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Research Article

Numerical Modelling and Simulation-Based Optimization of NPID Controller for Robotic Manipulator System Using Genetic Algorithm

Aditi Saxena*, Jitendra Kumar, Vinay Kumar Deolia
Department of Electronics and Communication Engineering,
GLA University, Mathura, India.
** Corresponding Author: aditeesaxenaa29@gmail.com*

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ABSTRACT

Robotic manipulation has always posed a challenge for researchers and scientists, especially when dealing with the nonlinearity of manipulators. To address this issue, this paper proposed a robust non-linear proportional integral derivative (NPID) control structure for regulating a non-linear, coupled, two-link stiff robotic manipulator system. The NPID controller employs an error-dependent non-linear factor to enhance its performance. The gains of the controllers were optimized using the meta-heuristic optimization technique Genetic Algorithm, with the objective function defined as the integral of the absolute error change in controller output. The paper compared the performance of PID and NPI controllers with the NPID Controller for reference trajectory tracking, noise suppression, disturbance rejection, and model uncertainty. The simulation results showed that the proposed NPID controller outperformed the other controllers. The NPID controller's improved performance is because of its ability to handle the nonlinearity of the manipulators more effectively than the PID and NPI controllers. This study is a significant contribution to robotic manipulation, as it provides a viable solution to improve the performance of robotic manipulators in various applications.

Keywords: Nonlinearity, PID, NPID, Robotic manipulator, Genetic Algorithm, Integral Absolute error, model uncertainty.

INTRODUCTION

Robotic manipulators were developed a few decades ago to replace workers in hazardous industrial environments. “Spong et.al.[1] introduces the fundamental concepts of robot modelling and control”. These manipulators are examples of mechanically connected uncertain nonlinear plants that grip and carry the material along a preset path using arms and segment joints. “Gopal et.al.[2] provides a comprehensive guide to digital control and state variable methods in robotics, dynamic modelling in detail.” It remains a valuable resource for students and researchers in the field. These are generally utilized in difficult environments where many comparable activities must be completed quickly. Industrial robotic manipulators require material placement and selection. Combining artificial intelligence with traditional control systems boosts output in the automotive, textile, chemical, and food industries. Because various industrial processes are highly nonlinear, unpredictable, time-varying, linked, MIMO, and complicated, an intelligent strategy is necessary for their effective operation. Yang et.al. [3] presents a collection of advanced technologies used in modern robotic applications in their book "Advanced Technologies in Modern Robotic Applications." The book covers topics such as computer vision, machine learning, and swarm robotic manipulators are often utilised at remote industrial sites where repetitive tasks must be completed correctly and on time.

Guo.et.al.[4] This paper provides a comprehensive understanding of the kinematics, dynamics, and control system of a novel robot manipulator, which can be helpful for researchers and engineers working in the field of robotics also investigated the design and manufacturing of soft robots, which are made of soft materials to allow for more flexible design techniques.

According to the International Journal of Advanced Robotic Systems, Loudini.et.al [5] published an article in 2013 titled "Modelling and Intelligent Control of an Elastic Link Robot Manipulator.". Zhang.et.al [6] "Adaptive Fuzzy Sliding Mode Control for a 3-DOF Parallel Manipulator with Parameters Uncertainties" was published in Complexity journal in 2020. The paper discusses the development of an advanced controller that uses adaptive fuzzy sliding mode control to manage a parallel manipulator with parameter uncertainties. The controller was designed to address the challenges of controlling industrial manipulators and to improve their efficiency and precision. The limitations of nonlinear controllers have motivated academics and specialists to explore control engineering further in search of more effective solutions. In developing adaptive controllers such as MRAC, self-tuning regulators, and SMC, a precise mathematical description of the system is required for complete design. However, this can be a challenging task due to the complexity of the industrial manipulators. Similarly, the design of gain scheduling can be complicated by the number of operational points that need to be considered. Despite these challenges, researchers continue to explore new methods and techniques to develop effective controllers that can improve the efficiency and precision of industrial manipulators. In the field of control engineering, there is a constant search for more effective solutions to improve the performance of industrial manipulators. Nonlinear controllers have their limitations, which has prompted researchers to develop adaptive controllers such as MRAC, self-tuning regulators, and SMC. However, the design of these controllers requires a precise mathematical description of the system, which can be challenging due to the complexity of the manipulators. Gain scheduling can also be difficult due to the number of operational points that need to be considered. Despite these challenges, researchers continue to explore new methods and techniques, such as the use of fractional order fuzzy PID controllers and robust fractional order fuzzy P + fuzzy I + fuzzy D controllers, to develop effective controllers that can improve the efficiency and precision of industrial manipulators. Two papers that discuss these topics are "Performance analysis of fractional order fuzzy PID controllers applied to a robotic manipulator" by R. Sharma.et.al. [7] and V. Kumar.et.al. [8]

