Tilt-Integral-Derivative-Acceleration (TIDA) Controller based on Grey Wolf Optimization Technique

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Abstract – *The current paper introduces an efficient tilt-integral-derivative-acceleration (TIDA) controller for regulating nonlinear systems. The suggested control system structure consists of the conventional TID controller with added accelerator term to improve the transient response. The accelerator term 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. Furthermore, the optimization of TIDA parameters is achieved through the Grey Wolf Optimization (GWO) algorithm. As a result, it provides a high level of flexibility in dealing with disruptions and uncertainties in system output that affect system performance. The Grey Wolf Optimizer (GWO) is used to optimize the proposed TIDA controller parameters, and the optimal range for those parameters is determined by minimizing an integral time absolute error (ITAE) fitness function. The applicability and superiority of the given TIDA controller based on GWO are evaluated by simulating a nonlinear DC servomotor and comparing the results with that of existing controllers. Simulation tasks show that the proposed TIDA controller has a higher superiority response for system disturbances and step changes to the other approaches.*

***Keywords**: Tilt-Integral-Derivative (TID), Tilt-Integral-Derivative-Acceleration (TIDA), Grey Wolf Optimization (GWO), DC servomotor*

I. Introduction

PID control is a widely used control strategy that relies on three basic control elements - proportional, integral, and derivative terms - to regulate the system's output based on the error signal between the desired and the actual process variable. While PID control is effective in many applications, it may struggle to provide optimal control performance in complex systems with non-linearities, long time delays, or significant disturbances [1], [2].

On the other hand, Tilt integral derivative (TID) control [3]-[5] is an advanced control strategy that has gained significant attention in recent years due to its superior performance compared to traditional proportional-integral-derivative (PID) control in various industrial applications [6]. TID controller introduces a tilt parameter that adjusts the balance between the integral and derivative actions to enhance the system's response to disturbances, set-point changes and allowing for a more customized and flexible control response. In this regard, the key differences between TID control and PID control are explored [7], their advantages and disadvantages, as well as their applications in different fields.

One of the key advantages of TID control over PID control is its ability to achieve faster response times and improved stability in systems with unpredictable dynamics. By adjusting the tilt parameter, TID control can adapt to varying process conditions and optimize the control performance in real-time. This flexibility makes TID control particularly suitable for applications where rapid changes in set-points or disturbances are common, such as in robotics [8] and automotive systems [9]. Moreover, TID control offers better robustness against noise and model uncertainties compared to PID control [7]. This robustness is essential for improving the overall system reliability and performance, especially in critical applications where precision control is vital.

Despite its advantages, TID control also presents some challenges that need to be addressed for successful implementation. The tuning of the tilt parameter and other control gains can be more complex than tuning PID controllers, requiring a deeper understanding of the system dynamics and control objective. Additionally, the computational complexity of TID control might be higher than that of PID control, which could limit its applicability in real-time control systems with strict computational constraints but this drawback is vanished with high speed computing devices like quantum computers.

A PID Accelerator Controller (PIDA) [10] is an advanced variation of the classical PID controller [11], designed to enhance control performance in transient time, particularly in systems with large time delays or sluggish response characteristics. The PIDA controller incorporates an additional acceleration term that effectively predicts future system behavior based on the rate of change of the error signal, enabling faster and more responsive control action [12]. By incorporating information about the acceleration of the error signal, the PIDA controller effectively reduces the response time and improves system dynamics, making it particularly suitable for processes with significant inertia, delays, or nonlinearities [13], [14]. Nevertheless, this presents additional challenges for the controller's tuning, since the acceleration action parameter's physical meaning is less apparent than that of the other parameters, and automatic tuning techniques for this term is still going in research papers. This has led to the adoption of evolutionary algorithms to fine-tune controller parameters for particular uses [15]. Furthermore, the PIDA controller has been designed through the widespread application of contemporary optimization search metaheuristics techniques including the genetic algorithm (GA) [16], particle swarm optimization (PSO) [17], [18], current search (CuS) [19], firefly algorithm (FA) [20], and bat algorithm (BA) [21].

