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Application of the Fractional Order Proportional Integral Derivative Scheme for Two-Link Planar Robot Control

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Abstract

Robotic systems are increasingly important across modern technological and industrial sectors, yet their nonlinear dynamics and demanding operational requirements continue to challenge conventional control approaches. Linear controllers may not adequately manage such systems, whereas nonlinear controllers are often complex to implement. This study proposes and evaluates a Fractional-Order Proportional–Integral–Derivative (FPID) controller for a two-link planar robot and compares its performance with that of a conventional Proportional–Integral–Derivative (PID) controller. The analytical system model was adapted from Nazif et al. (2023), with frictional disturbance incorporated into the evaluation. Sinusoidal and step-response simulations were conducted using MATLAB/Simulink. Under sinusoidal input, the FPID controller improved tracking accuracy by 5% for Link 1 and 18% for Link 2 relative to the PID controller. Under step input, it reduced overshoot by 44% and 38%, improved settling time by 58% and 67%, and increased accuracy by 23% and 24% for Links 1 and 2, respectively. These results demonstrate that the FPID control scheme provides greater accuracy, faster response, lower overshoot, and more robust performance than the conventional PID scheme. The study establishes FPID control as a suitable approach for improving the dynamic performance of two-link planar robots under frictional disturbance and provides a basis for further controller refinement to achieve additional performance gains.

Keywords: Control Systems; Fractional-Order PID Control; Frictional Disturbance; PID Control; Two-Link Planar Robot

INTRODUCTION

Manipulator robotic systems are now popular in almost all vital sectors of the modern world. Robotic systems are widely known for their inherent high operational speeds, remarkable repeatability capabilities coupled with very high levels of accuracies in tasks executions. The high level of nonlinear nature of such systems and advancements in modern technologies pose continuous enhancement requirements for their smooth operations. Control systems play vital roles towards improved performance. The two or dual-link planar robot is specially designed to have to two separate links, which are coupled and constrained to only accomplish movement in just a particular direction or plane (Baccouch, and Dodds,2020; Jelacic et al., 2020).

Robotic manipulators are applied in numerous aspects of human endeavors such as; manufacturing industries, healthcare facilities, modern devices, astronomy and exploration of space and others. Credited to the capability of executing tasks that are complex with high accuracy rate, precision and repeatability (Baccouch, and Dodds,2020; Jelacic et al*.,* 2020; Sinuraya et al., 2025). The dual-link planar robot was popularly investigated which could be attributed to applications, simple nature of the system, acceptability, easier adaptation and similar dynamics with other more complex systems. Such systems by configuration are two degrees of freedom (DOF). The addition of robotic arm could facilitate independent link movements, giving rise to a planar (2D) motion with precision. In critical applications the control requirement could be stringent such as in applications like material handling, accurate welding, precision painting, hybrid prosthesis and minimal invasive surgery (Pasupuleti, 2019; Baccouch, and Dodds,2020; Boscariol et al.,2022; Kwok et al., 2022).

Control approaches were proposed for better operational performance in the two-link planar robotic systems. The works presented by Ilgen et al., (2018) was on the 'Sliding Mode Control (SMC)' method explored using combined Adam and MATLAB software.

Inherent robustness of the approach was reported. In another development Mohammed and Eltayeb, (2018), further evaluated the SMC and the 'Proportional-Integral-Derivative (PID)' for the system operation. The boundary projections SMC method was investigated in works of Han and Jia, (2020) and a simplified SMC was realized. Ji et al, (2022) improved the reaching law SMC method. In the presentation of Nguyen et al., (2020), the 'exponential reaching law type SMC was examined and in the works of Zou (2009), the Fuzzy Logic control was explored on the planar robotic system. Nazif et al., (2023) simplifies the 'exponential reaching SMC was investigated yielding results which are fruitful.

Literature therefore gave impression that the PID could have high difficulties in sufficiently correcting the operation performance of the two-link planar robotic structures which are characterised by being highly nonlinear, coupled with operational necessities. Nonlinear control schemes are highly complex which highly need simplification for practical implementation. The Fractional order coupled PID controller known as 'Fractional Order PID (FPID)' is a slightly improved PID controller was portrayed in some studies (Husnain and Abdulkader, 2023). Domonstration by authors was on 'articulated robotic manipulator'. This implied that, the FPID could be explored for better operation and performance of the 'two-link planar robots'. The popular version of the PID control approach found to suit 'two-link planar robot systems' was the 'Proportional Derivative (PD)' controller; with just the proportional and derivative components (Borase et al., 2021; Kumar and Kumari, 2024). Hence, for the work the PD version of the Fractional Order PID would be explored, alongside the PID.

