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Optimal Fuzzy Precompensated TID controller for Nonlinear Dynamical Systems

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

***Abstract*— An efficient fuzzy precompensated tilt integral derivative (FP-TID) controller is introduced for controlling nonlinear systems in the present work. The proposed control system structure combines two controlling modules; fuzzy logic control (FLC) and TID controller. This combination merges the benefits of fuzzy logic system and TID controller while designing the proposed control system. Consequently, it provides a high degree of flexibility to cope with disturbances and uncertainties in system parameters that affect system performance. The scaling factors of fuzzy precompensator and TID controller parameters are optimized using the Grey Wolf Optimizer (GWO) and the optimum range for those parameters is specified with minimizing an integral time absolute error (ITAE) fitness function. The applicability and superiority of the presented FP-TID controller based on GWO are evaluated through simulation of nonlinear continuous stirred tank reactor and its results are compared with other control techniques. Simulation tasks exhibit that the FP-TID presents a high superiority response for system disturbances and uncertainties compared to the other techniques.**

***Keywords*—TID controller, Fuzzy precompensator, Grey Wolf Optimizer, Uncertain nonlinear systems.**

I. INTRODUCTION

Fuzzy logic controller (FLC) is a type of intelligent control system, which incorporates fuzzy logic system (FLS) in control strategies. Fuzzy logic system is a mathematical framework that allows for the representation and manipulation of imprecise or uncertain information. Therefore, the flexibility of FLC can be enhanced in a valuable manner to increase its ability for controlling ill-structured, complex, and uncertain systems [1-3]. In this framework, FLC has high interest and recommendation from control engineers over the conventional controllers due to its characteristics such as [4, 5]: a) dynamical model isn't required where FLC is able to control nonlinear systems by mapping the input/output nonlinear relations without a mathematical model. b) FLC applies heuristic rules based on the human experts to obtain the required control action. c) its ability to overcome different forms of uncertainty, etc. Practically, FLC has been designed in different structures for developing a proper control strategy for improving nonlinear systems performances over the conventional counterparts [6-9].

On the other hand, tilt integral derivative (TID) controller is a form of fractional order controllers which is used in engineering applications for improving system stability and its closed loop performance [10,11]. TID controller presents some prominent advantages such as the flexibility of changing system's parameters, disturbance rejection and robustness to tackle nonlinear system issues [12]. For a brief description, TID controller uses fractional order calculus to obtain the control action. This controller looks like a proportional integral derivative (PID) controller in construction with the difference that the proportional part is multiplied by a tilted component [13]. This controller combines the concepts of integral control and derivative control to achieve better control over the system's response. Integral control, also known as integral action, is a control strategy that eliminates steady-state error. It calculates the integral of error signal and uses this information to adjust the control signal. By continuously integrating the error signal, integral control can eliminate any steady-state error that may arise due to disturbances or uncertainties in the system. Derivative control, on the other hand, takes into account the rate of error signal change. It calculates the derivative of error signal and uses this information to adjust the control signal. By considering the rate of error change, derivative action can anticipate the future system response and make adjustments to the control signal accordingly.

There have been several studies and research papers that have explored the application of TID controller in various engineering fields. For example, in the field of robotics, researchers have used this control strategy to improve the stability and accuracy of robot manipulators [14]. In the field of power systems, TID controller was introduced for enhancing multi-area power systems performances [11, 12, 15]. The researchers demonstrated that this control strategy could effectively stabilize the power system under different uncertainties and improve its performance. In [16], the cascade fractional order (FO) PI with FO proportional tilt integral derivative controller is introduced for controlling power system under different conditions. A decentralized TID controller has been designed for MIMO system [17]. The work in [18] designed cascade FO integral-derivative and tilt controller for wind power system and electric vehicles.

Fuzzy Tilt Integral Derivative (FTID) controller merges the fuzzy logic with the tilt integral derivative technique in its structure. This combination provides an effective strategy

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[1]Hossam Khalil is with Mechatronics Engineering Department, Faculty of Engineering, 6 October University, Cairo, Egypt, on leave from the Faculty of Electronic Engineering, Menoufia University, PO Box 32952, Menouf, Egypt.. (e-mail: hossam.khalil@el-eng.menofia.edu.eg). ([8]*Corresponding author)*

[2]Osama Elshazly is with the Mechatronics Engineering Department, High Institute of Engineering and Technology (HIET) – ElMahala Elkobra, Egypt, on leave from Faculty of Electronic Engineering, Menoufia University, PO Box 32952, Menouf, Egypt.. (e-mail: osama.elshazly@el-eng.menofia.edu.eg).

[3]Omar Shaheen is with the Electrical Engineering Department, Faculty of Engineering, 6 October University, Cairo, Egypt, on leave from Faculty of Electronic Engineering, Menoufia University, PO Box 32952, Menouf, Egypt.. (e-mail: omar.shahin@el-eng.menofia.edu.eg).

to control various systems including nonlinear level control [19], load frequency control (LFC) in microgrid system [13], and level control with uncertainty and disturbance in the process [20]. The idea behind FTID control lies in the utilization of fuzzy logic to handle uncertainties and nonlinearities, coupled with the tilt integral derivative method to provide robust and adaptive control. One of the pioneer works in the field of FTID control is the research study conducted in [21], in which a hybrid fuzzy proportional derivative–tilt integral derivative (FPD-TID) controller is proposed for load frequency control (LFC) of a standalone microgrid system. Also, fuzzy based TID controller was designed for solving LFC problem in [22].