In this work, TID accelerator TIDA is proposed here based on Grey wolf optimization (GWO) technique. TIDA is an innovative extension of the conventional TID controller, enriched with an accelerator term to enhance its control performance. This enhanced controller integrates the benefits of TID and an additional accelerator term like PIDA. The accelerator term 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. Furthermore, the optimization of TIDA parameters is achieved through the Grey Wolf Optimization (GWO) algorithm, a nature-inspired optimization technique inspired by the hunting behavior of grey wolves. This proactive adjustment allows the TIDA controller to swiftly counteract sudden disturbances or changes in set-points, improving transient response and overall control performance. The proposed TIDA controller based on GWO offers a robust and efficient solution for enhancing the performance of DC servo motors in various industrial applications. By providing responsive and adaptive control tailored to the specific requirements of DC servo motor systems, the TIDA controller is optimized by GWO contributes to improve productivity, reliability, and precision in automated systems and motion control applications under different operating and load conditions.

The organization of this paper is as follows. The structure of proposed TIDA controller is developed in section 2. Section 3 introduces the GWO optimization technique for TIDA controller. Case study based on the proposed controller results are displayed in section 4. Conclusions are introduced in section 5 followed by references.

II. The proposed Tilt-Integral-Derivative-Acceleration (TIDA) Controller

Fig. 1 shows the structure of the proposed TIDA controller. The proposed TIDA controller has a similar structure to PIDA controller [10], but it differs in the proportional part which is multiplied by a tilted component with transfer function $s^{-1/m}$. TIDA is an innovative extension of the conventional TID controller, enriched with an accelerator term to enhance its control performance Thus the TIDA transfer function is:

$$G_{TIDA}(s) = \frac{K_t}{s^{1/m}} + \frac{K_i}{s} + K_d\, s + K_a\, s^2 \qquad (1)$$

Where, K_t, K_i, K_d and K_a are the four controller gains to be tuned based on GWO algorithm and m is a real number ($m \neq 0$) must be selected carefully to accurately control the system output.

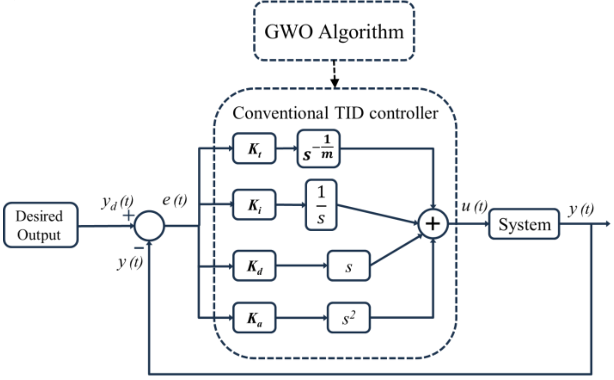

Fig. 1 Design of the proposed TIDA controller.

The output of TIDA controller is calculated as:

$$u_{TIDA}(t) = K_t\, D_{t_0}^{-\frac{1}{m}}\, e(t) + K_i \int e(t)\,dt + K_d\,\frac{de(t)}{dt} + K_a\,\frac{d^2 e(t)}{dt^2} \qquad (2)$$

where $e(t)$ is the calculated error signal defined as the difference between the desired output $y_d(t)$ and the system output $y(t)$ as:

$$e(t) = y_d(t) - y(t) \qquad (3)$$

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 [22]:

$$D_{t_0}^{\lambda} f(t) = \lim_{h\to 0} \frac{1}{h^{\lambda}} \sum_{j=0}^{[(t-t_0)/h]} (-1)^j \binom{\lambda}{j} f[t-jh] \qquad (4)$$

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

$$\binom{\lambda}{j} = \frac{\Gamma(\lambda+1)}{\Gamma(j+1)\,\Gamma(\lambda-j+1)} \qquad (5)$$

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

$$s^{\lambda} \approx \sum_{k=0}^{N} \frac{(-1)^k \binom{\lambda}{k}}{h} z^{-k} \qquad (6)$$

III. Optimization of the Proposed TIDA Controller

The TIDA controller's performance can be improved by optimizing its parameters using customizable performance indices. This section also discusses the optimization of TIDA controller parameters to minimize a stated objective function. This section describes the grey wolf optimization (GWO) algorithm [24] for optimizing the TIDA controller parameters; K_t, K_i, K_d, K_a, and m.

