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Fuzzy Precompensated Tilt-Integral-Derivative-Acceleration (TIDA) Controller for a Single Link Robot

Osama Elshazly[1,2*], Omar Shaheen[1], Hossam Khalil[1,3]

[1] Department of Industrial Electronics and Control Engineering Faculty of Electronic Engineering, Menoufia University, Menouf, Egypt.
[2] Mechatronics Engineering Department, High Institute of Engineering and Technology (HIET) – ElMahala Elkobra, Egypt
[3] Mechatronics Engineering Department, Faculty of Engineering, October 6 University, 6th of October, Giza 12585, Egypt.

* Corresponding author's email: osama.elshazly@el-eng.menofia.edu.eg
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Abstract – This study proposes a Fuzzy Precompensated TIDA (FP-TIDA) controller to enhance the control of nonlinear systems. Traditional controllers such as TIDA and FTIDA exhibit limitations, including high overshoot, slow settling time, and excessive control effort, affecting their efficiency in dynamic environments. To address these issues, FP-TIDA integrates a fuzzy logic-based precompensation mechanism, improving transient response, stability, and disturbance rejection. Simulation results demonstrate that FP-TIDA outperforms existing controllers, achieving the best rise time, settling time, peak time, and minimal overshoot. Additionally, FP-TIDA generates a smoother control signal, reducing energy consumption and ensuring efficient operation. Comparative analysis confirms its superior tracking accuracy and robustness under step input changes. The proposed approach enhances control system performance, making it a promising candidate for real-world applications. Future research will focus on further optimization through adaptive tuning, machine learning-based parameter adjustment, and experimental validation on hardware platforms. Additionally, extending the framework to multi-input multi-output (MIMO) systems and incorporating adaptive control strategies will improve its versatility and real-time applicability. The findings of this study contribute to advancing intelligent control strategies for nonlinear dynamic systems, offering improved precision, stability, and efficiency.

Keywords: Fuzzy Precompensator (FP), Tilt-Integral-Derivative-Acceleration (TIDA), Single-Link Manipulator, Fuzzy Control Systems.

I. Introduction

The Tilt-Integral-Derivative (TID) [1, 2] controller is an advanced variation of the traditional Proportional-Integral-Derivative (PID) [3] controller, designed to enhance system performance, particularly in nonlinear and uncertain environments. While the PID controller relies on three fundamental components—proportional, integral, and derivative actions—to regulate system behavior, it often faces limitations in handling complex dynamics, disturbances, and parameter variations. The TID controller addresses these challenges by incorporating a tilt term, which introduces fractional-order differentiation, allowing for more flexible and adaptive control. This additional degree of freedom improves the system's transient and steady-state performance by offering a smoother and more gradual correction mechanism compared to the abrupt nature of conventional derivative control in PID. Moreover, the TID controller enhances robustness against external disturbances and model uncertainties, making it a compelling choice for applications where precise and stable control is required. By effectively balancing responsiveness and stability, the TID controller serves as a powerful alternative to the traditional PID, particularly in modern control applications that demand higher performance and resilience.

TID controllers have been successfully applied in various domains to improve system performance. In power systems [4-6], they have been utilized for load frequency control, enhancing frequency stability and power balance between generation and demand. For instance, a study introduced a Tilt-Integral with Derivative Filter (TIDF) for load frequency control in multi-area power systems, demonstrating improved stability under load changes.

In the field of electric vehicles, TID controllers have been employed to enhance the speed control of brushless direct current (BLDC) motors [7]. Research indicates that TID controllers provide better input power management for BLDC drives compared to traditional PI and PID controllers, leading to improved torque and current stability, as well as enhanced speed regulation.

Additionally, TID controllers have been applied in motion control systems for wheeled mobile robots [8]. A hybrid controller combining TID with neural networks and optimization algorithms was developed to improve trajectory tracking of four-mecanum-wheeled mobile robots, resulting in reduced mean square errors in position and orientation compared to other control methods.

These applications underscore the versatility and effectiveness of TID controllers in addressing complex control challenges across various industries.

The Proportional-Integral-Derivative-Acceleration (PIDA) controller is an extension of the traditional PID controller, incorporating an additional acceleration term to improve system performance, particularly in fast and high-precision applications [9-11]. While the PID controller regulates a system using proportional, integral, and derivative actions, the PIDA controller introduces an acceleration component that enhances response speed and reduces overshoot. This makes it particularly effective for controlling higher-order and highly dynamic systems where rapid set-point tracking and disturbance rejection are critical. PIDA controllers have found applications in various fields, including robotics [12], where they improve trajectory tracking and stability in robotic arms and unmanned aerial vehicles (UAVs). In power systems [13], they enhance load frequency control by ensuring faster and more stable frequency regulation. Additionally, in high order systems [14], such as CNC machining and servo systems, PIDA controllers help achieve high accuracy with minimal lag. By incorporating the acceleration term, the PIDA controller offers superior control performance in systems requiring rapid and precise response, making it a valuable advancement over conventional PID control.