In the field of applied mathematics, Kong.et.al [9] explored normal parameter reduction in soft set based on particle swarm optimization algorithm in their paper titled "Normal parameter reduction in soft set based on particle swarm optimization algorithm" published in Applied Mathematics and Modelling. They presented a method to reduce the number of parameters in soft set, a technique used for dealing with uncertainty. Another paper titled "A cooperative ant colony optimization-genetic algorithm approach for the construction of energy demand forecasting knowledge-based expert systems" by Ghanbari. et.al [10] published in Knowledge-Based Systems, discussed the development of a knowledge-based expert system for energy demand forecasting using a cooperative ant colony optimization-genetic algorithm approach. The system is designed to assist energy managers in decision-making processes by providing accurate energy demand forecasts.

Many research gaps are associated with linear controllers, as they need more performance over various operating systems. Nonlinear controllers can handle systems with nonlinear dynamics and uncertainties more effectively and provide better performance and stability over a broader range of conditions. Another parameter is slow response and tracking accuracy. Nonlinear controllers often achieve faster response times and more accurate tracking of reference signals than linear controllers, making them suitable for systems requiring rapid responses or precise control over their outputs. Another major problem is sensitivity to disturbances and uncertainties. Nonlinear controllers can be designed to be more robust to disturbances and uncertainties in the system, leading to more stable and reliable operation, which is especially important for systems.

Another major problem is the inability to adapt to changing system dynamics. Nonlinear controllers can be designed to adapt to changing system dynamics, making them suitable for systems that exhibit time-varying or nonlinear characteristics, allowing the controller to maintain effective control even as the system's behavior changes. The other significant research gap is limited potential for energy efficiency. Nonlinear controllers can achieve better energy efficiency than linear controllers by exploiting the system's nonlinearities to optimize control actions, reducing energy consumption.

1. An intelligent NPID controller for a nonlinear and complex two-link stiff robotic manipulator system is proposed. The primary advantage of the suggested controller is its applicability to poorly defined systems.

2. It demonstrates resilient behavior throughout runtime, making it more useful for such systems.

3. Increase the robustness of the suggested NPID controller by multiplying the nonlinear component by the integral gain and optimizing it using a genetic algorithm.

4. NPID controller robustness is determined by comparing its performance to that of PID and NPI controllers for

trajectory tracking, noise suppression, disturbance rejection, and model uncertainty.

The paper is organized as follows: after an introduction, a system description and mathematical model are developed . A complete overview of controllers is provided in next Section followed by results including a detailed description of how the gains of all controllers are tuned by genetic algorithm, as well as their trajectory tracking performance, error performance, and controller output result. Finally, the suggested work's conclusions are presented

NUMERICAL MODELLING OF PLANT

The structure of a two-link manipulator used as a plant in this work is described below by Lin.et.al [11].and Saxena.et.al [12]. A list of the mathematical equations required to create the mathematical model is provided below and a diagram representing a two link manipulator with the help of these equations are being shown below in Fig(1)

Here you can see that $A_{11}, A_{12}, A_{21}, A_{22}, B_{11}, B_{21}, V_{r1}, V_{r2}, Wn_{1p}, Wn_{2p}$ are the parameters which are the combinations of mass, length, lengthwise centroid inertia etc.