III.1 Grey Wolf Optimization (GWO) Algorithm

Grey wolf optimization (GWO) is a powerful and efficient technique that has become popular for tackling optimization issues. Inspired by wolves' social structure and hunting techniques, GWO emulates the cooperative behaviour of a wolf pack in search of the optimum solution. GWO relies heavily on changing the positions of alpha (α), beta (β), and delta (δ) wolves. These wolves represent the finest solutions discovered thus far, and their positions are modified based on wolf hunting behaviour. By simulating wolf pack leadership and cooperation, GWO ensures that global solutions are kept and iteratively enhanced.

Prey search, prey update, and encircling are the three primary operators used by GWO. By gathering and encircling possible prey, the encircling operator mimics the wolf's hunting behaviour. The prey search operator represents the wolves' actual hunting procedure, which involves searching surrounding areas for the prey. A wolf's present position is disturbed by the prey update operator based on the positions of other wolves in the pack.

The $\vec{\mathcal{D}}$ vector denotes the distance between the prey and wolf positions. To compute $\vec{\mathcal{D}}_\alpha$, take the following actions.

$$\vec{\mathcal{D}}_\alpha = \left|\vec{\mathcal{C}}_\alpha . \vec{x}_\alpha - \vec{x}\right| \qquad (7)$$

where $\vec{x}$ represents the prey's position and $\vec{\mathcal{C}}_\alpha$ is the coefficient vector, which may be expressed as follows:

$$\vec{\mathcal{C}}_\alpha = 2\,.\,\vec{b}.\vec{r}_\alpha - \vec{b} \qquad (8)$$

A random vector with values between 0 and 1 is created using the variable $\vec{r}_\alpha$. This vector can be used for a number of things and will be entirely random. The vectors for the remaining wolves are determined to be $\vec{\mathcal{C}}_\beta$ and $\vec{\mathcal{C}}_\delta$, in the same manner. Noteworthy, $\vec{b}$ is computed as [25] and falls exponentially from 2 to 0 as the loop goes on.

$$\vec{b} = 2 * \left(1 - \frac{k^2}{N^2}\right) \qquad (9)$$

where N is the total number of iterations and k is the current iteration. Ultimately, the α wolf, for instance, updates its position using the equation that follows:

$$\vec{x}(k+1) = \vec{x}_\alpha(k) + \vec{r}_\alpha.(\vec{x}_\alpha(k-1) - \vec{x}_\alpha\,(k-2)) \qquad (10)$$

The Pseudo code of GWO used in this work is the same as in [26].

III.2 Optimization of TIDA Controller Parameters based on GWO

To improve the accuracy of the TIDA controller, GWO algorithm is used to optimize the TIDA controller's parameters (K_t, K_i, K_d, K_a, and m). The goal here is to minimize a given performance index. The performance index in this study is the integral time absolute error (ITAE) criterion, which may be represented mathematically as follows:

$$ITAE = \int_0^{\infty} t\left|e(t)\right| dt \qquad (11)$$

where $e(t)$ represents the difference between desired and actual outputs.

IV. Case Study

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) which are defined as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(e(k))^2} \qquad (12)$$

$$ISE = \int_0^{\infty} [e(t)]^2 dt \qquad (13)$$

$$IAE = \int_0^{\infty} \left|e(t)\right| dt \qquad (14)$$

N represents the total number of samples.

IV.1 Position Control of DC servomotor

The schematic diagram of the DC servomotor is shown in Fig. 2.

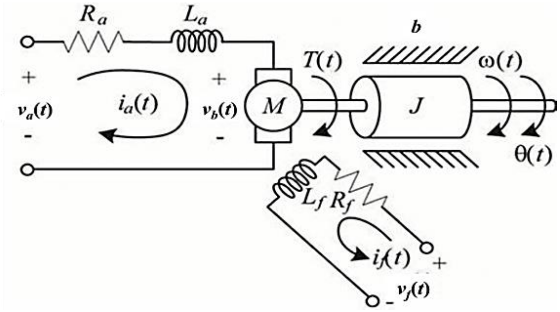

Fig. 2 Schematic diagram of DC servomotor.