METHODOLOGY

The two-link planar robot as depicted in Figure 1 is the plant in the system under consideration. The subsystem required to follow a desired pattern trajectory of which in control systems is accomplished with the aid of the controller. The controller makes decisions by acting based on results obtained by comparing the desired positions or trajectory and the response or links positions. The error is the outcome of the comparison and the feedback subsystem assist in obtaining the response and converting to similar parameter as the reference.

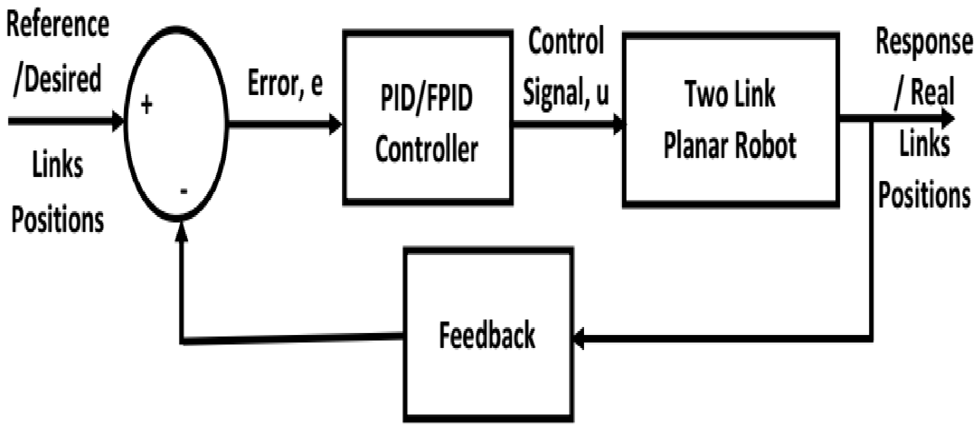

Figure 1. System Block Diagram

The two-link planar robot as the name implies consist of two independent rigid bodies connected together. Configured in two degrees of freedom (DOF) in a particular plane. The analytical model was conceived from the works of Mailoh and Poh, 2005, Gao and Book, 2006, Baccouch, and Dodds, 2020 and Nazif et. al., 2023. The equations (1) – (12) gives the description of the two-link planar robot system. The torques are given by the vector τ producing the required torques by the links, the gravity by g, M the inertia and C the Coriolis vector. The masses of the links is given by m, L the links lengths, the angular positions are θ, its derivative $\dot{\theta}$ the links angular velocities and second derivative $\ddot{\theta}$ the links angular accelerations.

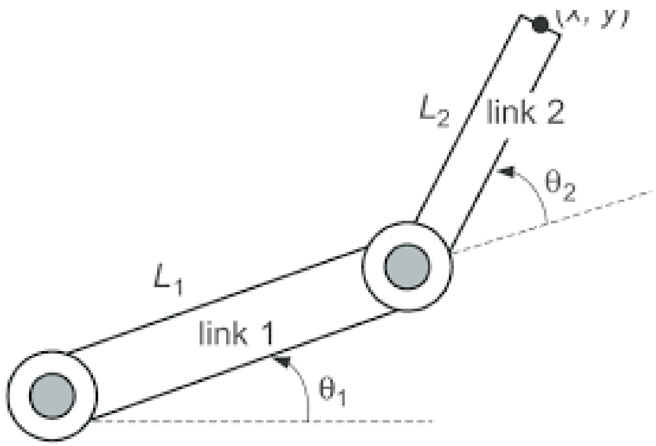

Figure 2. The Two-Link Robot Structure

(Mailah and Poh, 2005; Gao and Book, 2006; Nazif et al., 2023)