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} \ddot{\theta_{11}} \\ \ddot{\theta_{22}} \end{bmatrix} + \begin{bmatrix} B_{11} \\ B_{21} \end{bmatrix} + \begin{bmatrix} V_{r1} \\ V_{r2} \end{bmatrix} + \begin{bmatrix} Wn_{1p} \\ Wn_{2p} \end{bmatrix} = \begin{bmatrix} \tau x_{1p} \\ \tau x_{2p} \end{bmatrix} \quad (1)$$

$$A_{11} = E_{g1p} + H_{1p} + M_{l1}E_{c1}^2 + M_{l2}E_{c2}^2 + 2M_{22}E_{g1}E_{c2}\cos\theta_{22} + M_{vp}E_{g1}^2 + M_{vp}E_{g2}^2 + 2M_{vp}E_{g1}E_{g2}\cos\theta_{22} \quad (2)$$

$$A_{12} = I_{2P} + N_{22}E_{c2}^2 + N_{22}E_{11}E_{c2}\cos\theta_{22} + N_{vp}E_{22}^2 + N_{vp}E_{11}E_{22}\cos\theta_{22} \quad (3)$$

$$A_{21} = A_{12} \quad (4)$$

$$A_{22} = I_{2P} + N_{22}E_{c2}^2 + N_{vp}E_{22}^2 \quad (5)$$

$$B_{11} = N_{22}E_{11}E_{c2}(2\dot{\theta_{11}} + \dot{\theta_{22}})\dot{\theta_{22}}\sin\theta_{22} - N_{vp}\,E_{11}E_{22}\left(2\theta_{11} + \dot{\theta_{22}}\right)\theta_{22}\sin\theta_{22} \quad (6)$$

$$B_{21} = N_{22}E_{11}\dot{\theta}_{11}^2E_{c2}\sin\theta_{22} + N_{vp}\,E_{11}\dot{\theta}^2{}_{11}E_2\sin\theta_{22} \quad (7)$$

$$V_{r1} = C_{1vp}\dot{\theta_{11}} \quad (8)$$

$$V_{r2} = C_{2vp}\dot{\theta_{22}} \quad (9)$$

$$Wn_{1p} = N_{11}E_{c1}g\cos\theta_{11} + N_{22}g(E_{c2}\cos(\theta_{11} + \theta_{22}) + E_{11}\cos\theta_{11} + N_{vp}g(E_{22}\cos(\theta_{11} + \theta_{22}) + E_{11}\cos\theta_{11} \quad (10)$$

$$Wn_{2p} = N_{22}E_{c2}g\cos(\theta_{11} + \theta_{22}) + N_{vp}E_2g\cos\left(\theta_{11} + \theta_{22}\right) \quad (11)$$

$$\ddot{\theta_{11}} = \frac{\tau X_{1p} - Wn_{1p} - V_{r1} - B_{11} - A_{12}*\ddot{\theta_{22}}}{A_{11}} \quad (12)$$

$$\ddot{\theta_{22}} = \frac{(\tau X_{2p} - Wn_{2p} - V_{r2} - B_{21} - A_{12}*\ddot{\theta_{11}})}{A_{22}} \quad (13)$$

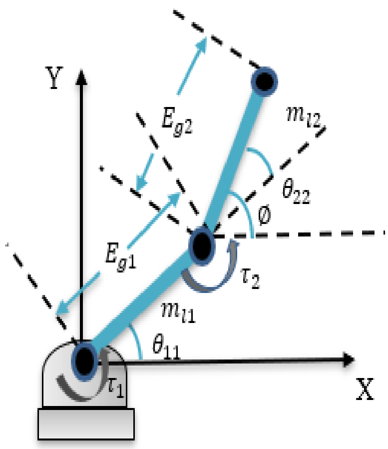

Figure 1. Two link manipulators

$\ddot{\theta}_{11}$ and $\ddot{\theta}_{22}$ represents the links position; the control outputs or torques produced are τX_{1p} and τX_{2p} ; V_{r1} and

V_{r2} are the dynamic friction coefficients; the masses are N_{11} and N_{22} respectively. E_{11} and E_{22} represents lengths and Lengthwise centroid inertia is expressed by I_{1p} , I_{2P}. The payload with a mass limit of 0.56699kg is defined. The different parameters observed are specified in a tabular form in Table I.

Table 1. Parameters Description

Parameters	**Link 1**	**Link 2**
Mass m_{l1}	0.1 kg	0.1 kg
Length (E_{g1})	0.8 m	0.4 m
Gravity (G)	9.81 m/s^2	9.81 m/s^2
Payload (N_{vp})	0.5 kg	0.5 kg