In this paper fuzzy precompensated-TID (FP-TID) controller is developed based on GWO for tuning controller parameters. The developed algorithm here deals with nonlinear systems such as continuous stirred tank reactor (CSTR). All the parameters of the proposed precompensated FP-TID are optimized for the controlled system to track the desired concentration of a specific substance inside the reactor. The results show how the FP-TID controller based on GWO is a robust controller that can handle nonlinearities and uncertainties in the CSTR system. The key contributions of this work are summarized as:

1) Introducing fuzzy precompensated tilt integral derivative (FP-TID) controller that combines benefits of fuzzy logic system and TID controller to cope system nonlinearities and uncertainties with a robust performance.
2) Optimal parameters for the designed (FP-TID) controller are obtained based on GWO algorithm for improving the controller performance.
3) The efficacy of FP-TID controller is confirmed with the application to control nonlinear CSTR with a huge capability to tackle system uncertainties.

The organization of this study is as follows. The proposed fuzzy precompensated TID (FP-TID) controller is developed in section 2. Section 3 introduces the optimization technique for the proposed FP-TID controller. Simulation results for the proposed controller structure are displayed in section 4. Conclusions are introduced in section 5 followed by references.

II. The Proposed Fuzzy Precompensated Tilt Integral Derivative (FP-TID) Controller

Fig. 1 shows the structure of the proposed FP-TID controller. It combines two controlling modules connected in series, which are fuzzy logic control (FLC) and TID controller. The combination of both controllers is expected to provide flexibility for the controller to cope parameter uncertainties and disturbances. The description and processing configuration of the two modules are introduced in the following subsections.

A. Fuzzy Precompensator

The FLC has two inputs and one output variable to modify the desired output for TID controller. The inputs are error and change of error which are normalized by two scaling factors; G_e and G_{de} as:

$$E(k) = G_e\, e(k) = G_e\,(y_d(k) - y(k)) \tag{1}$$

$$\Delta E(k) = G_{de}\, \Delta e(k) = G_{de}\,(e(k) - e(k-1)) \tag{2}$$

where $y_d(k)$ is the desired output and $y(k)$ is the controlled system output and k is the sampling instant.

The process of the fuzzy precompensator module includes four operations: fuzzification, rule base, fuzzy inference engine and defuzzification operation. Firstly, the inputs are fuzzified to convert the crisp inputs into membership grades, $\mu(E(k))$ and $\mu(\Delta E(k))$ through fuzzification operation. Then, the fuzzy inference engine is employed to infer the fuzzy output using Mamadani fuzzy rules that described as

$$Rule\, i: IF\;\; E(k)\; is\; \tilde{A}_i\;\; AND\;\; \Delta E(k)\; is\; \tilde{B}_i\;\; THEN\;\; U_{fp}(k)\; is\; \tilde{C}_i \tag{3}$$

This rule represents the fuzzy relation and its firing strength is counted using the product t- norm as

$$\mu_{Ri} = \mu_{\tilde{A}_i}(E(k)) \cdot \mu_{\tilde{B}_i}(\Delta E(k)) \tag{4}$$

The defuzzification stage is processed to account the crisp output of fuzzy precompensator using the centroid defuzzification method as

$$U_{fp}(k) = \frac{\sum_{s=1}^{N} y_s\, \mu_{Ri}(y_s)}{\sum_{s=1}^{N} \mu_{Ri}(y_s)} \tag{5}$$

where $U_{fp}(k)$ is the normalized output of fuzzy precompensator and y_s (s =1,…, N) are discrete points in output domain. The output variable $u_{fp}(k)$ is counted by scaling the fuzzy precompensator output; with scaling factor G_u; as:

$$u_{fp}(k) = G_u\, U_{fp}(k) \tag{6}$$

The modified desired output for FLC module is obtained as:

$$q_m(k) = u_{fp}(k) + y_d(k) \tag{7}$$

B. Tilt Integral Derivative (TID) Controller

TID controller has the same structure as PID controller, but it differs in the proportional part which is multiplied by a tilted component with transfer function $s^{-1/n}$. Thus the TID transfer function is:

$$G_{TID}(s) = \frac{K_t}{s^{1/n}} + \frac{K_i}{s} + K_d\, s \tag{8}$$

Where, K_t, K_i and K_d are three tuneable gains and n is a real number ($n \neq 0$). Moreover, in comparison with PID controller, the TID controller provides the ability to face parameter uncertainties, disturbances and the easy of controller parameters tuning [13].