The Tilt-Integral-Derivative-Acceleration (TIDA) [15] controller is a sophisticated control architecture designed to address limitations in traditional PID and advanced TID controllers, particularly in systems with high nonlinearities, time-varying dynamics, and complex resonant modes. By integrating tilt action, integral control, derivative damping, and acceleration feedback, the TIDA achieves superior performance in precision motion control, robotics, and industrial automation.

In this paper, the fuzzy precompensated tilt integral derivative acceleration (FP-TIDA) controller is proposed as an advanced hybrid control approach designed to improve the performance of single-link robotic manipulator by integrating the adaptability of fuzzy logic with the enhanced dynamics of the TIDA controller. Traditional PID controllers often struggle with nonlinearities, external disturbances, and variations in system parameters, particularly in robotic applications where precise trajectory tracking and vibration suppression are critical. The proposed FP-TIDA controller addresses these challenges by incorporating a fuzzy precompensator that dynamically adjusts control actions based on real-time system behavior, enhancing robustness against uncertainties and payload variations. Meanwhile, the TIDA component extends conventional PID control by introducing tilt and acceleration terms, which improve transient response, reduce overshoot, and enhance the stability of the manipulator. The tilt term allows for fractional-order differentiation, offering smoother corrections, while the acceleration term enables the controller to predict and counteract rapid changes in system dynamics. These features make the FP-TIDA controller highly effective in achieving precise motion control, suppressing residual vibrations, and ensuring smooth trajectory tracking even under varying load conditions. The performance of the proposed FP-TIDA for controlling a single link manipulator is introduced here in this work.

The main contributions of this paper are:

1. Proposing FP-TIDA controller that gives the benefits of fuzzy logic system and TIDA controller.
2. The effectiveness of the FP-TIDA controller is validated by its application in regulating a nonlinear single-link manipulator, demonstrating its capacity to address system disturbances.

This work is organized as follows: Section 2 delineates the architecture of the proposed FP-TIDA controller. The findings of the case study based on the suggested controller are presented in section 3. Conclusions are presented in section 4, followed by references.

II. Structure of The Proposed Fuzzy Precompensated Tilt-Integral-Derivative-Acceleration (FP-TIDA) Controller

Figure 1 presents the structure of the proposed FP-TIDA Controller, which integrates two main control modules: a Fuzzy Logic Controller (FLC) and a TIDA controller. These components are connected in series, allowing the system to adapt to parameter uncertainties and external disturbances. The combination of both controllers provides enhanced flexibility and robustness in dynamic environments. The following subsections describe the operational details of each module.

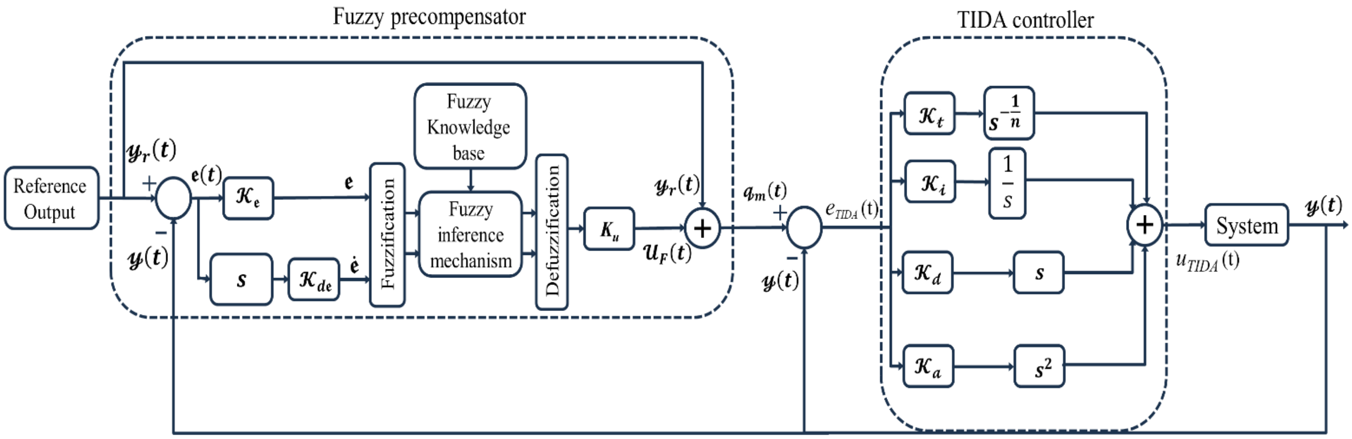

Fig. 1. Structure of the developed FP-TIDA Controller.