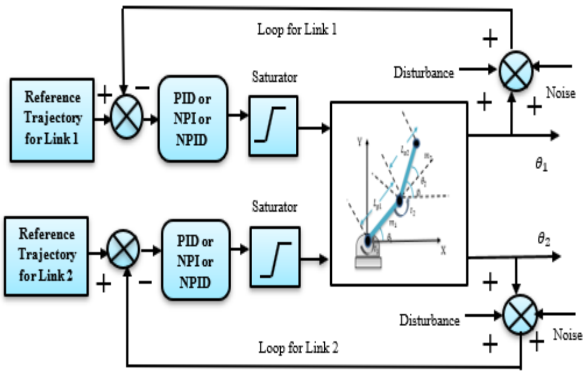

Figure 2. Block Diagram of Two link manipulators

Fig(2) shows how the two link manipulators are controlled using a sine wave as a reference. The controllers used in this case include both linear and non-linear controllers. After the controller output is obtained, it is fed to the plant designed using equations. Simulation is then carried out using both linear and non-linear controllers to ensure accurate results and minimize error values.

DESIGN OF CONTROLLERS

This section covers the architecture of linear and nonlinear controllers. Linear controllers include PID controllers, and Nonlinear controllers include NPI and NPID controllers. These nonlinear controllers have robust adaptability. The fundamental structure of these controllers consists of P, I, and D controllers in addition to a nonlinear control factor.

LINEAR CONTROLLERS- PROPORTIONAL INTEGRAL DERIVATIVE CONTROLLER (PID)

A linear controller with a wide operating target range will likely be unstable. Because the system's nonlinearities cannot be remedied, the model must be more adequately complete or contain parameters with only partially determined values. In that case, the algorithm based on such limited data will not produce accurate results, and the linear controller's performance may suffer and become unstable. To overcome this challenge, we must develop nonlinear dynamics methods. Here PID controller is discussed.

$$U_{PID}(t) = [K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt} e(t)] \quad (14)$$

The structure of PID Controller is shown below in fig (3) Where u(t) is the controller input, e(t) is the control error, which is the difference between the desired and actual response, and f(t) is the feedback constant.

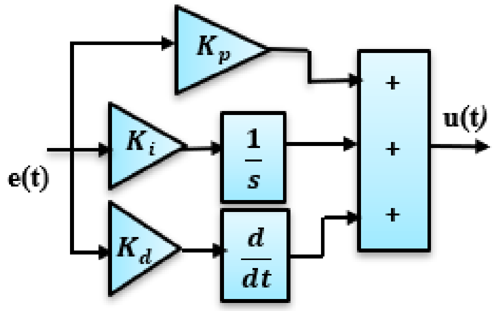

Figure 3. Block Diagram of PID Controller

The parameters for PID control are Kp, Ki, and Kd. Consequently, the control variable consists of three parts. The proportional controller reduces steady-state error while simultaneously enhancing system stability. The integral of the Error signal is perfectly balanced with the output of the Integral Controller due to the integrator. This operation substantially impacts the control of input and output waves.

NONLINEAR CONTROLLER-NONLINEAR PROPORTIONAL INTEGRAL CONTROLLER (NPI)

The PI and PID controllers have become widely used in industrial applications due to their ability to compensate for the bulk of practical industrial processes. These controllers offer several advantages over conventional controllers, including increased speed, precision, and system stability. They effectively reduce steady-state error, produce robust transient response, and preserve resistance to nonlinearity. The equation involves 'e' and 'r', which represent instantaneous error and error derivation, and 'a' and 'b', meaning the parameters for the law of nonlinear control. The reduction occurs when the rate of change of error and the error itself reaches zero. The equation also includes K_p and K_i as proportional and integral gains, respectively, with (t) representing the time. The necessary gain is changed using a nonlinear time-varying factor φ(t). The control action of NPIC is represented by uNPI (t), while e (t) represents the error signal. The equation demonstrates that the output of the NPIC controller has an integral action that is adaptive. In contrast, a traditional PI controller maintains a consistent proportional and integral action throughout its operation.

$$U_{PID}(t) = [K_p e(t) + K_i \int e(t)dt] \quad (16)$$

$$\varphi(t) = \left[1 - exp\{-\left(ae^2(t) + br^2(t)\right)\}\right]^2 \quad (17)$$

$$u_{NPI}(t) = K_p e(t) + (\varphi(t) K_i) \int e(t)\mathrm{dt} \quad (18)$$

NONLINEAR PROPORTIONAL INTEGRAL DERIVATIVE CONTROLLER (NPID)

There are many techniques to improve the performance of linear PID controllers. One of the most effective methods for industrial applications is the Nonlinear PID (N-PID) control. The N-PID controller has a structure that is shown below:

The Nonlinear PID (N-PID) control whose structure is shown below (fig 4) is the ultimate solution for improving the performance of linear PID controllers in industrial applications. N-PID control includes a structure that accommodates nonlinearity in nonlinear systems and delivers higher tracking precision, more excellent damping and decreased rising time for a step or quick inputs.