The final output of TID controller is the control signal for the controlled system. The continuous-time control law of TID controller is:

$$u_{TID}(t) = K_t\, D_{t_0}^{-\frac{1}{n}}\, e_c(t) + K_i \int e_c(t)\, dt + K_d\, \frac{de_c(t)}{dt} \tag{9}$$

where $e_c(t)$ is the measured error signal which is calculated as the difference between the modified desired q_m and the system output y as:

$$e_c(t) = q_m(t) - y(t) \tag{10}$$

In fractional calculus, one of the main methods for the determination and approximation of fractional order operator is the Grunwald –Letnikov (GL) which is defined as [20]:

$$D_{t_0}^{\lambda} f(t) = \lim_{h \to 0} \frac{1}{h^{\lambda}} \sum_{j=0}^{[(t-t_0)/h]} (-1)^j \binom{\lambda}{j} f[t - jh] \quad (11)$$

where h is the step size and $\binom{\lambda}{j}$ is the Newton's binomial that given as

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

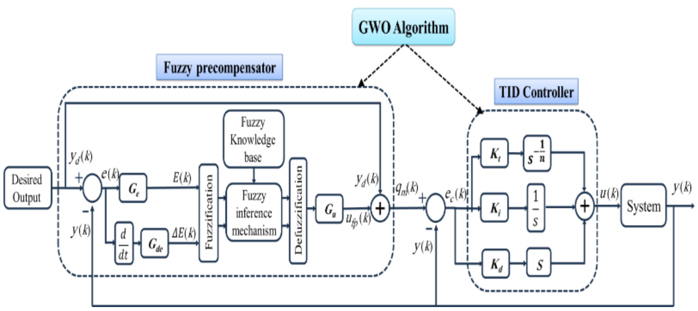


Fig. 1 Design of fuzzy precompensated TID controller.

The dynamic behaviour of the FO transfer function can be approximated using GL approximation that is given as [23]:

$$s^{\lambda} \approx \sum_{k=0}^{N} \frac{(-1)^k \binom{\lambda}{k}}{h} z^{-k} \quad (13)$$

Using the above GL definition, the discrete TID control law can be derived from the continuous TID control law in Eq. 9. as [24]:

$$u_{TID}(k) = K_t \, {}^{GL}_{k_0}\sum_{k}^{\lambda} e_c(k) + K_i \sum_{j=0}^{k} e_c(j) + K_d \left(e_c(k) - e_c(k-1)\right) \quad (14)$$

Where k_0 is the initial time and the integral regulator term ${}^{GL}_{k_0}\sum_{k}^{\lambda} e_c(k)$ is given as:

$${}^{GL}_{k_0}\sum_{\eta}^{\lambda} e_c(k) = {}^{GL}_{k_0}\Delta_k^{-\lambda} e_c(k) = e_c(k) + \sum_{j=0}^{k} w_j^{-\lambda} e_c(k-j) \quad (15)$$

where $0 < \lambda$, $k_0 = 0$, and the forgetting factor $w_j^{-\lambda}$ is given as

$$w_j^{-\lambda} = (-1)^j \binom{-\lambda}{j} \quad (16)$$

The TID controller offers numerous benefits such as maintaining system response stability during disturbances, and parameter variations and being easy to tune. This makes the proposed FP-TID controller more robust to disturbance and parameter changes.

III. Optimization of the Proposed FP-TID Controller

The FP-TID controller performance can be improved by tuning its parameters with personalized performance indices to the optimal values. Along with controller parameters, the optimization of fuzzy precompensator and TID controller parameters is presented in this section to minimize a defined objective function. This section presents the grey wolf optimization (GWO) algorithm [25] for optimization of the FP-TID controller parameters.

A. *Grey Wolf Optimization (GWO) Algorithm*

Grey wolf optimization (GWO) is a powerful and efficient algorithm that has gained popularity in solving optimization problems. Inspired by the social hierarchy and hunting strategies of wolves, GWO mimics the cooperative behaviour of a wolf pack in searching for the best solution. GWO has several advantages over other optimization algorithms. It has a simple and intuitive implementation, making it easy to understand and apply. The algorithm requires few parameters to be tuned, reducing the complexity of optimization problems. Additionally, GWO exhibits fast convergence and robustness, allowing it to find high-quality solutions with fewer function evaluations.

One of the key components of GWO is the updating mechanism of the positions of alpha (α), beta (β), and delta (δ) wolves. These wolves represent the best solutions found so far, and their positions are updated based on the hunting behaviour of wolves. By imitating the leadership and cooperation within a wolf pack, GWO ensures that the global solutions are retained and improved upon iteratively.

GWO utilizes three main operators: encircling, prey search, and prey update. The encircling operator simulates the hunting behaviour of the wolves by grouping and surrounding potential prey. The prey search operator symbolizes the actual hunting process, where the wolves explore nearby areas to locate the prey. The prey update operator perturbs the current position of a wolf based on the positions of other wolves in the pack.

The distance vector between the prey and wolf positions known as $\vec{\mathcal{D}}$. To calculate $\vec{\mathcal{D}}_{\alpha}$, follow these steps.

$$\vec{\mathcal{D}}_{\alpha} = \left|\vec{\mathcal{C}}_{\alpha}.\vec{x}_{\alpha} - \vec{x}\right| \quad (17)$$

where $\vec{x}$ is the prey's position and $\vec{\mathcal{C}}_{\alpha}$ the coefficient vector to be formulated as:

$$\vec{\mathcal{C}}_{\alpha} = 2\,.\vec{b}.\vec{r}_{\alpha} - \vec{b} \quad (18)$$

The variable $\vec{r}_{\alpha}$ is used to generate a random vector that includes values between 0 and 1. This vector will be completely random and can be used for various purposes.