An elementary mathematical physical laws can be used to determine the relationship between the shaft angular position (θ) and the voltage input (V_a) to the DC motor. The following equations describe the dynamic behaviour of the DC servomotor with armature current regulation. The motor's air gap flux (φ) is directly proportional to the field current $i_f(t)$, meaning that

$$\varphi = K_f \cdot i_f(t) \tag{15}$$

It is thought that the armature current and air gap flux have a linear relationship with the torque that the motor (T_m) develops:

$$\begin{aligned} T_m &= K_l \cdot \varphi \cdot i_a(t) \\ &= K_l \cdot K_f \cdot i_f(t) \cdot i_a(t) \end{aligned} \tag{16}$$

K_f and K_l are constants in this case. When a field coil's field current is brought to a steady state. The torque of the motor is calculated as:

$$T_m = K_m \cdot i_a(t) \tag{17}$$

Which is given in frequency domain as:

$$T_m(s) = K_m \cdot I_a(s) \tag{18}$$

The armature current is proportional to the input voltage applied to the armature.

$$V_a(s) = R_a I_a(s) + L_a s I_a(s) + V_b(s) \tag{19}$$

Where V_b(s) is the back *emf* voltage that depend on the motor's speed defined as:

$$V_b(s) = K_b s\theta(s) \tag{20}$$

From Eqs. (19) and (20), the armature current is obtained as:

$$I_a(s) = \frac{V_a(s) - K_b s\theta(s)}{R_a + L_a s} \tag{21}$$

The total torque supplied by the servomotor is the addition of both load torque (T_l) and disturbance torque (T_d) defined as:

$$\begin{aligned} &T_m(s) = T_l(s) + T_d(s), \qquad T_d(s) \approx 0 \\ &T_l(s) = Js^2\theta(s) + bs\theta(s) \end{aligned} \tag{22}$$

So, the transfer function of the motor load combination with T_d = 0 is:

$$\begin{aligned} \frac{\theta(s)}{V_a(s)} &= \frac{K_m}{s((R_a + L_a s)(Js + b) + K_m K_b)} \\ &= \frac{K_m}{L_a J s^3 + (R_a J + L_a b)s^2 + (R_a b + K_m K_b)s} \end{aligned} \tag{23}$$

The servomotor is considered as a single input single output (SISO) system where the angular displacement θ(s) is the output and V_a(s) as the input. The parameters of the DC servomotor considered here is given in Table I [13].

TABLE I
PARAMETERS OF DC SERVOMOTOR

Parameter	Value
Moment of inertia of rotor (*J*)	0.01 $Kg\ m^2$
Motor Viscous friction constant (b)	0.1 *N ms*
Back *emf* constant (K_b)	0.01 *V/rad/sec*
Motor torque constant (K_m)	0.01 *N m/A*
Armature resistance (R_a)	1.0 Ω
Armature inductance (L_a)	0.5 *H*

Taking the parameters of the DC servomotor given in Table 1, the transfer function of the system under study is given as:

$$\frac{\theta(s)}{V_a(s)} = \frac{2}{s^3 + 12s^2 + 20.02s} \tag{24}$$

For controlling the DC servomotor position, the TIDA is developed to achieve no steady state error with minimum overshoot.

IV.2 TIDA CONTROLLER FOR DC SERVOMOTOR

The parameters that are restricted when using GWO are listed in Table II. The GWO algorithm depends on the feasible range of the TIDA controller parameters to improve ITAE values.

TABLE II
THE FEASIBLE RANGE FOR THE TIDA CONTROLLER PARAMETERS.

Parameter Range
$k_t \in [0,5]$
$k_i \in [0,5]$
$k_d \in [0,5]$
$k_a \in [0,5]$
$m \in [0,2]$

Three simulation tasks are used to assess the performance of the TIDA controller: output tracking response, time-varying controlled system, and disturbance in system output. The suggested TIDA controller's simulation results are contrasted with those of the other controllers.