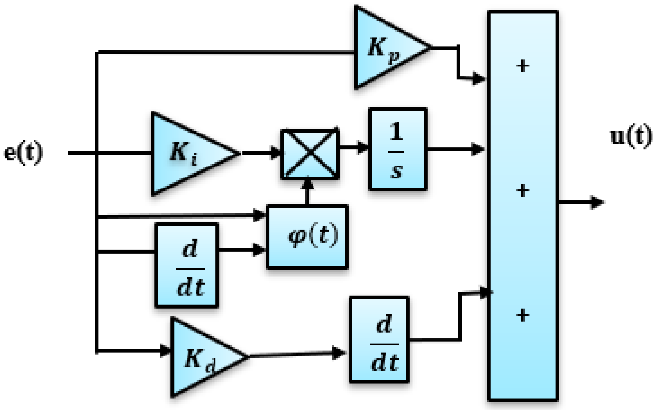

Figure 4. Block Diagram of **N**PID Controller

Nonlinear controllers provide faster deployment, speed, precision, and less control energy, which can support a more complex design strategy. The N-PID controller's block diagram involves the integral controller multiplying with the time variable factor (φ(t)). Due to the automated gain adjustment, N-PID controllers benefit from a high initial gain to produce a quick response, followed by a low gain to prevent oscillation. With the N-PID control, you can achieve consistent results under various situations and experience the benefits of faster deployment, higher efficiency, and greater precision. NPID controllers are known for their superior performance compared to conventional controllers. This is due to their adaptive nonlinear control action, which allows them to handle nonlinear systems and disturbances more easily. With adaptive parameters and improved response to setpoint changes, NPID controllers can achieve accurate tracking without overshooting or instability, thereby enhancing the overall control performance.

$$u_{NPI}(t) = K_p e(t) + (\varphi(t)K_i)\int e(t)dt + K_d \frac{d}{dt} e(t) \qquad (19)$$

RESULTS

The Nonlinear PID (N-PID) control is a sophisticated solution that enhances the performance of linear PID controllers in industrial applications. Nonlinear systems can benefit from N-PID control because they can accommodate nonlinearity and deliver higher tracking precision, exceptional damping, and decreased rising time for step or quick inputs. With faster deployment, speed, accuracy, and less control energy, nonlinear controllers can support a more complex design strategy. The objective function IAE that is used in applying the Genetic algorithm can be numerically expressed as

$$IAE = \int_0^\infty |e(t)| dt \qquad (20)$$

The Integral Absolute Error (IAE) objective function has specific constraints that necessitate careful consideration in its application. One such constraint is its tendency to prioritize quick responses to errors, which can lead to overshooting or instability in some systems. Hence, IAE might not be the optimal objective function for systems that require precise control, but these limitations can be improved by choosing different combinations of controllers The genetic algorithm was run for 100 generations to determine which of the three controllers had the highest fitness value; the fitness value versus generation graph is depicted below in Table (2) and Fig (5).

Table 2. Various Controllers and their OBF Values

Controllers	OBF Values
PID Controller	0.0424
NPI Controller	0.0260
NPID Controller	0.0156

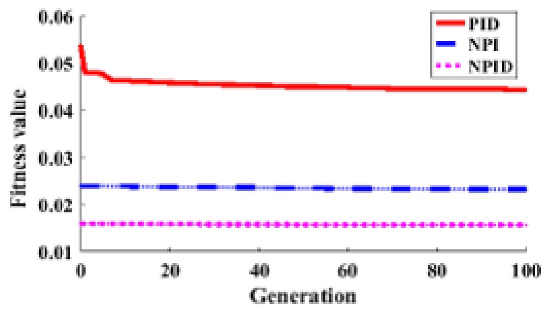

Figure 5. Fitness Values of three controllers

N-PID controllers are a type of control system that provide several advantages over other controllers. One of the significant benefits of N-PID controllers is their automated gain adjustment. This feature allows for a high initial gain to produce a quick response, followed by a low gain to prevent oscillation, making N-PID control a reliable and efficient choice for various applications. In terms of the Integral of Absolute Error (IAE) performance index, N-PID controllers are superior to N-PI and PID controllers. They integrate the absolute error over time, resulting in consistent and precise performance. N-PID controllers are a popular choice in industrial and manufacturing settings due to their faster deployment and higher efficiency. To illustrate their performance, several figures are provided in this analysis. Figures (6) and (7) demonstrate the tracking of the reference wave and links 1 and 2, respectively, while Figures (8) and(9) provide detailed information on the error curve for links 1 and link 2 Figure (10) and (11) depict the controller output for the respective links, offering a comprehensive overview of the performance of N-PID controllers in various applications.

