ISSN: 0067-2904

Automatic Tuning of the PID Controller Based on the Artificial Gorilla Troops Optimizer

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Received: 9/2/2023 Accepted: 28/4/2023 Published: 30/5/2024

Abstract:

Tuning a PID controller is a crucial task in control engineering to achieve optimal performance of the system. However, manual tuning of PID parameters can be inaccurate and difficult without extensive experience. One approach to tuning the PID controller is by utilizing heuristic algorithms. These algorithms are based on natural phenomena and can efficiently search for the optimal set of PID parameters. Therefore, utilizing met heuristic algorithms for tuning PID controllers can significantly improve the system's performance and reduce costs associated with manual tuning. In this paper, a new method for tuning parameters of the PID controller of DC motors using a hybrid adaptive PID_GTO predictive model based on the artificial gorilla troop optimizer algorithm (GTO) is proposed. The empirical results are compared based on four types of error indicator functions: integral time squared error (ITSE), integral time absolute error (ITAE), integral absolute error (IAE), and integral squared error (ISE), as well as with other previously published techniques in the literature, such as the Ziegler-Nichols and PSO Optimizer algorithms. The empirical results show that this method outperforms other techniques in improving steady-state error, stability, overshoot, rising time, and settling time of the DC motor.

Keywords: DC Motor, PID Controller, Heuristic Optimization, Gorilla Troops Optimization, Particle Swarm Optimization.

الضبط التلقائي لوحدة التحكم PID بناءاً على مُحسن قوات الغوريلا الاصطناعية

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الخلاصة:

تعتبر أدوات التحكم النسبي – المتكامل – المشتق (PID) من بين أكثر أنواع أجهزة التحكم الصناعية استعمالاً. تستعمل عادة لتنظيم سرعة الدوران لمحركات التيار المباشر (DC). تم تحسين إعدادات وحدات تحكم PID باستعمال طريقة تحسين قوات الغوريلا (GTO). على وجه الخصوص ، تساعد هذه الطريقة في تحديد وتحقيق القيم التناسبية والتكاملية والمشتقة المثلى لوحدة تحكم PID. تم إنشاء طريقة GTO واختبارها في MATLAB. لأي مجموعة من إعدادات PID ، ستحدد خوارزمية GTO خطأ مربع الوقت المتكامل (ITSE) ، وخطأ المربع المتكامل ، والخطأ المطلق المتكامل وإصدارات الخطأ المطلق للوقت المتكامل من PID_GTO المقترحة. بعد حساب ومقارنة الأنواع الأربعة من قيم الخطأ ، تم تحديد ITSE لتوفير أقل قيمة

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تكلفة ، وبالتالي ، سيكون معدل هذا الخطأ هو الأفضل بين الأنواع الأربعة. وبالتالي ، فإن منحنى أداء GTO مغلق قدر الإمكان إلى نقطة التحديد بأداء عالٍ مقارنة باستراتيجيات ضبط PID التقليدية ، مثل تقنية تحسين سرب الجسيمات وطريقة Ziegler–Nichols. تُظهر هذه الأساليب تحسينات كبيرة في عدد من المجالات الرئيسية ، بما في ذلك خطأ الحالة المستقرة ، واستقرار استجابة خطوة وحدة التحكم ، والتجاوز ، والوقت المتزايد ، ووقت الاستقرار.

1. **Introduction**:

PID controllers (proportional, integral, and derivative) are among the most commonly used types of industrial controllers. Although modern controllers, such as the fuzzy controller, have been developed, PID controllers are still extensively used [1]. The current error is calculated using the proportional value. The sum of errors is used for the integral value. The derivative value is used to compute the response on the basis of the error's rate of change. To enter a regulated system, the total weight of these three operations is utilized [2]. Intelligent methodologies, such as those based on genetic algorithms and particle swarm optimization, have been proposed to improve PID tuning beyond the capabilities of conventional PID parameter tuning methods. With the development of computational methods in recent years, optimization techniques have been frequently presented to modify the control parameters and thus achieve optimum performance [3].

PID controllers are commonly used to regulate the rotational speed of direct current (DC) motors. A PID controller is widely acknowledged as the de facto standard approach for a wide variety of nonlinear control systems. However, PID controllers have a number of drawbacks, such as the aforementioned unwanted overshoot, slow operation due to rapid changes in load torque, and the sensitivity of parameters K_i and K_p to controller gains. The correctness of a model and the parameters of a control system are also critical for the success of a PID controller. Fuzzy logic control, genetic algorithms (GA), and particle swarm optimization (PSO) are among the most popular soft computing and artificial intelligence techniques used to regulate DC motor speed and mitigate the effects of the aforementioned drawbacks on traditional PID controllers [4] and [5].

The increasing popularity and practicality of DC machines can be attributed to their numerous desirable characteristics, such as high start torque, rapid response, portability, and compatibility with a wide range of control tuning approaches. DC motors have recently found widespread usage in a wide range of control applications, including robotics, electric vehicle applications, disk drives, machine tools, and servo valve actuators. A DC motor may operate at a variety of speeds by altering the terminal voltage [6]. A dynamic model of any system is necessary for constructing an appropriate controller to deliver the desired responses without compromising system stability. In this regard, precise values are necessary for all system parameters. If a data sheet that details relevant system parameters is available, then such information may be utilized to build a model of a system [7].