Likewise, the vectors for other wolves are calculated to be $\vec{\mathcal{C}}_{\beta}$ and $\vec{\mathcal{C}}_{\delta}$, respectively. It is worth noting that $\vec{b}$ decreases exponentially from 2 to 0 as the iteration progresses and it is computed as [26]:

$$\vec{b} = 2 * \left(1 - \frac{k^2}{N^2}\right) \quad (19)$$

where k is the current iteration and N is the total number of iterations. Eventually, for example α wolf update its position based on the following equation:

$$\vec{x}(k+1) = \vec{x}_{\alpha}(k) + \vec{r}_{\alpha}.\left(\vec{x}_{\alpha}(k-1) - \vec{x}_{\alpha}(k-2)\right) \quad (20)$$

The Pseudo code of GWO used in this work is as the same in [27].

B. *GWO for Optimization of FP-TID Controller Parameters*

Grey Wolf Optimization (GWO) algorithm is applied to optimize the scaling factors of FLC (G_e, G_{de} and G_u) and the parameters of TID controller (K_t, K_i, K_d and n) in order to minimize a specified performance index to enhance the accuracy of FP-TID controller. In this paper, the integral time absolute error (ITAE) criterion is used as the performance index which is mathematically expressed as:

$$ITAE = \int_0^\infty t\left|e(t)\right|\,dt \tag{21}$$

where $e(t)$ is the difference between the desired and actual outputs. ITAE delivers an output that settles faster than the other performance indices because of the time integrated together the absolute value of the error, and therefore it simultaneously improves the transient and steady-state performances of time response of the system. However, sometimes its outputs are lethargic.

IV. Simulation Result

The prime goal of this part is to show the effectiveness of the proposed FP-TID controller based on GWO to control highly nonlinear systems. As example of highly nonlinear system, continuous stirred tank reactor (CSTR) is considered here to be controlled under different operating conditions [25]. The responses of the proposed FP-TID are estimated and compared to that of TID controller [11], and FPD-TID [21]. This comparison is formulated in terms of root mean square error (RMSE), integral squared error (ISE), and integral absolute error (IAE) that are defined as

$$RMSE = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left(e(k)\right)^2} \tag{22}$$

$$ISE = \int_0^\infty \left[e(t)\right]^2 dt \tag{23}$$

$$IAE = \int_0^\infty \left|e(t)\right| dt \tag{24}$$

where N is the total number of samples.

A. *System Model*

Real world applications are the ultimate challenge for any controller. In this work the developed controller is well designed and tuned to control a continuous stirred tank reactor (CSTR) which is highly nonlinear system due to their nature of exothermic reactions. The system can be described in state space equations as [28].

$$\left.\begin{aligned}
\frac{dz_1}{dt} &= 1 - z_1 - (\varpi_1 + \Delta\varpi_1)z_1 + (\varpi_2 + \Delta\varpi_2)z_2^2 \\
\frac{dz_2}{dt} &= -z_2 + (\varpi_1 + \Delta\varpi_1)z_1 - (\varpi_2 + \Delta\varpi_2)z_2^2 - (\varpi_3 + \Delta\varpi_3)d_2(t)z_2^2 + u \\
\frac{dz_3}{dt} &= -z_3 + (\varpi_3 + \Delta\varpi_3)d_2(t)z_2^2 \\
y &= z_3
\end{aligned}\right\} \tag{25}$$

To achieve the control objective of tracking a desired output $y_d = 0.5$ without steady state error, the FP-TID controller is developed for CSTR system with reactant A, middle reactant B, and product C, denoted by z_1, z_2, and z_3 respectively. The system parameters including ϖ_1, ϖ_2, and ϖ_3 are defined as $\varpi_2 = k_1 d_1 V/F$, $\varpi_2 = k_2 d_1 V/F$, and $\varpi_3 = k_3 V/F$, where d_1 is a constant activity and d_2 has time-varying behavior. The initial values of system parameters are appointed as $\varpi_1(0) = 3, \varpi_2(0) = 0.5, \text{and}\ \varpi_3(0) = 1$. The value of control signal is limited to be within the range [0, 1].

B. *FP-TID Controller for CSTR*

The proposed FP-TID controller uses five triangular membership functions for the two inputs and the output as shown in figure (2). The rule base for FLC in fuzzy precompensator module is considered as described in Table 1 which was chosen as in [29].

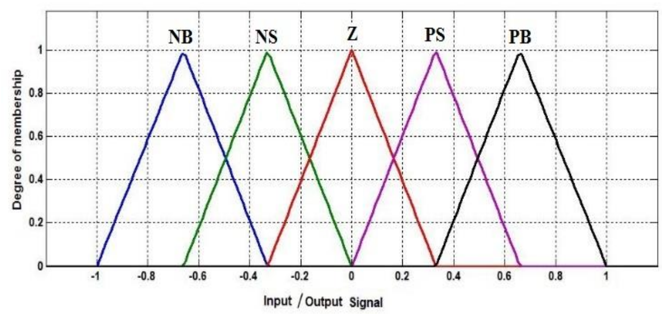


Fig. 2. membership functions

Table 1: Rule base for the PF-PID controller.