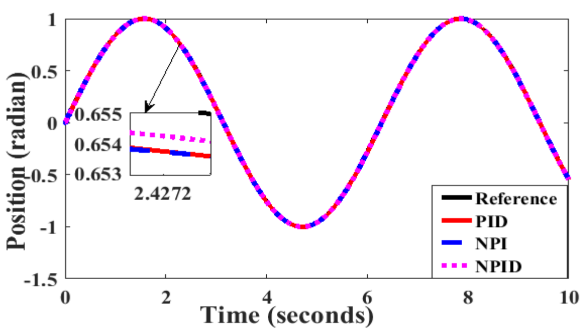

Figure 6. First link tracking result.

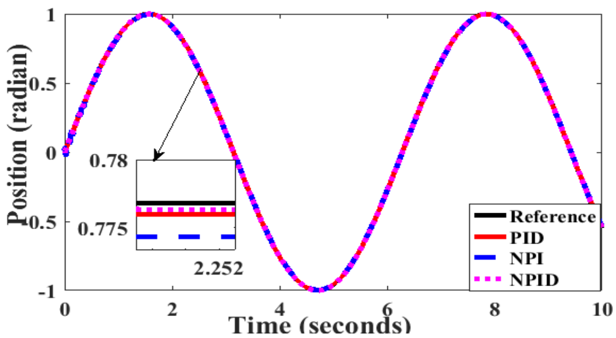

Figure 7. Second link Tracking result

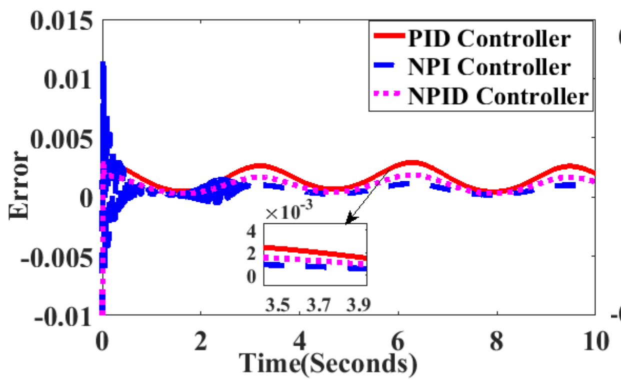

Figure 8. Error Curve for the first link

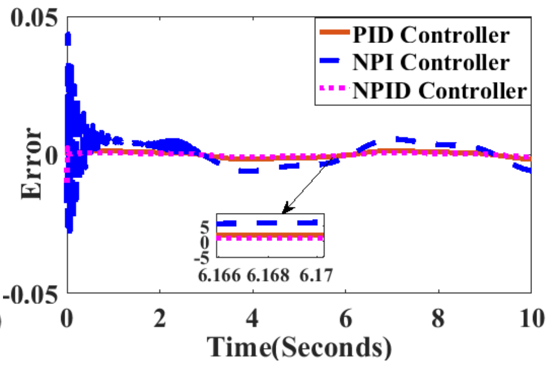

Figure 9. Error Curve for Second link

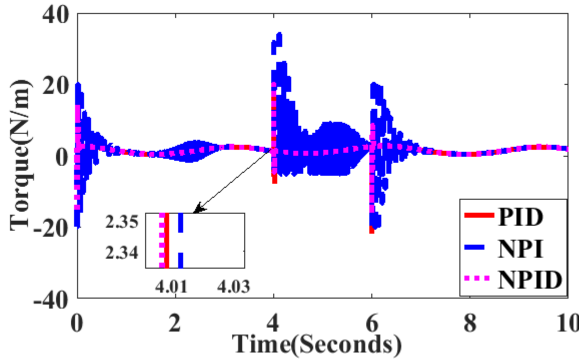

Figure 10. Controller output for the first link

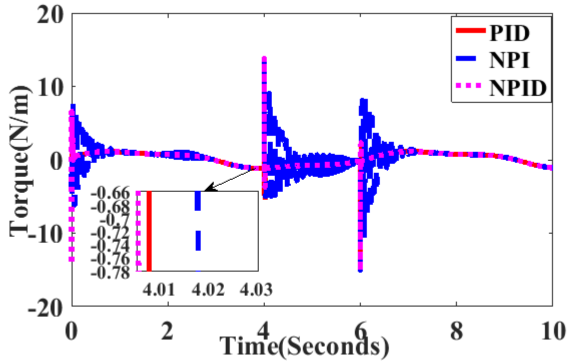

Figure 11. Controller output for second link

After receiving the simulated results for error and controller output, a disturbance signal in the form of noise has been inserted. Then, a comparison of all three controllers has been carried out. Eliminating noise in closed-loop control systems can be a highly challenging task. Random oscillations can often disrupt and impede a smooth trajectory, making it difficult to maintain optimum performance. However, controllers can help minimize the impact of unforeseen disturbances on the feedback control loop, ensuring that the system performs at its best. A disturbance signal was created to test the robustness of three controllers, producing unique error values for each controller. Comparing