In the previous decade and in cited articles, a resurgence of interest in these controllers has been observed amongst academics and professionals in the field. Automatic tuning advancements and expanded model predictive control applications have made this situation feasible [8]. Conventional methods for tuning the PID controllers of nonlinear independently excited DC motor systems have been presented, and scheduling for PID tuning parameters that employs the gorilla troop optimization (GTO) technique for DC motor speed control is provided. As a cutting-edge intelligent optimization approach, we suggest using a GTO-based method to fine-tune the settings of a PID controller [9].

2. Related Work

A PID controller is a common control mechanism, and its success as a controller is determined by how well its parameters are tuned, combined, and collocated. The Ziegler-Nichols (Z-N) tuning approach for PID parameters was proposed by Ziegler and Nichols in 1942 [10] after analyzing how the PID tuning parameters of a first-order inertial pure lag link were optimized. Since then, experts worldwide have refined the Z-N tuning method while proposing a plethora of novel tuning techniques, including the Cohn-Coon tuning method, the relay feedback tuning technique [11], and the refined Z-N tuning technique for PID parameters in internal mode [12].

Considering the advances in industrial control technology and the proliferation of power electronic devices, tuning PID parameters for maximum performance may be difficult when the object under control exhibits a time delay or other nonlinear properties. Many researchers use swarm intelligence algorithms to fine-tune the PID parameters of complex control objects in a variety of contexts.

In 1994, a fuzzy logic approach was used to generate the rules for PID controllers [13]. A fuzzy PID controller was designed [14]. In 1997, the authors of [15] tested the viability of their GA-based PID parameter tuning strategy in a simulated environment to ensure its efficacy. With regard to the self-tuning of a PID controller's parameter, the authors of [16] used an immune information processing technique in 2013 to fine-tune PSO and address the issue of algorithm prematurity [17].

In 2011 [18], a PID neural network controller was developed by applying a training method to a neural network to fine-tune PID parameters. Conventional engineering applications of a PID controller are shown in Figure 1, which is a block diagram of a control system. Three basic parts comprise this system: a PID controller, an actuator, and the object being controlled. The linear control function of deviation combines the proportional, integral, and differential controllers in a linear manner to form a linear controller. To finalize the control of the controlled object, the output of the control function is applied to the actuator by entering the current deviation computation.

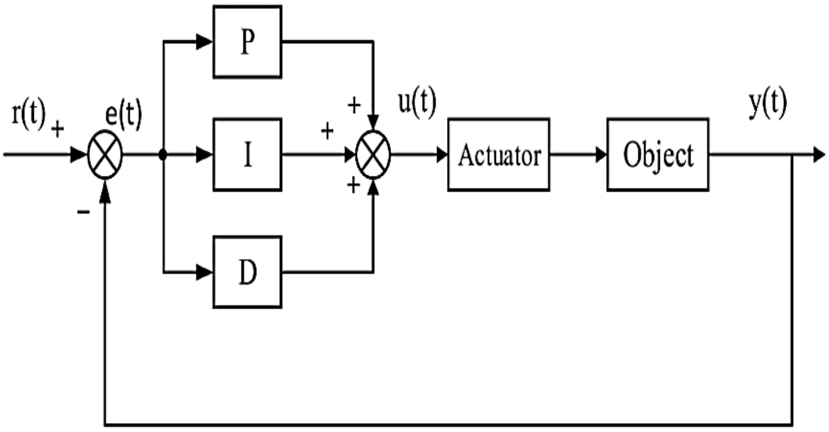


Figure 1: Diagram of a PID controller [19].

In Figure 1, the intended input r(t), the actual output is y(t), the difference between the two is e(t), and the output controlled by the controller is u(t). The integrator time constant (I) and the differentiator time constant (D) are related to the proportionality constant (P).

3. Fundamentals of DC Motors

A DC motor is a type of rotary machine that can transform mechanical energy into DC electricity. A standard DC motor has three major components: a rotor (armature), a stator (magnetic pole), and a reversing mechanism [8]. The rotor of a DC motor spins due to the influence of electromagnetism. Given their low power requirements, broad speed range, and lightning-fast reaction, DC motors are increasingly being used in practical applications. DC motors are ubiquitous. They are found in a variety of objects, ranging from toys and equipment to electric cars. In accordance with [20], the transfer function is G_v(s). The formula for converting DC motor voltage into rotational speed is

$$G_v(s) = \frac{1/K_e}{(t_m s + 1)\,(t_e s + 1),} \tag{1}$$

where $\mathrm{K_e}$ stands for the constant coefficient, $\mathrm{t_m}$ for the mechanical time constant, and $\mathrm{t_e}$ for the electric time constant. The transfer function in (1) may be written more simply because $\mathrm{t_e}$ is substantially smaller than $\mathrm{t_m}$.

$$G_v(s) \approx \frac{1/K_e}{(t_m s + 1)} \tag{2}$$

The transfer function in (2) is a first-order system with two parameters. The following second-order transfer function describes the behavior observed between armature voltage and rotational position [21]:

$$G_p(s) \approx \frac{1/K_e}{s(t_m s + 1).} \tag{3}$$

The DC motor is controlled, and its voltage is applied by a distinct power source. Its voltage may be adjusted in a unique manner without affecting the field voltage. As shown in Figure (2), some useful relations are described in Equations 4–9.