Derivative of Error Signal	***Error Signal***				
	NB	**NS**	**Z**	**PS**	**PB**
NB	*NB*	*NB*	*NS*	*NS*	*Z*
NS	*NB*	*NB*	*NS*	*Z*	*PS*
Z	*NB*	*NS*	*Z*	*PS*	*PB*
PS	*NS*	*Z*	*PS*	*PS*	*PB*
PB	*Z*	*PS*	*PB*	*PB*	*PB*

GWO is used with constraints on the parameters as given in Table 2. The feasible range for the FP-TID controller parameters is important for GWO algorithm because it determines the possible range of the tuned parameters which was chosen experimentally to limit the control signal of the system to be within the range [0,1] and better values of ITAE are obtained.

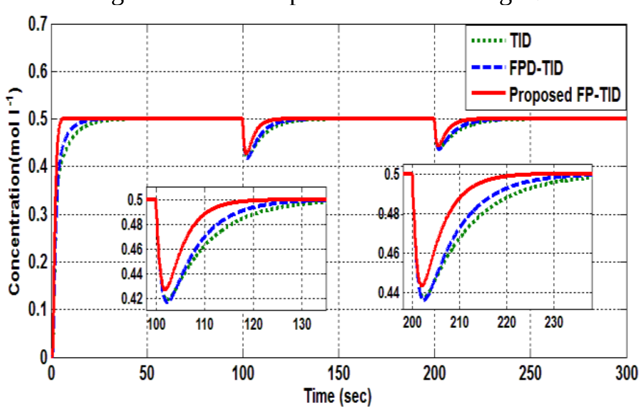
Table 2. The feasible range for the FP-TID controller parameters.

$G_e \in [0,2]$ $G_{de} \in [0,1]$ $G_u \in [0,1]$	$k_t \in [0,5]$ $k_i \in [0,5]$ $k_d \in [0,5]$ $n \in [0,2]$

The performance of FP-TID controller is evaluated through five simulation tasks including uncertainty in system parameters, the time-varying nature of the controlled system, and output tracking response. The simulation results for the proposed FP-TID controller are compared with that of the other controllers.

***Task* 1:**

An uncertainty in ϖ_3 with value $(\Delta\varpi_3 = -0.15)$ is activated at t = 100s, and it is further increased to $(\Delta\varpi_3 = -0.25)$ at t = 200s. CSTRT responses with all controllers are represented in Figure 3. Compared to the conventional TID and FPD-TID controllers, the developed FP-TID controller based on GWO exhibits a much faster response, indicating that it can effectively handle uncertainty in system parameters. Also, FP-TID controller has lower values of MAE than that of the other controllers. Although all controllers based on TID controller are robust to system's parameters uncertainties, but the proposed controller gives a faster response to those changes.



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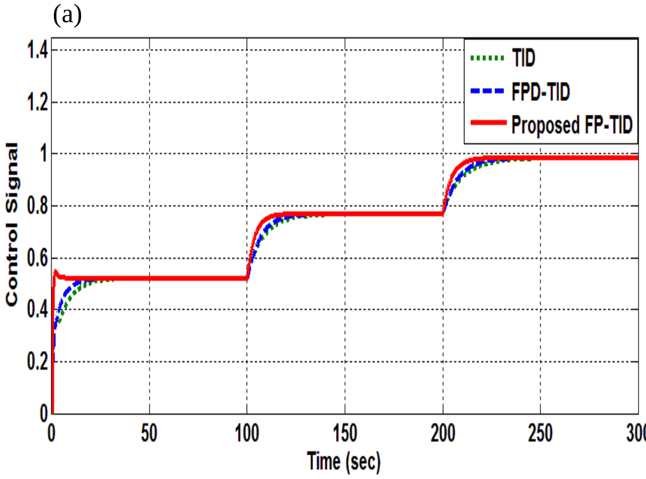

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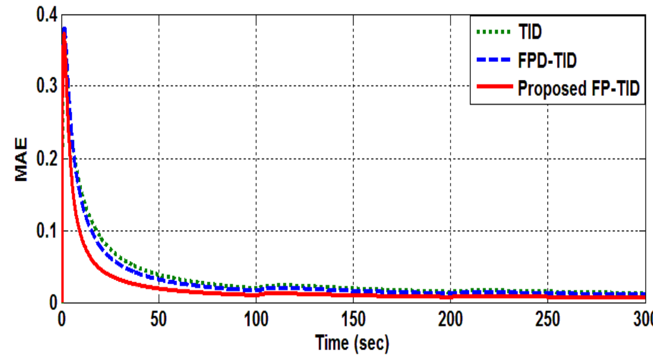


(c)

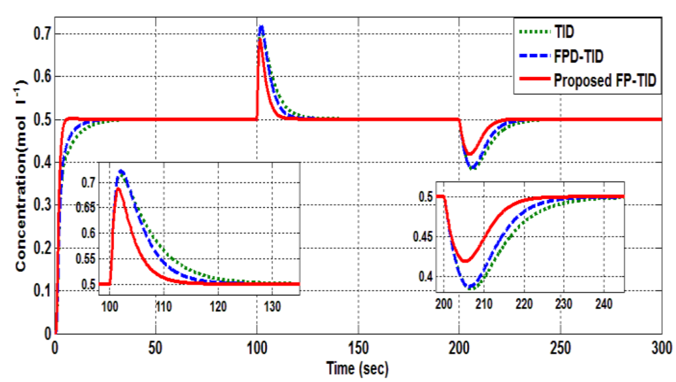
Fig. 3 CSTR system response (Task 1). (a) system output (b) control signal (c) MAE curve.