TASK 1: STEP RESPONSE

A step input is applied to the DC motor to check the performance of the proposed controller with other controllers as represented in Fig. 3. The developed TIDA controller based on GWO has a much faster response than the conventional TID and PIDA controllers, indicating that it can effectively handle step changes for the system under study. While the TID and PIDA controllers provide a good response, as shown here, the TIDA significantly improves the transient response by responding faster to those step changes. Fig. 4 shows the mean absolute error (MAE) for the proposed TIDA and other controllers. It is noted that, the proposed TIDA controller has lower values of MAE than the other controllers.

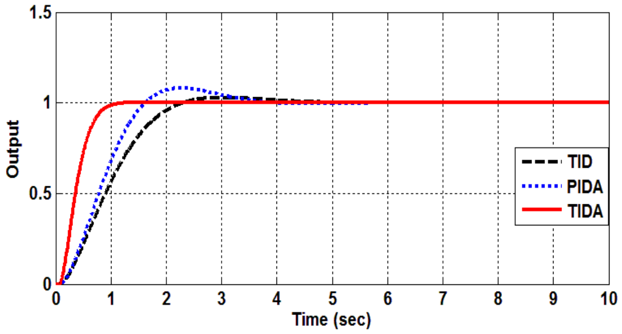

Fig. 3. DC Servomotor response (Task 1)

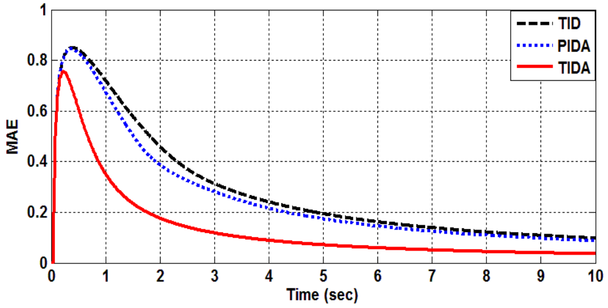

Fig. 4. MAE of DC Servomotor response (Task 1)

TASK 2: EXTERNAL DISTURBANCE

In this task, a load disturbance equals 20% of the system output is applied to the measured output at 8 sec and then it is increased to 50% at 12 sec. Fig. 5 shows the DC motor response due to external disturbance. The proposed TIDA controller can overcome the external disturbance faster than TID and PIDA controllers where the proposed TIDA controller has better transient and steady state responses. The MAE for all controllers is shown in Fig. 6, where the values of MAE with TIDA are lower than the values of the other two controllers.

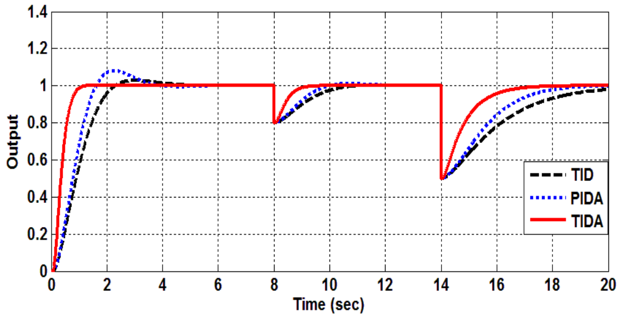

Fig. 5. DC Servomotor response (Task 2)

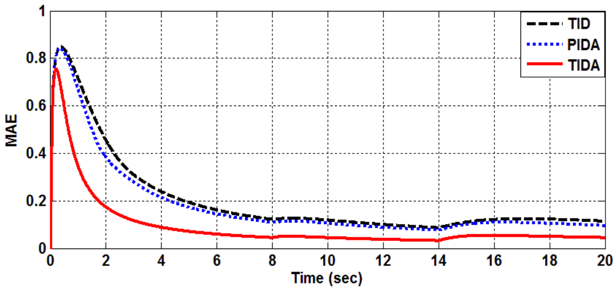

Fig. 6. MAE of DC Servomotor response (Task 2)

TASK 3: OUTPUT TRACKING

This challenge, which is difficult for many controllers, proves the viability of utilizing this controller under various operating situations. The desired output is changed with the subsequent values:

$$\theta_d(t) = \begin{cases} 1 & 0 \le t \le 6 \\ 2 & 6 \le t \le 14 \\ 0.5 & 14 \le t \le 20 \end{cases} \tag{25}$$

The output of DC servomotor for this task is displayed in Fig. 7. In comparison to other controllers, the suggested TIDA in this task turns out to be the most potent and fastest, resulting in the lowest settling time and the steadiest response. Also, the proposed TIDA controller has lower values of MAE rather TID and PIDA controllers as indicated in Fig. 8.