$\tau = M(\theta)\ddot{\theta} + C\left(\theta, \dot{\theta}\right) + g(\theta)$	(1)
$\tau = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix}$	(2)
$V = \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$	(3)
$C_1 = -m_2 L_1 L_2 (2\dot{\theta}_1 \dot{\theta}_2 + \dot{\theta}_2^2) \sin\theta_2$	(4)
$C_2 = m_2 L_1 L_2 \dot{\theta}_1^2 \sin\theta_2$	(5)
$g = \begin{bmatrix} g_1 \\ g_2 \end{bmatrix}$	(6)
$g_1 = (m_1 + m_2) g l_1 \cos(\theta_1) + m_2 g l_2 \cos(\theta_1 + \theta_2)$	(7)
$g_2 = m_2 g l_2 \cos(\theta_1 + \theta_2)$	(8)
$M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$	(9)
$M_{11} = (m_1 + m_2) l_1^2 + m_2 l_2^2 + 2 m_2 l_1 l_2 \cos\theta_2$	(10)
$M_{12} = M_{22} = m_2 l_2^2$	(11)
$M_{21} = m_2 l_2^2 + m_2 l_1 l_2 \cos\theta_2$	(12)

The PID and the FPID control laws are depicted by equation (13) and equation (14) respectively. As earlier mentioned the PD versions of the control schemes were implemented even though the complete is mentioned that was for easy understanding. The controller variables are: the error e(t), proportional gain KP, the derivative gain KD and the fractional power of the derivative component of the derivative μ.

$U_{PID} = e(t)KP + \left(\frac{de(t)}{dt}\right)KD$	(13)
$U_{FPID} = e(t)KP + \left(\frac{de(t)}{dt}\right)^{\mu}(KD)$	(14)

RESULTS

The results are presented for the sinusoidal and the step response with and without frictional disturbance. The two test signals were chosen as the were the closest replica of the expected signals deriving the system mimicking the trajectory as well as the actuating signals in the robotic system. The coefficient of frictional disturbance applied in the study was 0.15. The error estimate was obtained from the results of position tracking of the system.

Figure 3 shows the position and speed tracking using the sinusoidal reference signal for the PID and FPID controllers with and without disturbance effect for link1 and Figure 4 was link2. The plot in Figure 5 indicated the cumulative error in the sinusoidal response for the position tracking. Low amount of disturbance was considered which make the responses with and without disturbances very close that one is superimposed on the other as depicted in Figures 3 and 4. Figure 5 gave further explanation in the levels of errors resulted for the position tracking. As depicted the amount of error resulted with the FPID was about 380, which was about 400 for the PID for link1. The errors were 180 and 220 with the FPID and PID respectively for link2. This indicated about 5% and 18% improvements for the links 1 and 2 respectively with the FPID over the PID controller on the system.

Figure 6 and Figure 7 are the step response of Link1 and Link2 respectively. The references are 1.0473 radians (60^0) and 1.5710 radians (90) for the links accordingly. Results showed that an overshoot of 10% and settling time of 0.5s with the FPID, they were 18% and 1.2s respectively with the PID respectively for link1. The overshoot was 5% and settling time 0.4s with the FPID, whereas they were 8% and 1.2s with the PID accordingly for link2. The total errors were 22 radians and 17 radians with the PID and FPID respectively for link1, the errors were 58 radians and 38 radians with the PID and FPID accordingly for link2. These showed improvements of 44% and 38% for links 1 and 2 respectively in terms of overshoot with FPID over with the PID. In terms of settling times the improvements are 58% and 67% for the links accordingly (that is link1 and link2) over the PID scheme. In the case of the level of accuracy, the improvements are 23% and 24% for link1 and link2 respectively over the system with the PID compared with the FPID.

The system robustness can be evaluated based on the ability of the system to maintain the system response close to the desired value. It can be seen for the references; that is sinusoidal and step references, the system with the FPID results in the lowest amount of errors for both the links. Hence, it made the FPID more robust than the PID scheme.