***Task* 2:**

This control task demonstrates the effectiveness of FP-TID controller in handling variation of system parameters over the time. The CSTR parameter $d_2(t)$ follows a specific pattern given as:

$$d_2(t) = \begin{cases} 1 & 0 \le t \le 100 \\ 1+5(1-e^{-0.4(t-100)}) & 100 \le t \le 200 \\ 6-5(1-e^{-0.4(t-200)}) & t \ge 200 \end{cases} \quad (26)$$

Figure 4 shows the CSTR concentration output response under varying parameters. The developed controller responds with better performance and lower values of MAE than both the FPD-TID and TID controllers. Hence, the developed FP-TID controller based on GWO is robust for time-varying systems.



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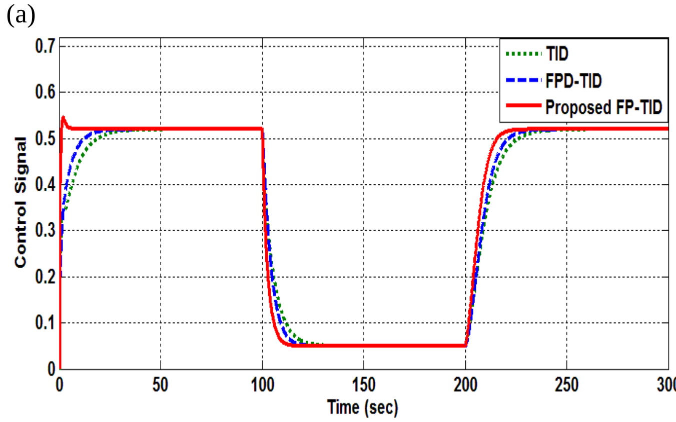

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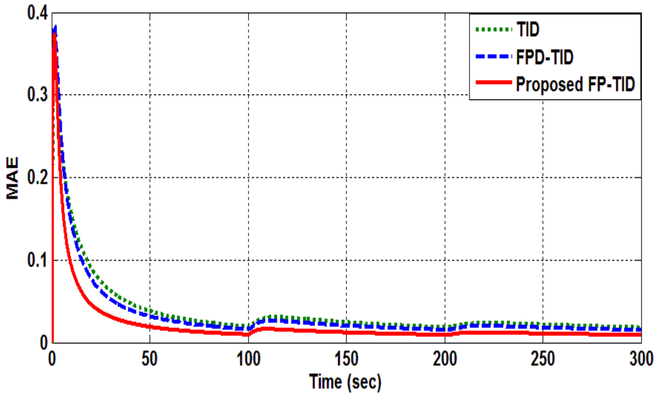
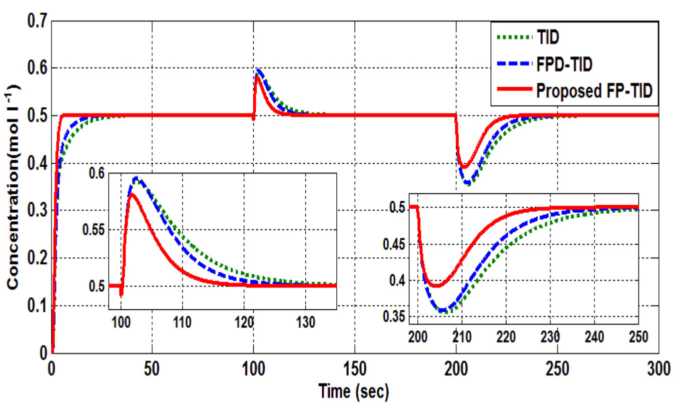


(c)

Fig. 4 CSTR system response (Task 2). (a) system output (b) control signal (c) MAE curve.

***Task* 3:**

As mentioned above, the developed controller is tested with different types of uncertainties applied to the system. In this task the two types of uncertainties applied in the first and second tasks are applied here. This means that we have both parameter uncertainties in ϖ_3 and use the same pattern of $d_2(t)$ used in the previous task. Fig. 5 depicts the CSTR response due to the two uncertainties. Even the two uncertainties are applied at the same time, the controllers still follow the desired output but the developed FP-TID still the fastest and the most accurate response comapared to the other countrparts.



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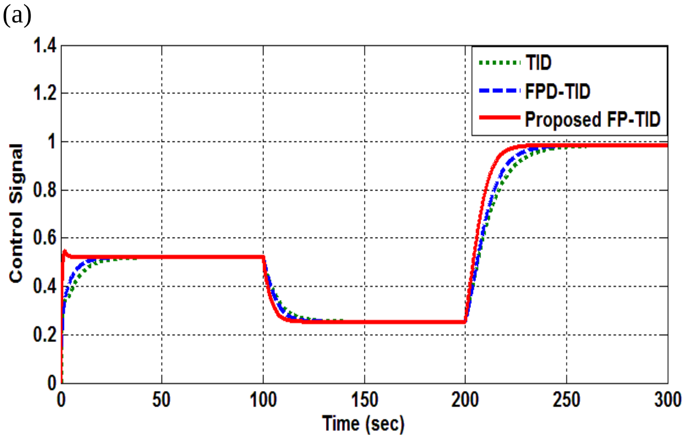