II.1 Fuzzy Precompensator

The Fuzzy Logic Controller (FLC) functions as a precompensator, modifying the reference signal before it is processed by the TIDA controller. It takes two input variables (e) error and change of error $(\Delta \mathrm{e})$ which are normalized using scaling factors $(\mathcal{K}_{\mathrm{e}})$ and $(\mathcal{K}_{de})$, respectively. These are mathematically expressed as:

$$\mathcal{E}(l) = \mathcal{K}_{\mathrm{e}}\mathrm{e}(l) = \mathcal{K}_{\mathrm{e}}\big(y_r(l) - y(l)\big) \tag{1}$$

$$\Delta\mathcal{E}(l) = \mathcal{K}_{de}\Delta\mathrm{e}(l) = \mathcal{K}_{de}\big(\mathrm{e}(l) - \mathrm{e}(l-1)\big) \tag{2}$$

where y_r is the reference system output, y represents the actual output, and l is the discrete time index.

The fuzzy precompensator consists of four key processing stages: fuzzification, rule base, fuzzy inference engine, and defuzzification. In the fuzzification phase, the input variables are mapped to fuzzy membership functions $\xi(\mathrm{e})$ and $\xi(\Delta\mathrm{e})$. These inputs are then processed by the fuzzy inference engine using Mamdani fuzzy rules, which take the general form:

$$\text{Rule}_i\text{: IF } \mathcal{E}(l) \text{ is } \mathcal{A}_i \text{ and } \Delta\mathcal{E}(l) \text{ is } \mathcal{B}_i \text{ then } \mathcal{U}_{FP}(l) \text{ is } \mathcal{C}_i \tag{3}$$

where $\mathcal{A}_i$, $\mathcal{B}_i$, and $\mathcal{C}_i$ denote fuzzy sets. The activation strength of each rule is determined using the product t-norm:

$$\xi_i = \xi_{\mathcal{A}_i}(\mathrm{e}) \cdot \xi_{\mathcal{B}_i}(\Delta\mathrm{e}) \tag{4}$$

In the defuzzification phase, a crisp output value is derived using the centroid defuzzification method:

$$\mathcal{U}_F = \frac{\sum_{s=1}^{M} \xi_s y_s}{\sum_{s=1}^{M} \xi_s} \tag{5}$$

where y_s represents discrete values in the output domain. The final precompensated reference signal is obtained by scaling the fuzzy output $\mathcal{U}_F$ with a gain factor $\mathcal{K}_{\mathcal{U}}$, as given by:

$$\mathcal{U}_F(l) = \mathcal{K}_{\mathcal{U}} \cdot \mathcal{U}_F \tag{6}$$

The FLC module's altered intended output is as follows:

$$q_m(l) = \mathcal{U}_F(l) + y_r(l) \tag{7}$$

II.1.1. Tilt Integral Derivative Acceleration (TIDA) Controller

The TIDA controller extends the conventional Tilt Integral Derivative (TID) controller by incorporating an acceleration term, which enhances the system's response to dynamic changes. Unlike traditional PID controllers, the TIDA controller features a tilted proportional component governed by the fractional transfer function $s^{-\frac{1}{n}}$ and an additional acceleration term. Its transfer function is expressed as:

$$C_{TIDA}(s) = \mathcal{K}_t s^{-\frac{1}{n}} + \mathcal{K}_i s^{-1} + \mathcal{K}_d s + \mathcal{K}_a s^2 \tag{8}$$

where $\mathcal{K}_t, \mathcal{K}_i, \mathcal{K}_d$ and $\mathcal{K}_a$ are the controller's tunable parameters, and n is a fractional exponent (where $n \neq 0$). Compared to standard PID or TID controllers, the TIDA controller improves robustness against disturbances, simplifies parameter tuning, and enhances overall system stability. The continuous-time control law for the TIDA controller is formulated as:

$$\mathcal{U}_{TIDA}(s) = \mathcal{K}_t \mathcal{D}_{t_0}^{-\frac{1}{n}} \mathrm{e}_{TIDA}(t) + \mathcal{K}_i \int \mathrm{e}_{TIDA}(t)dt + \mathcal{K}_d \frac{d\mathrm{e}_{TIDA}(t)}{dt} + \mathcal{K}_a \frac{d^2\mathrm{e}_{TIDA}(t)}{dt^2} \tag{9}$$