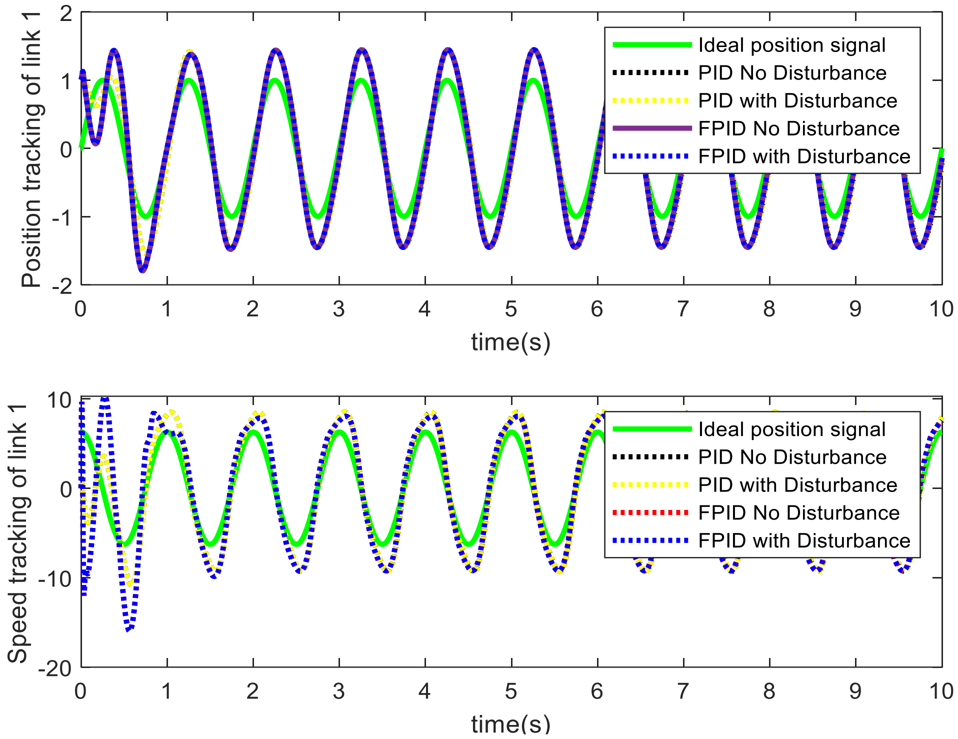

Figure 3. Sinusoidal Response of the Two-Link Robot for Link1

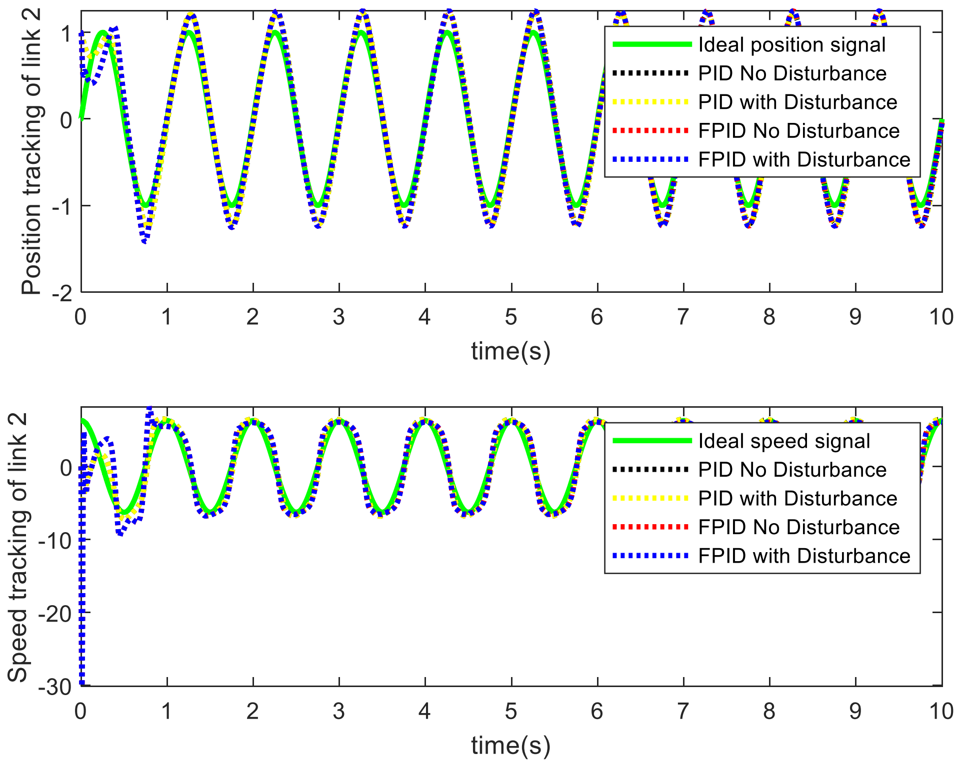

Figure 4. Sinusoidal Response of the Two-Link Robot for Link

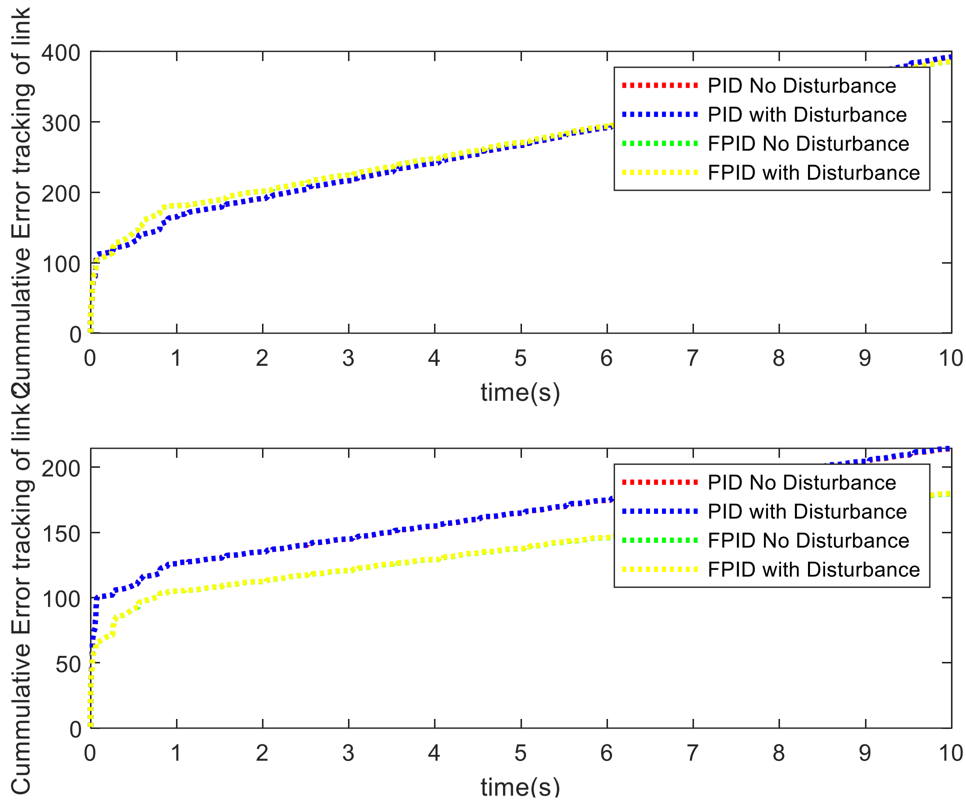

Figure 5. Sinusoidal Response Cumulative Errors of Link1 and Link2

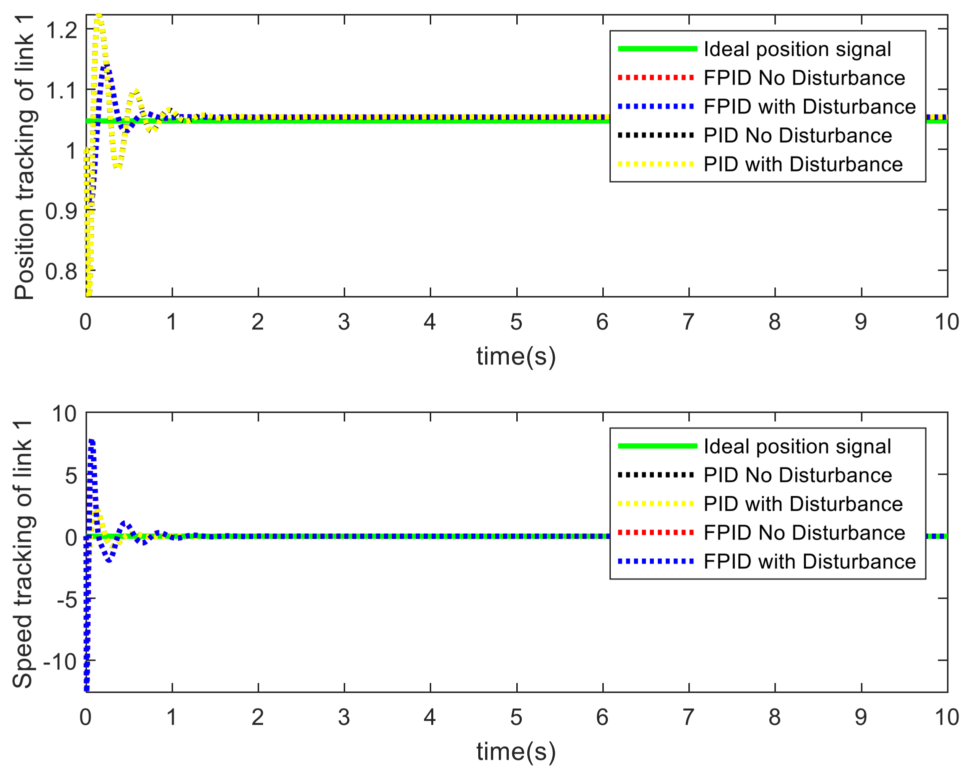

Figure 6. Step Response of the Two-Link Robot for Link1

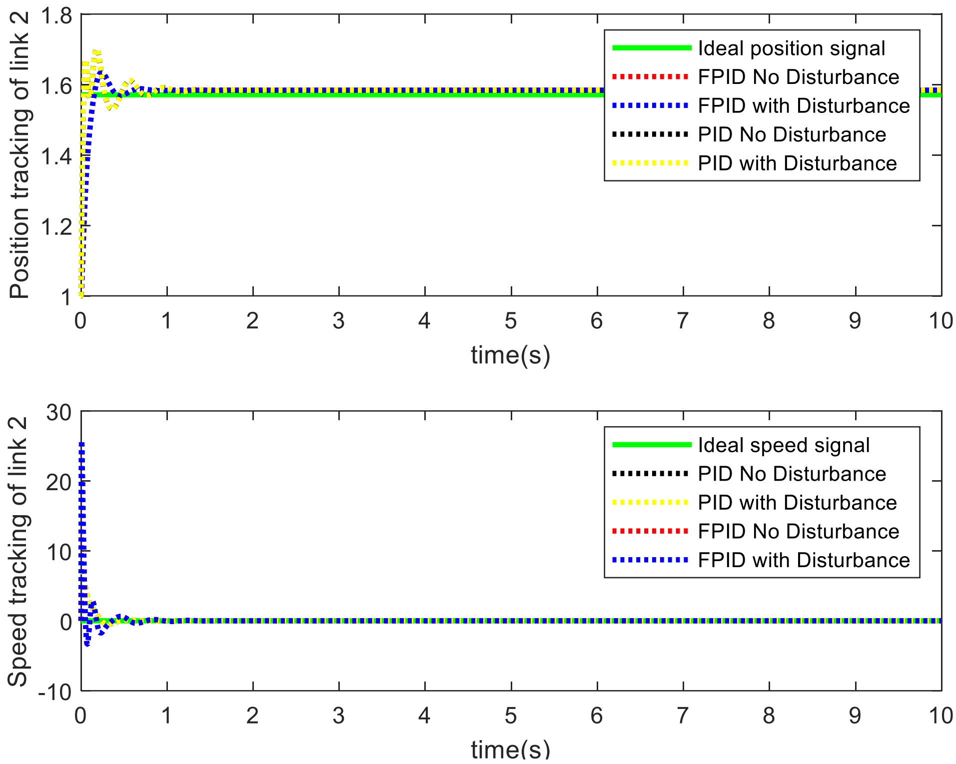

Figure 7. Step Response of the Two-Link Robot for Link2

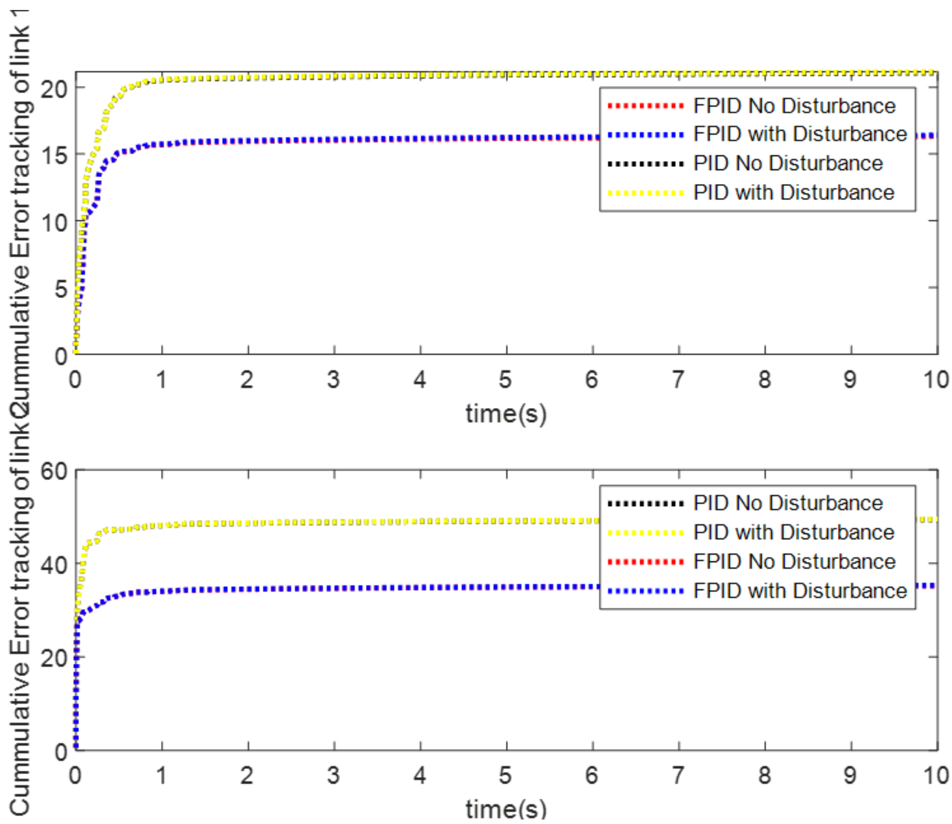

Figure 8. Step Response Cumulative Errors of Link1 and Link2

DISCUSSION

The results from sinusoidal response showed that the amount of error resulted with the FPID was about 380, which was about 400 for the PID for link1 and the errors were 180 and 220 with the FPID and PID respectively for link2. This indicated about 5% and 18% improvements for the links 1 and 2 respectively