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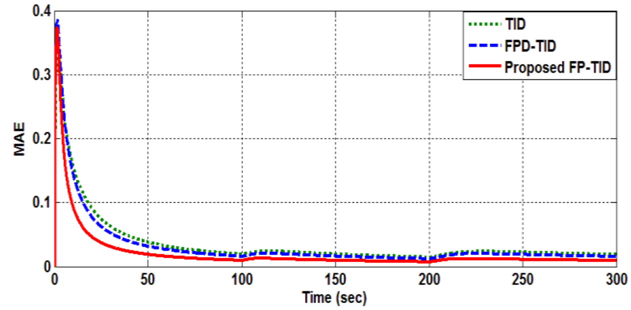


(c)

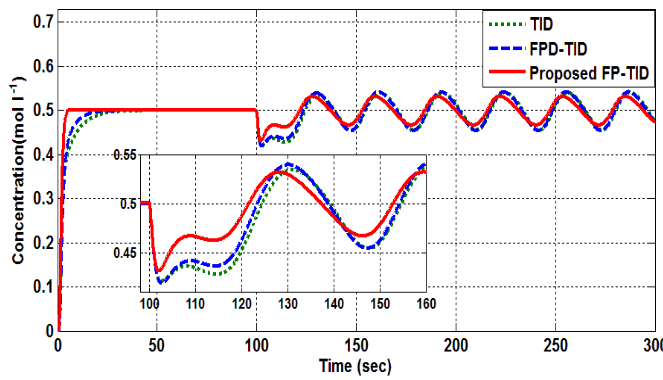
Fig. 5 CSTR system response (Task 3). (a) system output (b) control signal (c) MAE curve.

***Task* 4:**

This task considers a sinusoidal variation of $d_2(t)$ as:

$$d_2(t) = 1 + 0.25\sin(kt/5) \qquad t \geq 100 \qquad (27)$$

Fig. 6 depicts the CSTR response under sinusoidal disturbance, where the proposed FP-TID shows a better performance comparing to other controllers. Hence, the presented controller is more immune to this type of disturbance.



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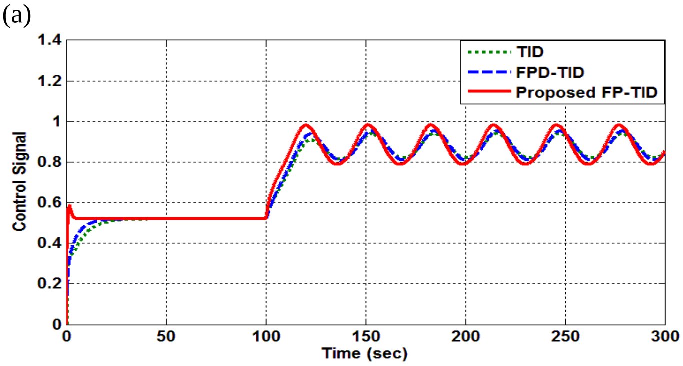

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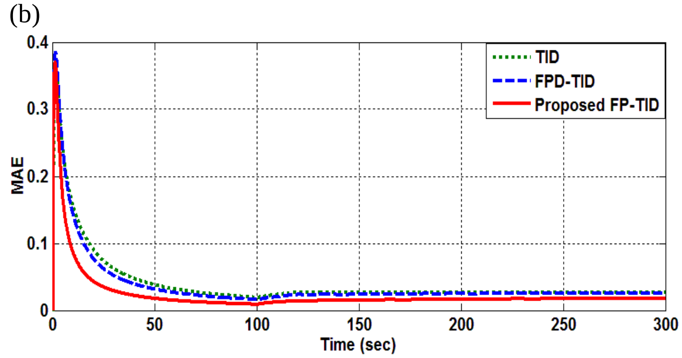


(c)

Fig. 6 CSTR system response (Task 4). (a) system output

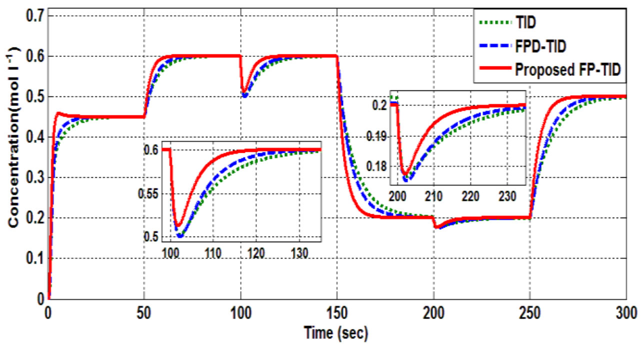
(b) control signal (c) MAE curve.

