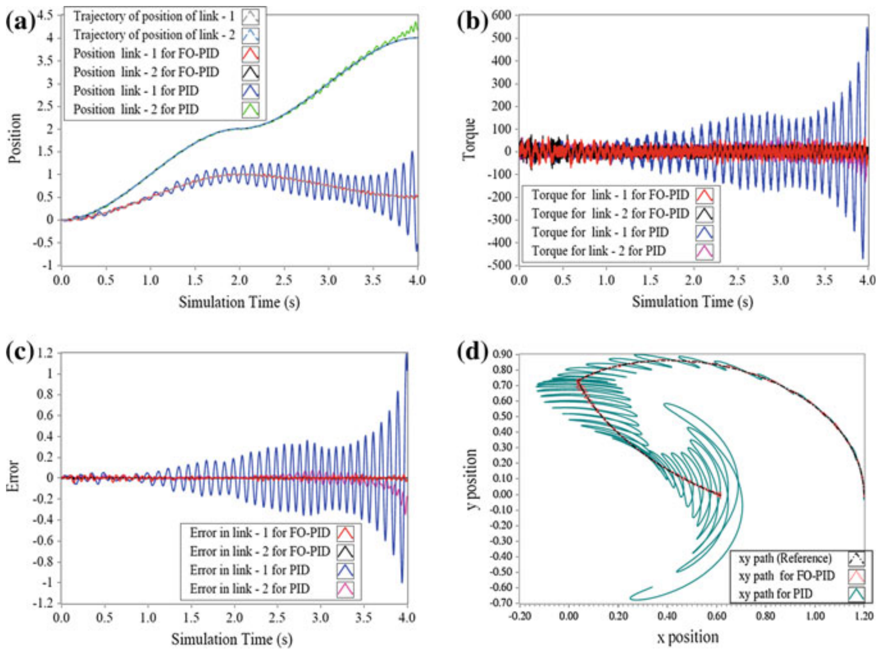


Fig. 11 Closed-loop response of link-1 and link-2 of robotic manipulator with UWN controller noise of amplitude 24 in both links. **a** Position. **b** Applied torque. **c** Error. **d** xy curve

reasonable value of IAE. Figure 13 illustrates the set-point tracking response of FO-PID and PID controller for standard deviation of GWN of 21 in both links. Again, it shows the advantage of FO-PID controller over PID controller.

7.3 Sensor and Controller Noise

In the highly noisy environment, the operation of robotic manipulator can be contaminated by random noises at various areas of closed loop system which would considerably degrade the effectiveness and accuracy of the manipulator. In this section, UWN and GWN are added together in the control action as well as in the sensor in both links. The tracking performance responses of robotic manipulator with UWN sensor and controller noise of the amplitude 0.002 and 24 respectively in both links are shown in Fig. 14. Also, the closed loop responses of the manipulator with GWN sensor and controller noise of the standard deviation of 0.0007 and 21 respectively in both links are shown in Fig. 15.

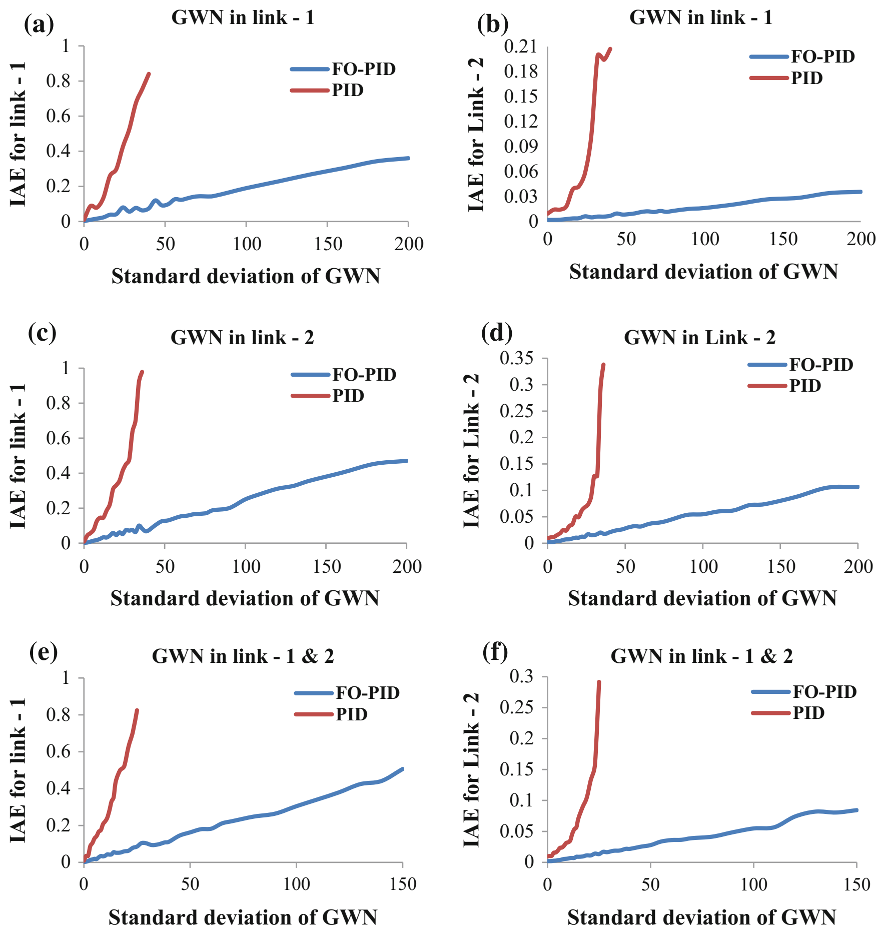


Fig. 12 Effect of controller noise (GWN) in closed-loop. **a** and **b** in link-1. **c** and **d** in link-2. **e** and **f** in link-1 and link-2