with the FPID over the system with the PID controller. Results showed that an overshoot of 10% and settling time of 0.5s with the FPID controller, which were 18% and 1.2s respectively with the PID scheme respectively for link1. The overshoot was 5% and settling time 0.4s for the system with the FPID, and were 8% and 1.2s with the PID controller accordingly for link2. The total errors were 22 radians and 17 radians with the PID and FPID respectively for link1. The errors were 58 radians and 38 radians with the PID and FPID accordingly for link2. Thus, indicating improvements of 44% and 38% for links 1 and 2 respectively on overshoot with FPID over with the PID. Considering settling times, the improvements are 58% and 67% for the link1 and link2 accordingly over the system with the PID scheme. The level of accuracy improvements on the system were 23% and 24% for link1 and link2 respectively over the system with the PID compared with the FPID. All these indicated the superior performance of the FPID scheme over the PID in terms of accuracy, faster response ability and robustness. The system is also expected to be stable due to the fact that the level of the error signal diminishes with time as indicated by the step responses.

CONCLUSION

The FPID was successfully implemented on the two link robot system. The robotic systems have become part of the modern world. Advances in technology made operational requirement of such systems more stringent. Control systems have been applied to meet such challenges, but the linear control schemes may not be able to meet the requirements due to the systems and the nonlinear approach are very complex. Therefore, the FPID which is a simple but slightly advanced control was investigated on the system to ascertain its employability on such systems. Results indicated 5% and 18% improvements with the FPID for the links 1 and 2 respectively over the system with the PID controller in respect of the sinusoidal system response in terms of accurate tracking. Upon considering the step response, the improvements were 44% and 38% for links 1 and 2 respectively on overshoot with FPID over with the PID. Regarding the settling times, the improvements are 58% and

67% for the link1 and link2 accordingly over the system with the PID scheme. And for the level of accuracy improvements on the system, it indicated 23% and 24% for link1 and link2 respectively over the system with the PID compared with the FPID. Hence, it is clear that with the FPID some level of improvements on the system performance were witnessed with regards to accuracy, faster response ability, stabilty and robustness. It is even expected that with careful further research much better outcomes might be achieved.

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