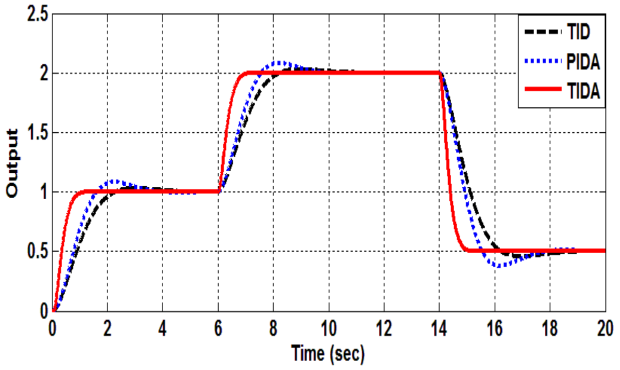

Fig. 7. DC Servomotor response (Task 3)

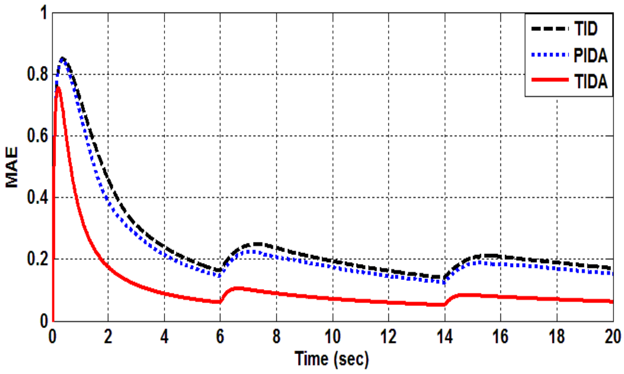

Fig. 8. MAE of DC Servomotor response (Task 3)

The step response data including rise time, settling time, overshoot, and peak time are given in Table III for the proposed controller comparing to both PIDA and TID controllers. Table IV 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.

TABLE III
STEP RESPONSE INFORMATION OF DC SERVOMOTOR WITH ALL CONTROLLERS.

Controller	**Rise Time (s)**	**Settling Time (s)**	**Overshoot (%)**	**Peak Time (s)**
TID [27]	1.43	1.96	2.82	3.02
PIDA [10]	1.06	2.91	8.05	2.27
Proposed TIDA	**0.54**	**0.82**	**0.03**	**1.5**

V. Conclusion

This work proposes an efficient TIDA controller that combines the characteristics of TID controller and an accelerator term to address the transient response of the DC servomotor. First, the suggested controller is composed of the conventional TID controller plus an accelerator term. This combination has proven to be a reliable and efficient control technique for handling nonlinear dynamical systems. In addition, a systematic optimization technique based on GWO is proposed to minimize ITAE performance index of the proposed TIDA controller. The suggested control structure is used to regulate nonlinear DC Servomotor with a variety of tasks such as output tracking with reference change under different disturbances. The simulation results showed that the TIDA controller can regulate nonlinear systems with significantly better performance than other controllers. Three performance indices are measured for evaluating the performance of the proposed controller and it is indicated that the proposed TIDA controller has lower RMSE, ISE and IAE values. Future studies could include controlling additional complicated dynamical systems and implementing different optimization and adaptive techniques.

TABLE IV
RMSE, ISE, AND IAE FOR DC SERVOMOTOR.

Cases of Study	**RMSE**			**ISE**			**IAE**		
	TID [27]	**PIDA [10]**	**TIDA**	**TID [27]**	**PIDA [10]**	**TIDA**	**TID [27]**	**PIDA [10]**	**TIDA**
Task 1	0.2529	0.2362	**0.1573**	0.6277	0.5463	**0.2368**	0.9717	0.8707	**0.3549**
Task 2	0.2228	0.2057	**0.1385**	0.9816	0.8348	**0.3732**	2.2949	1.8990	**0.8866**
Task 3	0.3662	0.3420	**0.2256**	2.6679	2.3264	**1.0065**	3.3997	3.0470	**1.2420**

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