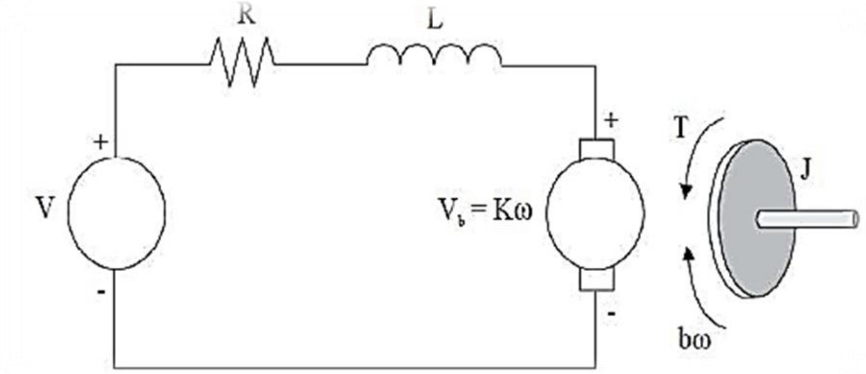


Figure 2: Structure of a DC motor[22].

$$V_a(t) = R_a R_i\,(t) + L_a\,\frac{dia(t)}{dt} + V_B(t) \tag{4}$$

$$V_B(t) = K_b w(t) \tag{5}$$

$$T(t) = K_i i_a(t) \tag{6}$$

$$T(t) = T_m(t) - T_i(t) = J_m \frac{dw(t)}{dt} + B_m w(t) \tag{7}$$

where L is the armature inductance, R is the armature resistance, V(t) is the applied armature voltage, and w(t) is the motor angular velocity. The transfer function for the DC motor utilized in the current study may be derived by putting known values into the equations, taking the Laplace transform of the equations, and then writing the result in input/output form [23].

$$G(s) = \frac{w(s)}{V_a(s)} = \frac{K_t}{L_a J_m S^2 + (R_a J_m + L_a B_m)S + (R_a B_m + K_b K_{mt})} \tag{8}$$

Several experimentally determined parameter settings are available for the DC developer, and some physical parameters for the DC motor are constant [24]. $\mathrm{Kt} = \mathrm{Kb}, \mathrm{R} = 1'\Omega, \mathrm{L} = 0.5\ \mathrm{H}, \mathrm{Kt} = \mathrm{Kb} = 0.01, \mathrm{Kf} = 0.1\ \mathrm{Nms}$ and $\mathrm{J} = 0.02\ \mathrm{kgm}^2/s^2$.
Given the values of a motor’s constants, the transfer function of a DC motor is

$$TF = G(s) = \frac{0.01}{0.005S^2 + 0.06S + 0.1} \tag{9}$$

4. Gorilla Troops Optimizer

This section presents the GTO metaheuristic algorithm, which is inspired by the social behavior of gorilla groups. It includes the detailed mathematical procedures for the exploration and exploitation stages. The GTO method uses five distinct operators to mimic exploration and exploitation in the context of optimization [25]. In the exploration phase, three distinct operators have been used, moving to an uncharted area to expand GTO exploration.

A more balanced allocation of exploration and exploitation is achieved through the inclusion of a second operator, which moves the gorillas closer to the center. Migration towards a known site, which is the third operator in the exploration phase, considerably improves GTO’s capacity to search for alternative optimization spaces. In the exploitation phase, however, we employ two operators, significantly improving search speed. When trying to find a solution, GTO typically applies numerous rules, including the ones listed below.

- When solving an optimization problem by using the GTO method, three alternative outcomes are considered: X (the gorillas’ position vector), GX (the gorilla candidates’ position vectors formed at each iteration and used if they outperform the present solution), and Z (the current solution; other possible solutions). Silverback has emerged as the best option after several iterations.
- Only one lone wolf out of the entire population of search agents is selected for optimization.
- X, GX and silverback are all viable options for simulating the social lives of wild gorillas.
- Gorillas may fortify themselves in one of two ways: by increasing their food supply or by improving their status within a large and stable society.
- The GTO algorithm generates a fresh set of solutions after each GX iteration. If the new option outperforms the current one (GX), then it will be adopted in its place (X). However, recollections will last a lifetime (GX).

- The social nature of gorillas makes having solitary lives impossible for them. Consequently, they have neither abandoned their communal foraging nor their system of rule by a single silverback. Given that the weakest gorilla in the group represents the worst solution in the population, we devise a strategy in which all the gorillas strive to distance themselves from the weakest gorilla and get closer to the best solution (the silverback), enhancing their own standings. Given the unique characteristics of GTO in many optimization issues, this technique can have wider applications if it is motivated by the core notions of gorilla group life when hunting for food and living in a community.

Algorithm 1: General GTO Algorithm Steps

```
1 Start
2 Initialize the population: Create a pool of potential answers to the problem by using random generation.
3 Evaluate the population: Compute the fitness of each solution in the population.
4 Select the best solutions: Select the best solutions from the population based on their fitness.
5 Generate new solutions: Generate new solutions by combining the best solutions from the previous step.
6 Evaluate the new solutions: Calculate the fitness of the new solutions.
7 Select the best solutions: Select the best solutions from the population based on their fitness.
8 Repeat Steps 5–7 until a termination condition is met.
9 End
```

5. Proposed PID_GTO Controller

The suggested system employs a PID_GTO controller to focus on the best values for the DC motor’s speed-regulating variables. The best PID control block design for a DC motor is shown in Figure 3. Each particle in the proposed GTO technique is composed of subatomic particles I, P, and D. This condition necessitates the existence of a 3D search space and the requirement that the population "walk" in this space. The signal flow diagram for a PID_GTO controller is shown in Figure 4. The selection of PID parameters is modeled as a search space problem that has to be solved. Consequently, metaheuristic algorithms may be used to fine-tune the search space and locate highly linked parameter vectors. Examples of cases wherein the suggested technique was utilized to fine-tune PID settings Given that the values of the control unit were chosen randomly within a certain range between zero and ten, these values within the range are worked on repeatedly until the required values that make the motor current stable are obtained. To achieve a faster speed than the starting speed of the motor, the rated values of the motor voltage and current are set using PID_GTO.