where $\mathrm{e}_{TIDA}(t)$ represents the error signal, computed as the difference between the fuzzy precompensated reference (q_m) and the actual system output (y):

$$e_{TIDA}(t) = q_m(t) - y(t) \quad (10)$$

II.1.2. Discretization Using Grünwald-Letnikov Approximation

In fractional-order control systems, the Grünwald-Letnikov (GL) approximation is widely used for modeling and implementing fractional-order operators. It is given by:

$$D^{p} x(t) = \lim_{h\to 0} \frac{1}{h^{p}} \sum_{j=0}^{\infty} (-1)^{j} \binom{p}{j} x(t - jh) \quad (11)$$

where h is the step size, and $\binom{p}{j}$ represents the Newton binomial coefficient, computed using the gamma function (Γ) as:

$$\binom{p}{j} = \frac{\Gamma(p+1)}{\Gamma(j+1)\Gamma(p-j+1)} \quad (12)$$

Using the GL approximation, the discrete-time TIDA control law can be derived from its continuous-time counterpart:

$$\mathcal{U}_{TIDA}(l) = \sum_{j}^{\mathcal{N}} c_j \, e(l - j) \quad (13)$$

where c_j are coefficients determined from the fractional-order GL approximation. The integral regulator term is given as:

$$I_{\lambda}(t) = \sum_{j}^{k} w_j \, e(l - j) \quad (14)$$

where $\lambda > 0$, and the forgetting factor w_j is defined as:

$$w_j = \frac{(-1)^{j}\binom{\lambda}{j}}{h^{\lambda}} \quad (15)$$

II.1.3. Advantages of the FP-TIDA Controller

The FP-TIDA controller offers multiple advantages, including enhanced robustness against disturbances, improved adaptability to parameter variations, and superior response stability compared to traditional PID or TID controllers. By incorporating fuzzy logic, it can dynamically adjust to system nonlinearities and unpredictable variations, ensuring smooth and precise control. Additionally, the tilt and acceleration terms contribute to improved trajectory tracking, faster error convergence, and better disturbance rejection. These benefits make the FP-TIDA controller particularly effective in applications such as robotic manipulators, servo systems, and nonlinear dynamic systems, where precise motion control and stability are critical.

III. System under Control

The primary purpose of this section is to demonstrate the usefulness of the proposed TIDA controller based on GWO for controlling a nonlinear system. As an example of a nonlinear system, a DC servo motor is proposed to be managed under various operating conditions [13]. The responses of the proposed TIDA are estimated and compared to those of the PIDA [10] and the TID [27] controllers. This comparison is presented in terms of those performance indices including root mean square error (RMSE), integral squared error (ISE), and integral absolute error (IAE). The main objective of this section is to highlight the effectiveness of the proposed FP-TIDA controller in regulating a nonlinear system. A one-link motor-driven robotic manipulator is chosen as a case study to assess its performance under various operating conditions [16]. The controller's responses are analyzed and compared with those of the TIDA [15] and FTIDA [17] controllers. This evaluation is based on key performance indicators, including root mean square error (RMSE), integral squared error (ISE), and integral absolute error (IAE), which are defined in terms of number of samples ($\mathcal{N}$) as follows:

$$RMSE = \sqrt{\frac{1}{N}\sum_{\ell=1}^{N} (e(\ell))^2} \quad (16)$$

$$ISE = \int_0^{\infty} [e(t)]^2 \, dt \quad (17)$$

$$IAE = \int_0^{\infty} |e(t)| \, dt \quad (18)$$

III.1 Control of One-Link Motor-Driven Robotic Manipulator

III.1.1. Dynamic Modeling of an m-Link Motor-Driven Robotic Manipulator

The general equation describing the dynamics of a robotic manipulator with m serially connected motor-driven links can be formulated as follows:

$$\mathcal{M}(\mathcal{Y}_{\sigma})\ddot{\mathcal{Y}}_{\sigma} + \mathcal{C}(\mathcal{Y}_{\sigma}, \dot{\mathcal{Y}}_{\sigma})\dot{\mathcal{Y}}_{\sigma} + \mathcal{B}\dot{\mathcal{Y}}_{\sigma} + \mathcal{G}(\mathcal{Y}_{\sigma}) = \tau(t) \quad (19)$$

where:

- $\mathcal{Y}_{\sigma}, \dot{\mathcal{Y}}_{\sigma}$, and $\ddot{\mathcal{Y}}_{\sigma}$ represent the joint angular position, velocity, and acceleration, respectively.
- $\mathcal{M}(\mathcal{Y}_{\sigma})$ is the symmetric positive definite inertia matrix, which characterizes the mass distribution of the robotic system.
- $\mathcal{C}(\mathcal{Y}_{\sigma}, \dot{\mathcal{Y}}_{\sigma})$ is the centrifugal and Coriolis matrix, capturing the dynamic interactions between the links.
- $\mathcal{B}$ is a positive definite diagonal matrix, accounting for damping friction in the system.
- $\mathcal{G}(\mathcal{Y}_{\sigma})$ represents the gravitational torque acting on the joints.
- $\tau(t)$ is the input torque vector applied to the

III.1.2 Dynamic Model of a single Link Motor-Driven Robotic Manipulator

For a single-link robotic manipulator, the system consists of a DC motor connected to a rigid arm attached to its rotating shaft. The motor-driven link is capable of rotating 360°, making it suitable for various industrial applications. In practical implementations, multiple such links are connected in sequence, forming a serial robotic manipulator, where each additional link is actuated by a motor positioned at the previous link's end.

The second-order differential equation governing the motion of a one-link robotic manipulator is given by [16] as follows:

$$\mathcal{J}\frac{d^2\mathcal{Y}_\sigma}{dt^2} + B\frac{d\mathcal{Y}_\sigma}{dt} + m g \mathcal{L}\cos(\mathcal{Y}_\sigma(t)) = \tau(t) \quad (20)$$

where:

- $\mathcal{J} = m\mathcal{L}^2$ is the rotational inertia of the shaft.
- $\mathcal{L}$ represents the distance from the motor shaft to the link's center of mass.
- B denotes the rotational friction coefficient of the motor shaft.
- $g = 9.8\, m/s^2$ is the acceleration due to gravity.
- The parameters $m = 1\, kg, \mathcal{L} = 0.25\, m,$ and $B = 0.7\, kg.m^2/s$ are considered for this example.

To implement this model in a discrete-time framework, the system is discretized using a sampling period of $T = 0.01s$, leading to the following difference equation representation:

$$\mathcal{Y}_\sigma(l+1) = 2\mathcal{Y}_\sigma(l) - \mathcal{Y}_\sigma(l-1) - \frac{T^2 m g \mathcal{L}\cos(\mathcal{Y}_\sigma(-1))}{\mathcal{J}} - \frac{BT[\mathcal{Y}_\sigma(l) - \mathcal{Y}_\sigma(l-1)]}{\mathcal{J}} + T^2\tau(l-1) \quad (21)$$

This discrete model is widely employed in real-time control systems, allowing for computationally efficient implementation in digital controllers. The structure of a one-link robotic manipulator is depicted in Fig. 2, illustrating its mechanical design.

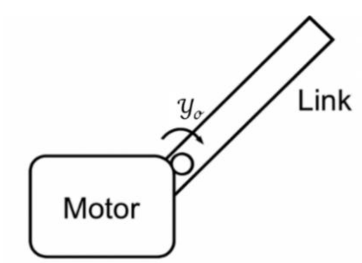

Fig. 2. Schematic diagram of One-Link Motor-Driven Robotic Manipulator.

IV. Results of the proposed FP-TIDA Controller for A One-Link Motor-Driven Robotic Manipulator

To evaluate the effectiveness of the proposed FP-TIDA controller, three simulation scenarios are considered: tracking the desired output, handling a time-varying system, and responding to disturbances in the system output. The simulation outcomes of the proposed FP-TIDA controller are compared with those of other controllers.

IV.1. Task 1: Step Response

The simulation results demonstrate the superior performance of the proposed FP-TIDA controller compared to FTIDA and TIDA. In the system output response (Figure3), FP-TIDA achieves faster settling with minimal overshoot, whereas FTIDA and TIDA exhibit more oscillations and a slower convergence to the reference. The control signal analysis (Figure 4) shows that FP-TIDA maintains a stable and less aggressive control effort, indicating improved efficiency. Furthermore, the mean absolute error (Figure 5) confirms that FP-TIDA consistently achieves lower error values than both FTIDA and TIDA, highlighting its enhanced tracking accuracy. Overall, FP-TIDA outperforms the other controllers by providing improved transient response, greater stability, and reduced tracking error while maintaining an efficient control effort.