***Task* 5:**

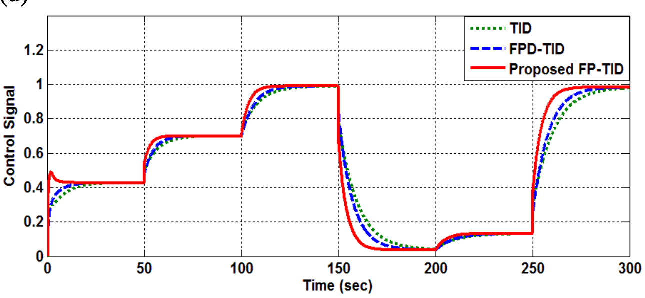
This task demonstrates the feasibility of using this controller under different operating conditions with different types of uncertainty which is a harsh task for many controllers. The same uncertainty effect in task 3 is tested along with changing the reference values with the following values:

$$y_d(t) = \begin{cases} 0.45 & 0 \le t \le 50 \\ 0.6 & 50 \le t \le 150 \\ 0.2 & 150 \le t \le 250 \\ 0.5 & 250 \le t \le 300 \end{cases} \quad (28)$$

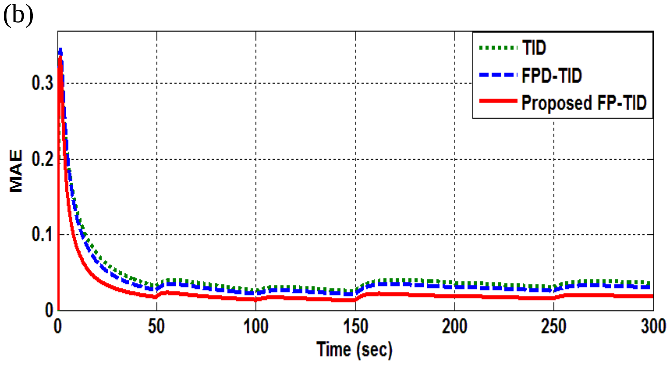
Fig. 7 shows the responses of CSTR under those conditions. The proposed FP-TID in this task proves to be the most powerful controller and the fastest among them which means that it has the lowest settling time and more stable response comparing to other controllers.



(a)



(b)



(c)

Fig. 7 CSTR system response (Task 5). (a) system output (b) control signal (c) MAE curve.

Comparison of the proposed controller FP-TID with other existing controllers FPD-TID and TID in terms of RMSE, ISE, and IAE are given in Tables 3, 4 and 5, respectively. The results explain how the proposed controllers gives better results comparing to other controllers. These results explain the powerful of the proposed FP-TID controller comparing to other existing controllers and still the control signal within the limits of the CSTR. Table 6 depicts the computation time for each controller for one iteration. All times are calculated on Matlab 2023 using a PC with 12th Generation Corei7 central processing unit and an installed random access memory (RAM) of 16 GB. As shown here in timing results, TID controller is the fastest one as expected. However, all the controllers are very fast comparing to the system sampling period of 0.1 second.

Table 3: RMSE values for CSTR system.

Controller	Task 1	Task 2	Task 3	Task 4	Task 5
TID [11]	0.0433	0.0534	0.0520	0.0495	0.0747
FPD-TID [21]	0.0414	0.0507	0.0491	0.0480	0.0710
Proposed FP-TID	**0.0355**	**0.0406**	**0.0396**	**0.0387**	**0.0560**

Table 4: ISE values for CSTR system.

Controller	Task 1	Task 2	Task 3	Task 4	Task 5
TID [11]	0.5361	0.8298	0.7853	0.7091	1.6523
FPD-TID [21]	0.5141	0.7706	0.7213	0.6903	1.5105
Proposed FP-TID	**0.3771**	**0.493**	**0.4711**	**0.4488**	**0.9413**

Table 5: IAE values for CSTR system.

Controller	Task 1	Task 2	Task 3	Task 4	Task 5
TID [11]	3.6413	5.4098	5.6278	7.9767	10.6404
FPD-TID [21]	3.0179	4.4863	4.6679	7.6555	8.8801
Proposed FP-TID	**1.7862**	**2.6501**	**2.7581**	**5.2668**	**5.2197**

Table 6: Computation time for all controllers.

Controller	Computation time (μs)
TID [11]	2.896
FPD-TID [21]	7.658
Proposed FP-TID	8.479

V. Conclusion

This paper proposes an efficient FP-TID controller, which combines the features of FLC and TID controller to tackle uncertainty and disturbance within nonlinear systems. Firstly, the proposed controller is structured with a precompensator fuzzy module cascaded with a TID controller. This combination has proven to provide a robust and efficient control system to handle uncertainties and nonlinearities in dynamical systems. Also, a systematic optimization strategy based on GWO is presented to optimize scaling factors of the precomensated fuzzy module and the tunable parameters of TID controller. The proposed control structure is applied for controlling nonlinear CSTR with the presence of different nonlinear tasks including uncertainties in the parameters, variation of system parameters with time and output tracking with reference change. The performance of FP-TID is compared with other existing controllers and three performance indices are measured for performance evaluation. The indicated simulation results revealed that FP-TID controller has the ability to control nonlinear uncertain systems with a significant performance better than the other controllers. The system's constraints must be taken into account while designing the proposed FP-TID controller. Controlling of other complex dynamical systems and applying other adaptive strategies can be considered as a future works. Moreover, type 2 FLC can be used as a precompensator for TID controller. Also, other optimization techinques such as ant colony and genetic algorithms can be used to tune the parameters of the proposed controller. Finally, the proposed controller needs to be implemented experimentally.

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