To maximize the domain constraints or reduce the preference constraints, the cost function for the optimization procedure is selected accordingly. The output speeds must be at their specified points so that we can count on accurate measurements as much as possible. Therefore, the error must be as small as possible, and no fluctuations must occur in the speed of the system once the required speed is reached.

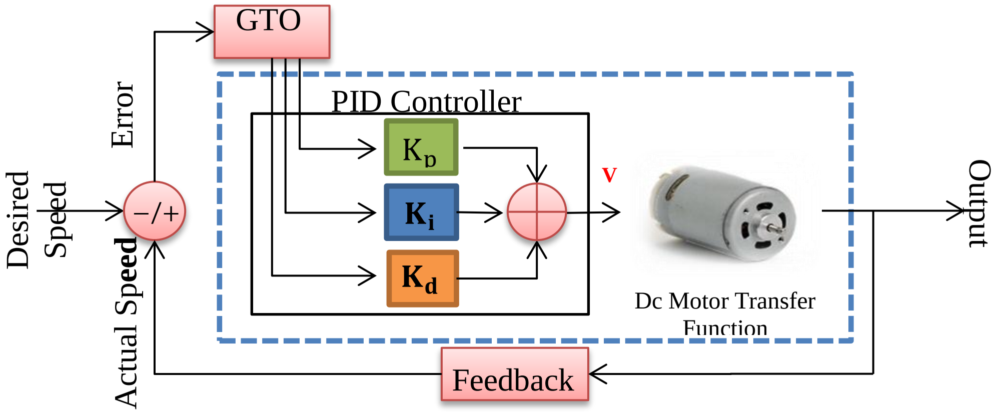


Figure 3: Optimal PID control of a DC motor presented as a block diagram.

The block diagram in Figure 3 shows that the DC motor is the system that we want to control. To achieve the desired controlled variable, the goal of any control system is to determine how to generate the corresponding actuation (desired speed; output speed). To ensure that the speed of the DC system is stable, feedback control must compare the actual speed to the target speed at which the system is operating. The controller's job is to consider the error term and translate it into instructions for the actuators, such that the error may be gradually reduced to zero. In summary, desired speed indicates what we want the system to accomplish, while error time means that we intend to minimize the error to zero. The proposed system compares the experimental results with those of other techniques, namely, Z-N and PID_PSO, by using four types of error evaluation indicators: integral absolute error (IAE), integral time absolute error (ITAE), integral square error (ISE), and integral time square error (ITSE), which are described in Equations 10–13, respectively. The PID controller indicates how we drive the error to zero over time by using the GTO technique. V is the actuating signal, which indicates how we generate V to obtain the controlled variable. Figure (4) shows the general scheme of the algorithm's process, wherein the best values for the parameters of the control units are generated and entered into the transfer function of the DC motor.

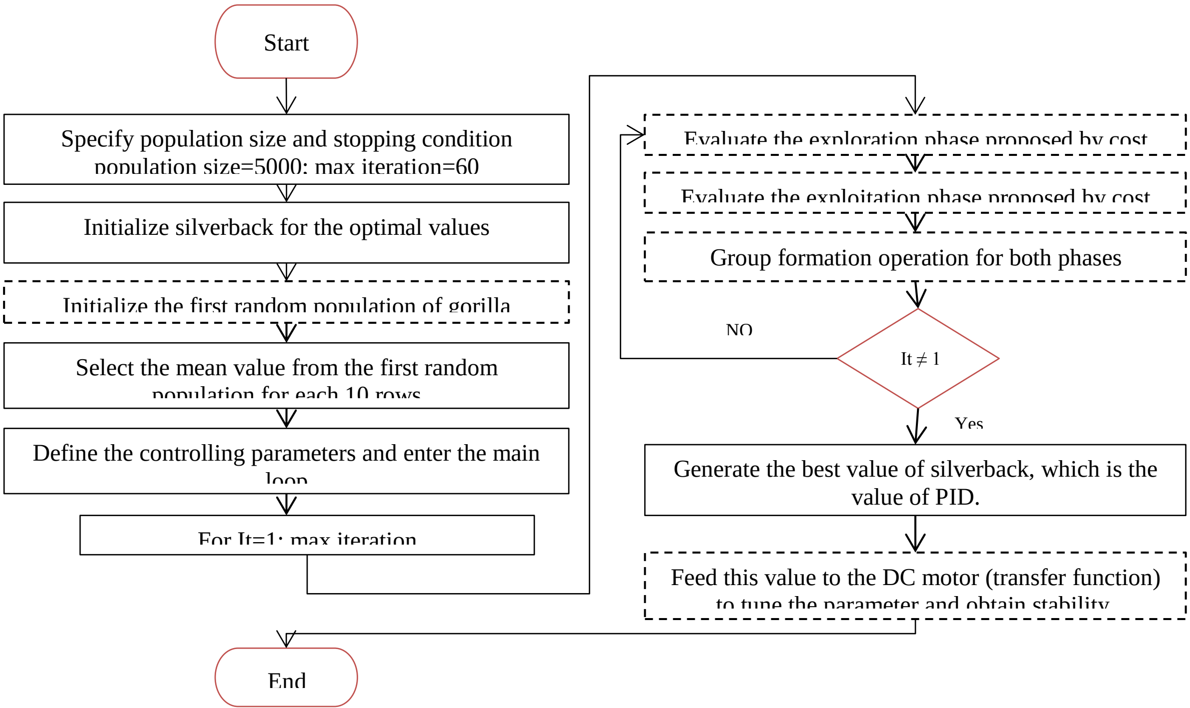


Figure 4: Flowchart of GTO for the optimization process.