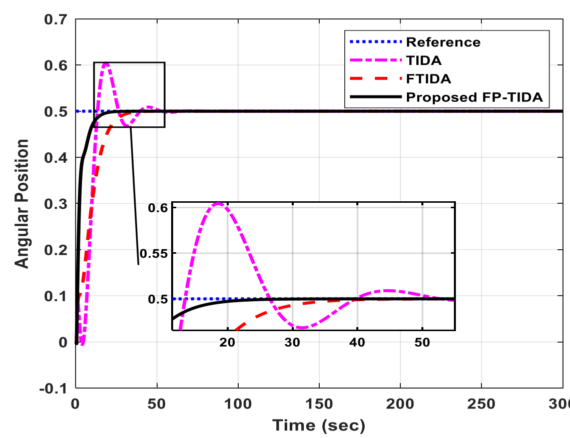

Fig. 3. Response of single-link robotic manipulator (Task 1)

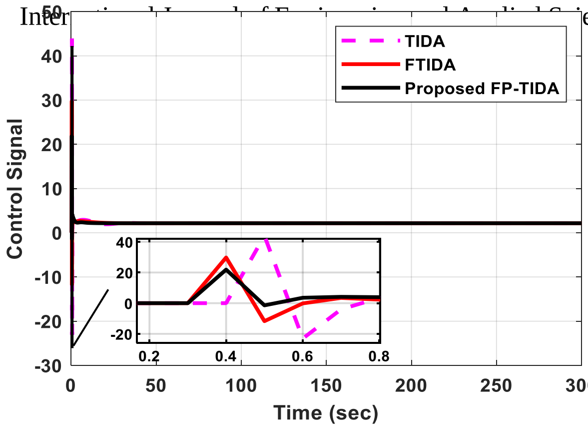

Fig.4. Control signal for single-link manipulator (Task 1)

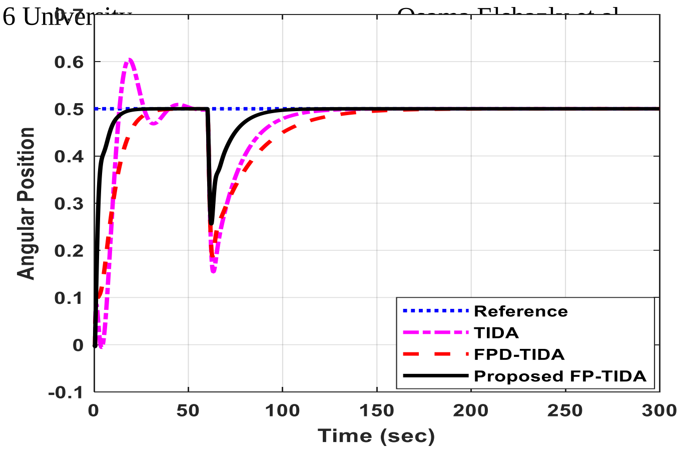

Fig. 6. Response of single-link robotic manipulator (Task 2)

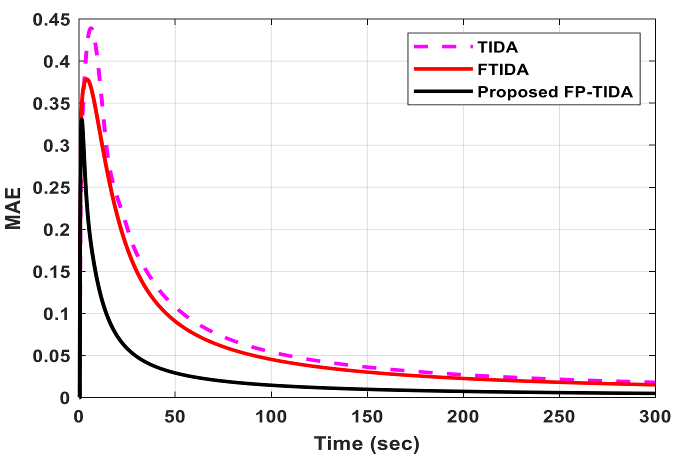

Fig. 5. MAE of Single-link manipulator response (Task 1)

IV.2. Task 2: External Disturbance

Figure 6 compare the performance of three control strategies TIDA, FPD-TIDA, and the proposed FP-TIDA in response to disturbances. This figure, depicting the angular position response, highlights that the proposed FP-TIDA controller achieves the fastest convergence to the reference signal with minimal overshoot and steady-state error. The TIDA controller exhibits the most oscillatory response, while FTIDA performs better but still lags behind the proposed FP-TIDA in terms of transient response.

In the same line, figure 7 shows the control signal, indicates that all controllers maintain a relatively stable control effort. However, the proposed FP-TIDA provides smoother control action with fewer fluctuations, demonstrating better disturbance rejection properties.