the error values in Table (3) revealed that the NPID controller outperformed the conventional controllers, with an impressively low error value of 0.05385, shown in Fig (12).Moreover, Figures (13) and (14) showcase the NPID controller's ability to track the reference wave set point precisely. The following statistics further demonstrate the controller and error performance, highlighting the superiority of the NPID controller in Figs. (15) and (16) . The controller output after noise insertion is shown in Fig (17) and Fig (18). From all the results, it is observed that even after any disturbance/noise insertion, the NPID controller outperformed other controllers in all other parameter

Table 3: Comparative Evaluation of Disturbance Inserted in Controllers

Amplitude of Disturbance Signal	PID	NPI	NPID
1	0.02734	0.06714	0.01606
2	0.0314	0.07751	0.01802
3	0.03576	0.08796	0.02063
4	0/0471	0.09958	0.02339
5	0.04567	0.111	0.02616
6	0.05064	0.1226	0.02893
7	0.05561	0.134	0.03169
8	0.06059	0.01456	0.03446
9	0.06557	0.1572	0.03723
10	0.07056	0.01686	0.04
11	0.07555	0.1806	0.04277
12	0.08055	0.1929	0.04554
13	0.08555	0.206	0.04831
14	0.09055	0.2199	0.05108
15	0.09556	0.2344	0.05385