6. Result and Discussion

The best values of PID can be obtained using GTO, wherein all possible values of the control parameters are used to reduce the target or cost function. Possible values are the values that appear in the results of the control units, which are overshoot, rising time, settling time, and steady-state error in this case. In the current study, we must generate an objective function to obtain the best values for the PID controller. To determine the PID controller with the least overshoot, shortest rising time, or fastest setting time, the PID_GTO function is developed. The goal function is iterated through the whole population of silverbacks, one by one. A silverback is then given a fitness rating, with a higher rating indicating better fitness. The optimizer for the gorilla troop considers the silverback's fitness value and utilizes it to generate a new population of the healthiest individuals. Each silverback has three strings: a P-term, an I-term, and a D-term, as declared by the three-row boundaries used during population construction.

For a PID_GTO-controlled system, the output may be represented by four indices: ISE, IAE, ITSE, and ITAE. The objective function will use the performance indicators given in Equations 10–13, respectively.

$$ISE = \int_0^\infty e(t)^2 \, dt \tag{10}$$

$$IAE = \int_0^\infty |e(t)| \, dt \tag{11}$$

$$ITSE = \int_0^\infty t \times e(t)^2 \, dt \tag{12}$$

$$ITAE = \int_0^\infty t \times |e(t)| \, dt \tag{13}$$

This feature of a PID controller design guarantees that the predicted controller settings produce a stable closed-loop system. The developed Simulink model is linked to the MATLAB code that implements the GTO-PID controller system. The suggested procedure is performed on a 2.4 GHz 8 GB RAM Intel ® Core TM i5-4700HQ computer that is running the MATLAB environment. General and specialized parameters are summarized in Table 1.

Table 1: Parameter setting

Elements	Value
Number of search parameters	3
Number of iterations	60
Dimension	5000
Domain search	0 – 10
B	3
W	0.8
P	0.03

Table (2) presents the parameter values of the PID controller that were obtained during the implementation period of the software part of each method. For the proposed system, the parameter values for each performance evaluation equation were extracted using the equation for each evaluation coefficient, i.e., (10), (11), (12), and (13). Table 3 presents the response step that we obtain when designing the emulator using Simulink, which is shown in Figure 8 as a model of how this emulator works. This model provided better results with respect to overshoot, settling time, rising time, and peak value compared with other methods.

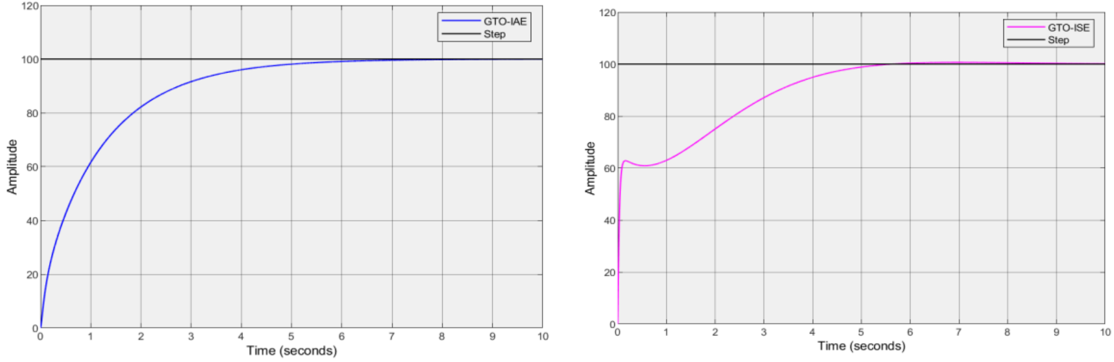
Table 2: PID parameter setting values

Method	P	I	D
ZN_PID	98.9	200	12.3
PSO_PID	600	200	18.9
GTO_PID ISE	10	10	10
GTO_PID IAE	7	9	1
GTO_PID ITSE	10	22	0.5
GTO_PID ITAE	10	12	1

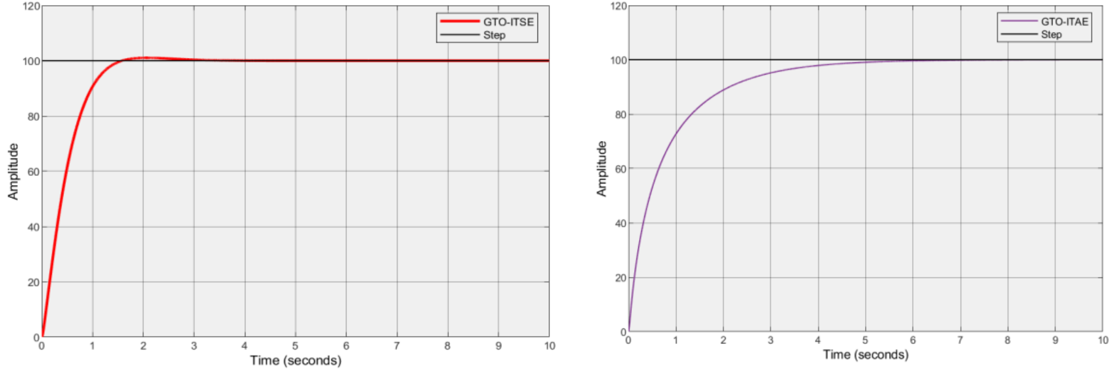
Table 3: Response step for the methods compared with the proposed system.