Moreover, figure 8, which presents the mean absolute error (MAE) over time, further confirms the superiority of the proposed FP-TIDA. It achieves the lowest error across the time horizon, with a significantly faster error reduction compared to TIDA and FTIDA. These results suggest that the proposed FP-TIDA controller provides improved tracking accuracy, better disturbance rejection, and a more stable control action than the other two controllers.

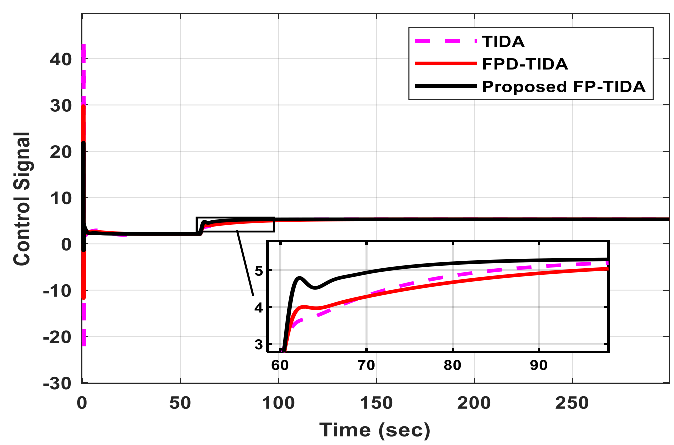

Fig.7. Control signal for single-link manipulator (Task 2)

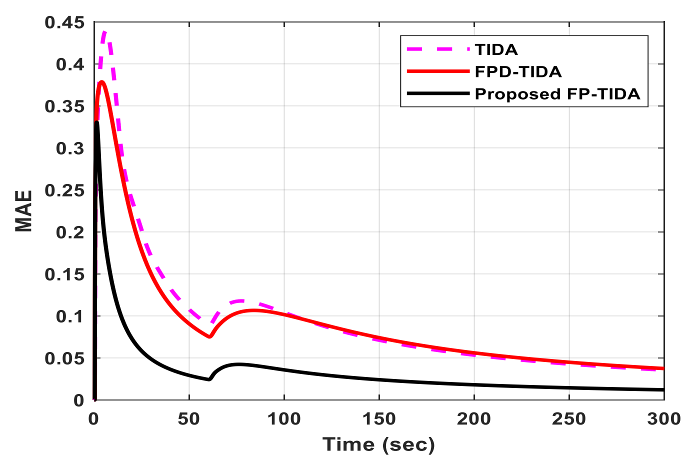

Fig. 8. MAE of single-link manipulator response (Task 2)

IV.3. Task 3: Output Tracking

In this task, the comparison of the three controllers TIDA, FTIDA, and the proposed FP-TIDA demonstrates the superior performance of the proposed FP-TIDA across multiple aspects. In the angular position response shown in Fig. 9, the proposed FP-TIDA closely follows the reference trajectory with minimal oscillations, whereas TIDA exhibits significant fluctuations, and FTIDA shows some improvement but still deviates. The control effort analysis depicted in Fig. 10 reveals that TIDA produces large and abrupt control signals, making it less practical, while FTIDA smooths the response but still shows spikes. The proposed FP-TIDA, however, maintains a more controlled and less aggressive response, indicating better robustness and energy efficiency. The mean absolute error (MAE) shown in Fig. 11, further supports these findings, as the proposed FP-TIDA consistently achieves the lowest error, while TIDA has the highest throughout. Overall, the proposed FP-TIDA outperforms the other controllers in terms of tracking accuracy, stability, and efficiency, making it a more effective choice for precise control applications.

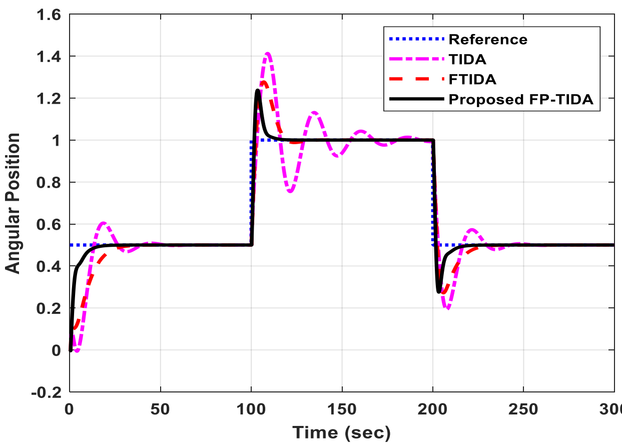

Fig. 9. Response of single-link manipulator (Task 3)

Table 1 compares the performance of the proposed TIDA controller with PIDA and TID controllers in terms of RMSE, ISE, and IAE. It is clear that, the suggested controller produces superior results and it is more potent than other alternative controllers. As expected, the accelerator term in TIDA augments the control signal based on the rate of change of the error signal, enabling faster response to sudden changes or disturbances in the system dynamics. This is clarified here in the results of TIDA in the three tasks comparing to PIDA and TID controllers which have slower response. This proves that TIDA improves the transient response of the DC servomotor.