The FO-PID controller shows better noise suppression in controller as well as in the sensor due to the fractional order derivative. The frequency response of the fractional and complete derivative is shown in Fig. 16. It is clear from the frequency response that fractional derivative has lower attenuation rate as compared to complete derivative. Specially, in the investigated case of link-1, the order of fractional derivative was around 0.17 and the gain remains below 0 dB till 100 Hz. Further, it is clear from the graph that slope of the fractional derivative is restricted below 20 dB/decade. Therefore, FO-PID is able to successfully suppress the sensor and controller noise for a manipulator.

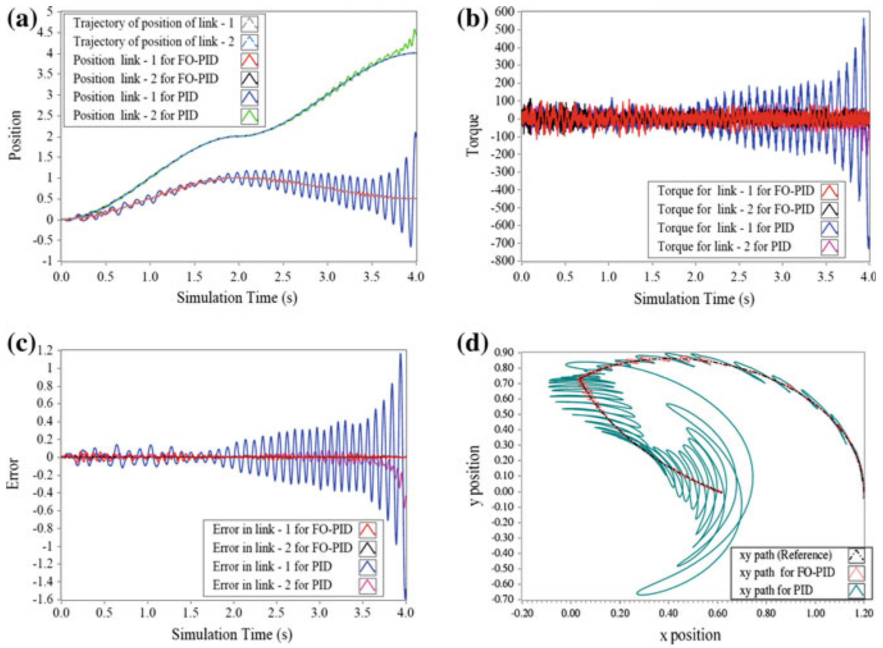


Fig. 13 Closed-loop response of link-1 and link-2 of robotic manipulator with GWN controller noise of amplitude 21 in both links. **a** Position. **b** Applied torque. **c** Error. **d** xy curve

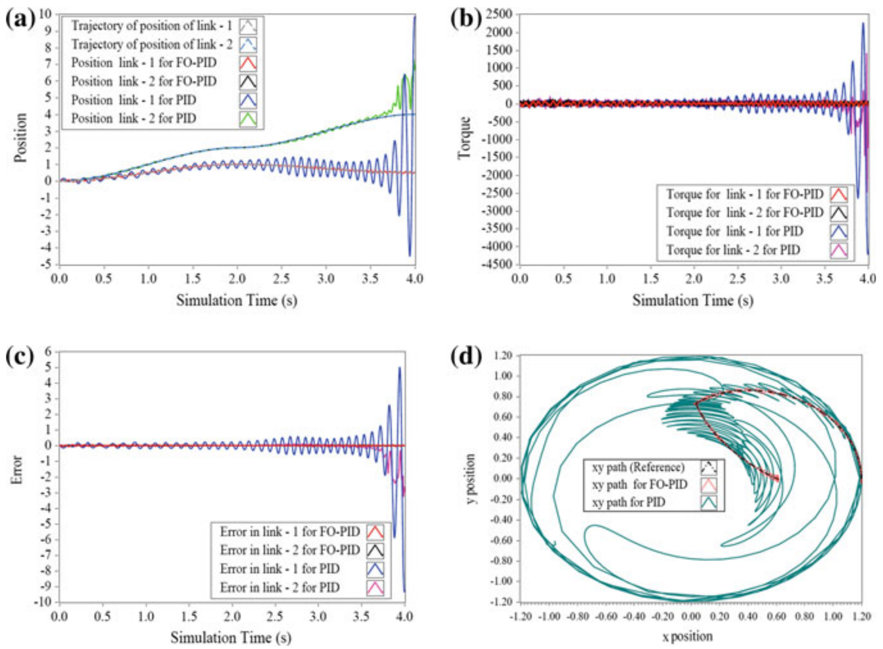


Fig. 14 Closed-loop response of link-1 and link-2 of robotic manipulator with UWN sensor and controller noise of amplitude 0.002 and 24 respectively in both links. **a** Position. **b** Applied torque. **c** Error. **d** xy curve