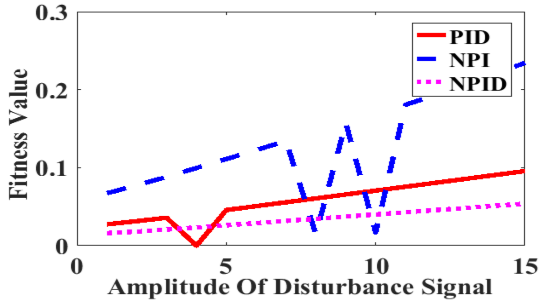

Figure 12. Amplitude of disturbance Signal

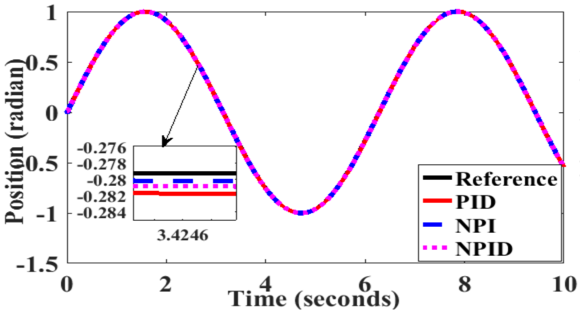

Figure 13. Trajectory Tracking for link 1

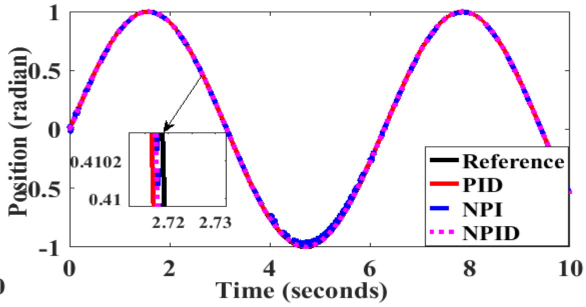

Figure 14. Trajectory Tracking for link 2

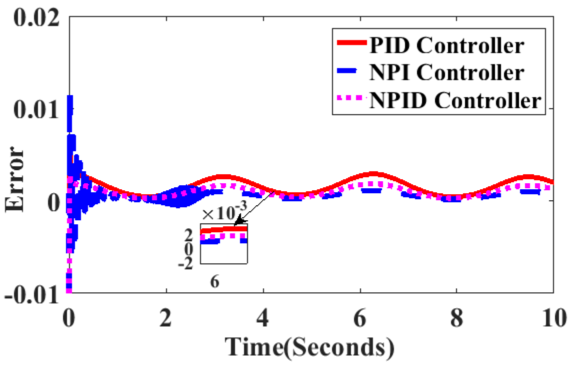

Figure 15. Error Curve for link 1

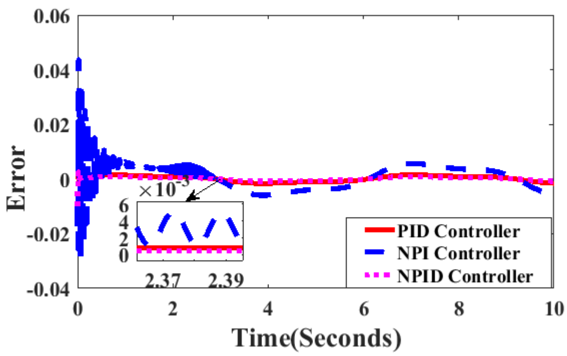

Figure 16. Error Curve for link 2

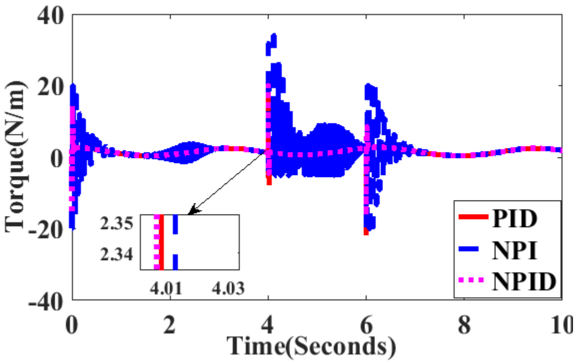

Figure 17. Controller output for link 1

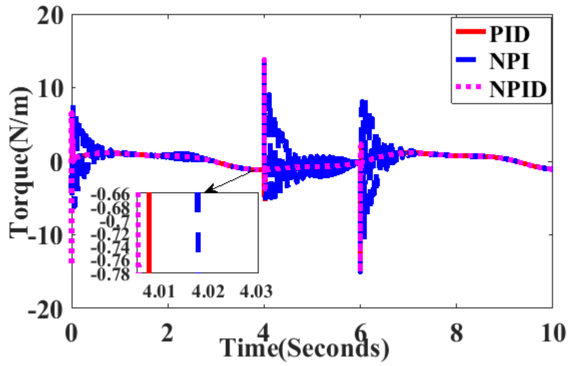

Figure 18. Controller Output for link 2

CONCLUSION

The study's findings illustrate that the NPID controller is incredibly efficient for controlling stiff two-linked robotic manipulator systems with payloads. The NPID controller outperforms traditional PID and NPI controllers' accuracy and reliability. The controller's outstanding performance is due to its exceptional ability to withstand external disturbances and accurately track trajectories, further improved by the two degrees of freedom design. The study also highlights the advantages of utilizing the NPI controller, which improves trajectory control and reliability and enhances the controller parameters when paired with genetic algorithm optimization. Such an approach can optimize the performance of the NPID controller, resulting in even better accuracy and reliability. Moreover, the NPID controller is remarkably robust and can handle disturbances with minimal error. Its ability to tolerate external disturbances makes it the ideal controller technique for robotic manipulator applications that require precise and accurate positioning, such as in nuclear power facilities and industrial operations where external disturbances can significantly impact the parameters. The NPID controller can also be utilized in various applications, including pneumatic control, robot control, and spot welding, making it a versatile and valuable tool in the industry. Nevertheless, it is essential to conduct further testing on the suggested controller to ensure its effectiveness in real-time operating robotic manipulators. The results of these tests will provide valuable insights and help improve the performance of the NPID controller in various applications.

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