V. Conclusions

The control of nonlinear systems, such as hydraulic and servomotor systems, presents challenges due to their complex dynamics and external disturbances. Existing controllers, including TIDA and FTIDA, struggle with high overshoot, slow settling time, and excessive control effort, highlighting the need for a more robust and efficient solution. To address these limitations, this study proposes the fuzzy precompensated TIDA (FP-TIDA) controller, integrating fuzzy logic as a compensator to enhance system adaptability and robustness. Simulation results demonstrate that FP-TIDA outperforms TIDA and FTIDA by achieving the lowest rise time, settling time, and peak time while maintaining a minimal overshoot, ensuring faster response and improved stability. Additionally, FP-TIDA generates a smoother control signal, reducing energy consumption and enhancing practical feasibility. The key contributions of this research include the development of an FP-TIDA controller, a comprehensive performance evaluation against existing controllers, and superior tracking accuracy in the presence of step input changes. Future work will focus on further optimizing FP-TIDA by incorporating adaptive control mechanisms, machine learning-based parameter tuning, and experimental validation on real-world hardware, extending its application to multi-input multi-output (MIMO) systems for enhanced versatility and robustness.

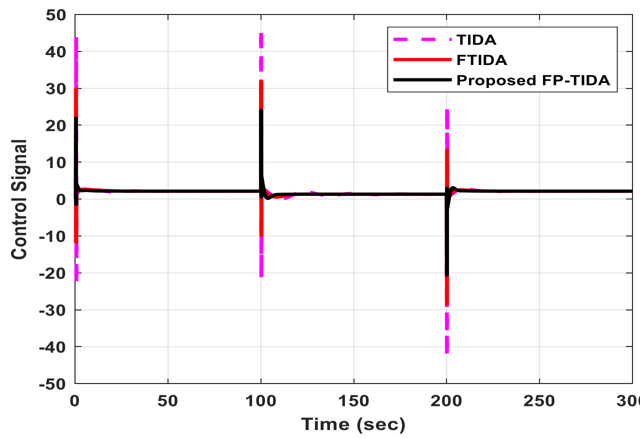

Fig.10. Control signal for single-link manipulator (Task 3)

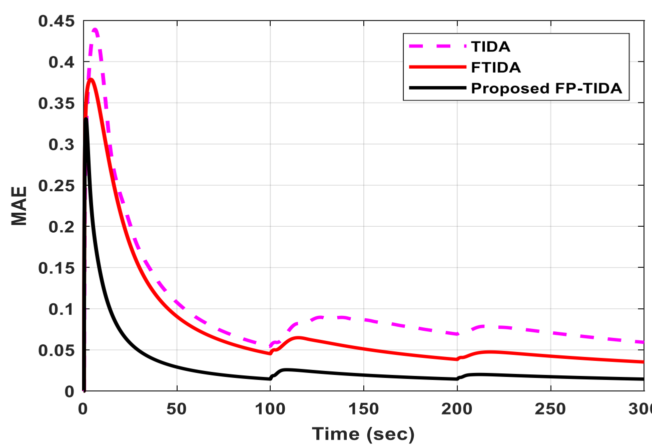

Fig. 11. single-link robotic manipulator (Task 3)

Availability of data and materials
The authors have not used any data in this study.

Competing interests
The authors declare that they have no competing interests.

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Authors' contributions
All authors contributed extensively to the work presented in this paper. All authors read and approved of the final

TABLE 1 RMSE, ISE, and IAE for single-link robotic manipulator.

Cases of Study	RMSE			ISE			IAE		
	TIDA [15]	FTIDA [17]	FP-TIDA	TIDA [15]	FTIDA [17]	FP-TIDA	TIDA [15]	FTIDA [17]	FP-TIDA
Task 1	0.0779	0.0653	**0.0328**	1.7956	1.2779	**0.3218**	5.4185	4.5314	**1.4589**
Task 2	0.0969	0.0877	**0.0438**	2.7874	2.3068	**0.5761**	10.666	11.203	**3.6005**
Task 3	0.1223	0.0918	**0.0559**	4.4555	2.5263	**0.9350**	17.758	10.593	**4.3537**

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