Method	Overshoot	Setting time	Rising time	Peak value
ZN_PID	12.5%	0.91 s	0.04 s	1.12
PSO_PID	26.6%	0.204 s	0.028 s	1.27
GTO_PID ISE	0.647%	4.7 s	3.3 s	1.01
GTO_PID IAE	0%	4.92 s	2.7 s	0.998
GTO_PID ITSE	1.23%	0.57 s	0.37 s	1.01
GTO_PID ITAE	0%	4.07 s	2.07 s	0.999

In addition to the results mentioned in the previous tables 2 and 3, in which the comparison was based on the time scale or the time domain, Figure 4 shows the improvement path for all three system parameters on the basis of the evaluation equations for the error that is retrieved from the control unit to determine the extent of the improvement that occurred.



(a)IAE (b)ISE



(c)ITSE (d)ITAE

Figure 4: Comparison amongst (a) IAE, (b) ISE, (c) ITSE and (d) ITAE PID_GTO for system response.

Compared with ITAE, ISE, and IAE, the PID_GTO ITSE-tuned system performs the best. It achieves 1.23% overshoot, the fastest settling time (0.57s), the rising time (0.37s), and the highest peak value (1.01). Figure (5) shows the step response in a closed loop for each tuning strategy.

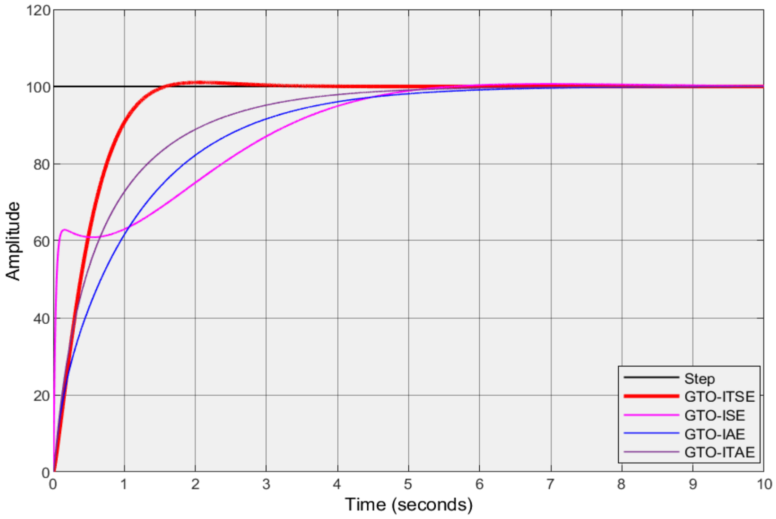


Figure 5: Analyzing the discrepancy amongst IAE, ISE, ITSE and ITAE from the perspective of an indicator of

Responses

Figure (6) presents a comparison of the proposed system GTO_PID with other methods. The highest value that must be reached is 100, as shown in the field (amplitude) on the coordinate line. The red color indicates that the proposed system provides more stability without overshooting. For the identical examination of the DC motor transfer function, the PSO and Z-N approaches exhibit maximal overshoot and excessive oscillations.

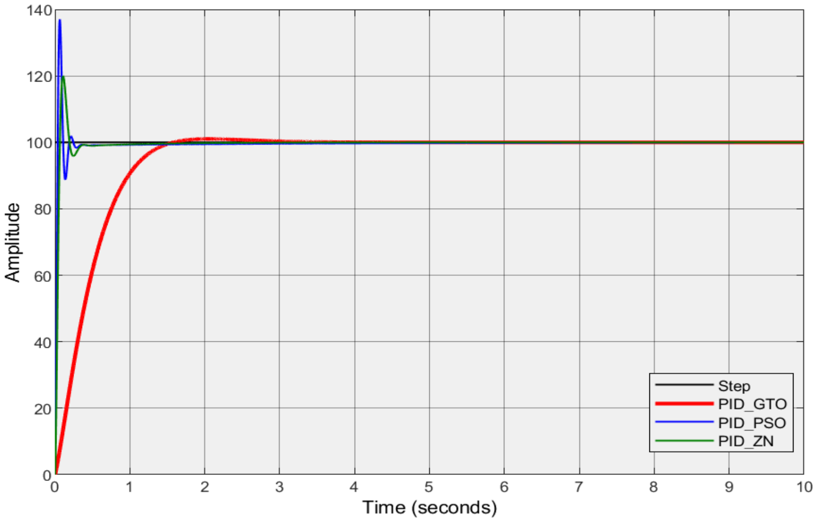
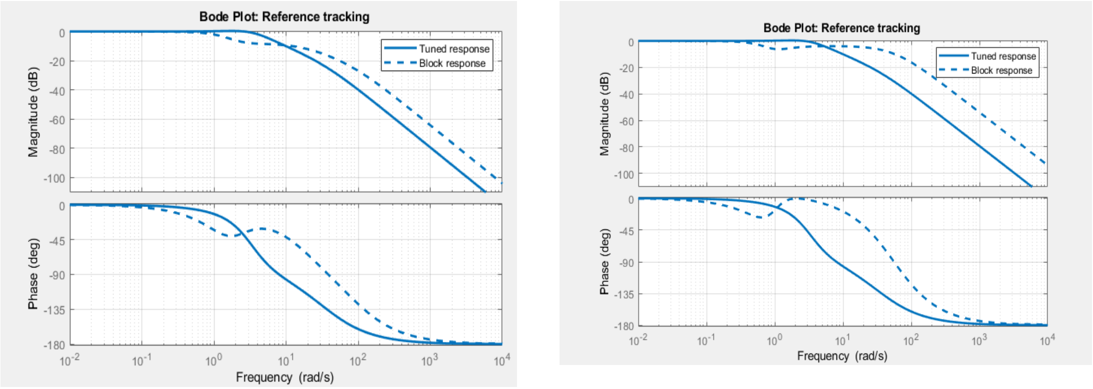