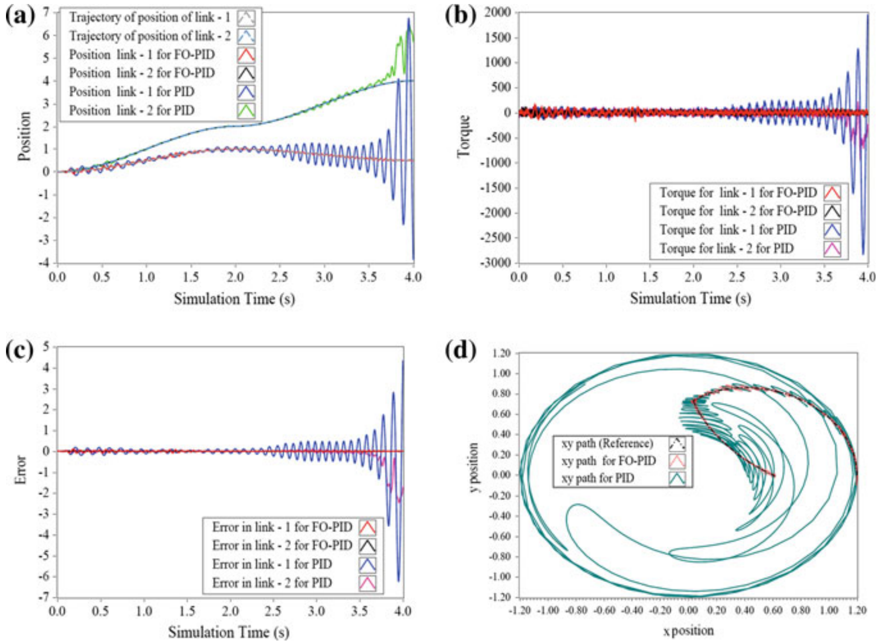


Fig. 15 Closed-loop response of link-1 and link-2 of robotic manipulator with GWN sensor and controller noise of standard deviation of 0.0007 and 21 respectively in both links. **a** Position. **b** Applied torque. **c** Error. **d** xy curve

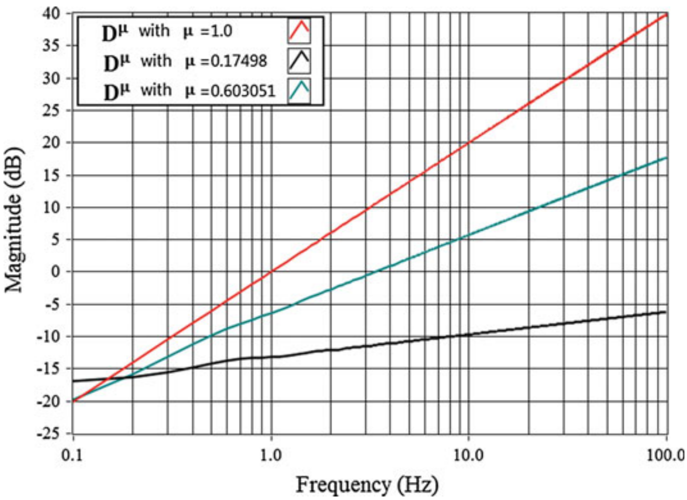


Fig. 16 Frequency response of the fractional derivative controller D^{μ} with $\mu = 1.0, 0.17498$ and 0.603051

8 Conclusion

Noise is an integral part of any real measurement and control experiment. It appears in many forms in control loop in process industry and introduces uncertainty in the system. Uncertain systems become a challenge for a control engineer. Conventional parallel PID controller fails to suppress all kind of random noise due to complete derivative term in it. But the fractional order derivative, employing effectively lower order derivative increases the noise suppression capability of Fractional Order-Proportional plus Integral plus Derivative (FO-PID) controller. The main contribution of this chapter has been to demonstrate the sensor and controller noise suppression of FO-PID over PID controller for 2-link rigid manipulator trajectory control.

In this chapter, FO-PID and PID controller were successfully implemented in closed-loop. The controllers were tuned for minimum weighted sum of Integral of the Absolute value of the Error (IAE) and Integral Square of Change in Controller output (ISCCO), for a non-linear 2-link rigid planner robotic manipulator, using Genetic Algorithm. UWN and GWN were considered for sensor and controller noise in the loop. It has been observed that FO-PID controller outperformed PID controller in both sensor and controller noise suppression in closed-loop.

The present study can be further extended in the future by realizing the fractional order calculus using different implementations techniques reported in the literature. Furthermore, similar investigation can also be performed on intelligent control schemes applied to complex plant. Also, the simulated results can be verified experimentally.

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