Figure 6: PID_GTO ITSE compared with other approaches in terms of response indicator.

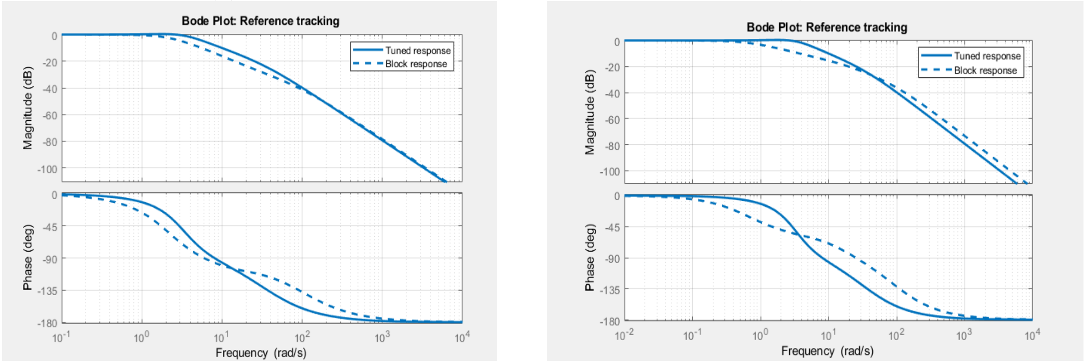
When the system is exposed to a step and load change, the proposed GTO_PID may also enhance design objectives such as gain margin, phase margin, and closed loop band width. Table (4) provides the values of phase and margin. Notably, the maximum value of phase = 82.6 and the minimum value of margin = 5 red/s are in the GTO_PID ITSE section, which represents the best frequency response for the system, similar to that in Figure (7). Figure (9) illustrates the good tracking of our proposed system.

Table 4: Phase and system gain.

Method	Phase	Gain
GTO_PID ISE	121	17.2 red/s
GTO_PID IAE	98.6	0.941 red/s
GTO_PID ITSE	82.6	5 red/s
GTO_PID ITAE	101	1.4 red/s



(a)IAE (b)ISE



(c)ITSE (d)ITAE

Figure 7: Comparison result of the phase and gain margin for frequency response by using PID_GTO with (a) IAE, (b) ISE, (c) ITSE and (d) ITAE.

Instability in supply voltages is only one of several variables that can exert a noticeable effect on the performance of a DC motor. To prove the activity of the proposed PID_GTO system, we monitored it while subjecting it to varying levels of supply voltage at various times, with sequence interpolation serving as the system's source, yielding a range of speeds that, in turn, allowed us to determine system performance. The results showed that the PID_GTO algorithm performs admirably as a control system, ensuring the fastest and most accurate responses. As shown in Figure (8), the GTO algorithm achieves the same level of efficiency regardless of the amount of work exerted.

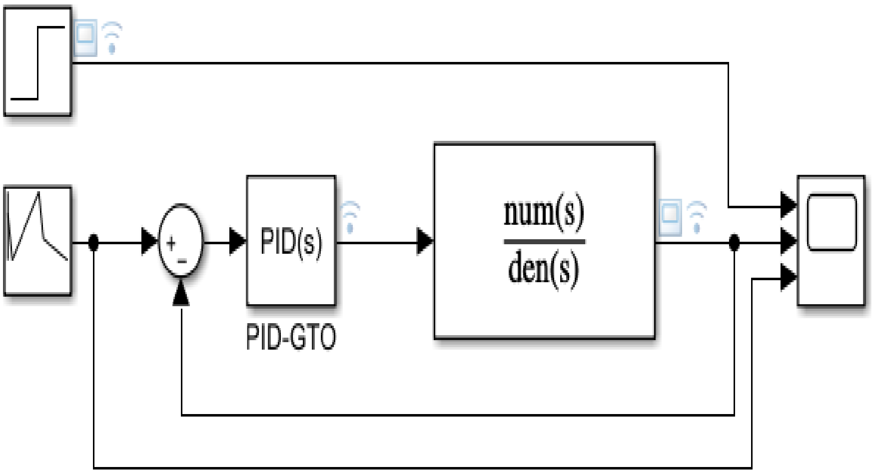
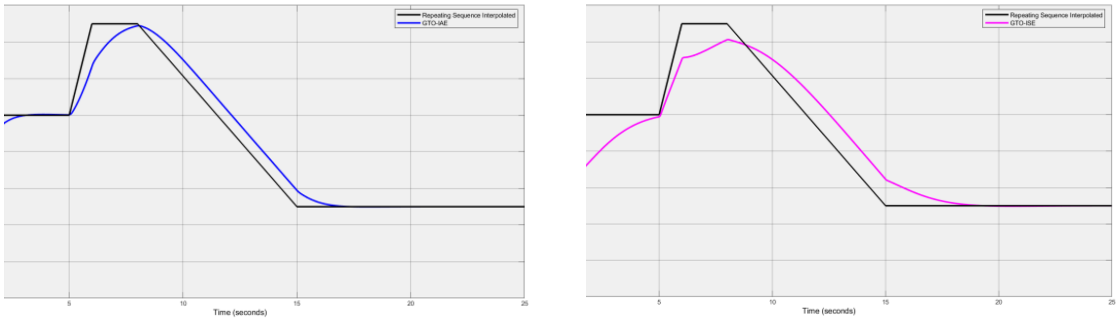


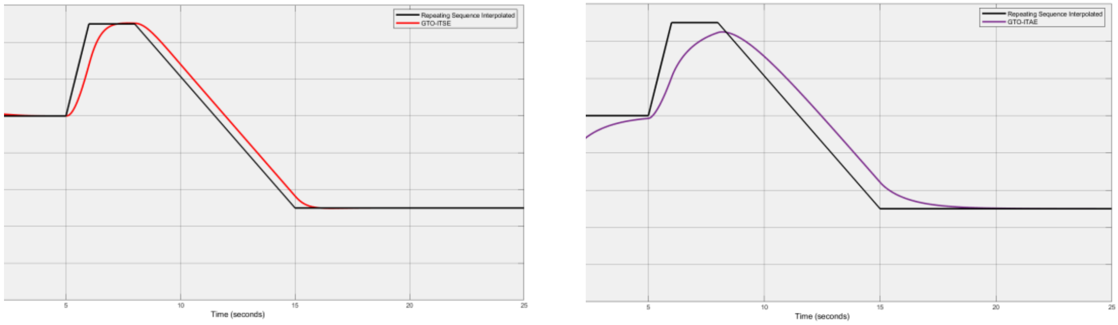
Figure 8: Basic architecture of the two-source PID_GTO controller.

Figure (9) illustrates how the cost function of the PID_GTO control system reacts to changing reference speeds. An accurate cost function is used to illustrate the capacity of the PID_GTO controller to monitor speed tracking with high accuracy based on the cost function. Numerous applications, including those involving DC motors, robots, and electric vehicles, are amenable to this type of testing.

Sample time =0.001
Vector of output value =[100,100,150,150,50,50].
Vector of time value = [0,1,5,8,15,25].



(a)IAE (b)ISE



(c)ITSE (d)ITAE

Sample time =0.001
Vector of output value =[100,100,150,150,50,50].
Vector of time value = [0,50,50.1,100,100.1,200].

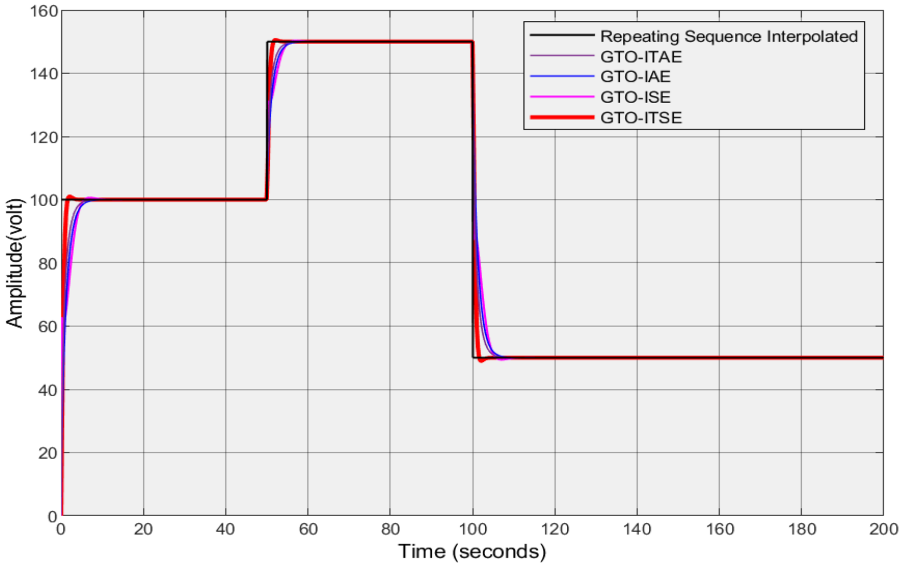


Figure 9: Good tracking of PID_GTO with IAE, ISE, ITSE and ITAE.

7. Conclusion:

Optimizing the settings of a PID controller by using the suggested system PID_GTO was proven to be better than using traditional PID or alternative tuning approaches, such as the PSO-based console or the Z-N tuning method. From our simulations, GTO can autonomously tune console settings without help. Using IAE, ISE, ITSE, and ITAE as performance response indicators, the proposed system outperformed four separate GTO releases. Through the use of parallel optimization parameter space, the system was able to provide optimal transient responses (rising time, stability time, decrease in settling time, and elimination of steady-state error).

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