LAUTECH Journal of Engineering and Technology 19 (2) 2025: 221-229

10.36108/laujet/5202.91.0232

Speed Control Enhancement of a Brushless Direct Current Motor using Transit Search Optimizer-based Proportional Integral Derivatives Controller

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Article Info

Article history:

Received: Mar. 02, 2025
Revised: Mar. 26, 2025
Accepted: Mar. 28, 2025

Keywords:

Transit Search Algorithm, Optimization, Exoplanet, Linear Quadratic Regulator, Proportional Integral Derivatives

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ABSTRACT

Brushless Direct Current (BLDC) motors are capable of achieving accurate speed control tailored to the requirements of various applications, making them suitable for devices that need high-precision motion management, such as robots and medical devices. However, most motors perform poorly as a result of commutation problems where the switching of current is controlled by an electronics speed controller (ESC) thereby causing variation in speed. Linear Quadratic Regulator (LQR) and Proportional Integral Derivatives (PID) controllers have been used to control the speed but with little expected result due to maximum overshoot which leads to system instability. This research aimed to control the Speed of a Brushless DC Motor using a Transit Search Optimizer (TSO) based PID controller. The dynamic mathematical model for the DC motor and PID controller was formulated. Then, the TSO-PID model for DC speed motor control was developed. Simulation of the developed model was done using MATLAB R2021a. The performance evaluation and comparison of the developed model with Simulated Annealing (SA) and Nelder Mead-PID (SA-NM-PID) using rise time, settling time, and percentage overshoot as metrics. The outcome of the results showed that the developed TSO-PID outperformed other conventional methods in terms of rise time, settling time, and percentage overshoot. The application of this work can be considered for domestic and industrial control of drives.

INTRODUCTION

An electric motor transforms electrical energy into mechanical motion and is classified into Direct Current (DC) motors and Alternating Current (AC) motors. DC motors require accurate speed regulation, making them more significant than AC motors. They have been utilized in industrial control applications for many years due to their excellent starting torque characteristics, rapid response performance, and straightforward implementation. Most of these motors are typically used in the delivery of linear or rotary motion to various electromechanical devices and servo systems. DC motors exhibit strong control responsively and a broad speed control range, making them prevalent in systems that demand high precision, such as rolling mills, double-hulled tankers, and high-precision digital tools, among others. In industrial applications, DC motors are extensively used in robotic manipulators, electric cranes, electric vehicles, and disk drives because their control mechanisms are relatively uncomplicated and they perform reliably across diverse operating conditions (Saranya and Pamela, 2012; Tripathi *et al*., 2016; Abba *et al*., 2022).

The Proportional Integral Derivative (PID) controller is widely recognized as one of the most frequently utilized control systems in industrial power distribution networks, thanks to its straightforward algorithm capable of delivering satisfactory performance across a broad range of processes (Grebennikov *et al*., 2022). PID controllers are the most favored type of control system in industrial settings. Their popularity stems from their simplicity, efficiency, and the ease with which control actions can be understood, as well as the realization of digital PID versions that have been employed in industrial process applications for many years (Agnihotri *et al*., 2018; Kushwah and Patra, 2014; Purnama *et al*., 2019; Sabir and Khan, 2014; El-Deen *et al*., 2015).

However, they do have drawbacks, such as inappropriate speed overshoot, and sluggish reaction to unexpected changes in load torque, which make it more sensitive to variations in controller gains. There are three parameters that when designing a PID controller can be adjusted and they are: Proportional gain (KP), Integral gain (Ki), and Derivative gain (Kd). The tuning of these parameters is based on the delays and instabilities introduced by the networked system, which ensures a safety margin concerning phase and gain margins (Abba *et al*., 2022). For optimal controller operation, the primary objective was to reduce the steady-state error, rise time, overshoot, and settling time. The effectiveness of the controller relied on the precision of the system design parameters (Kushwah and Patra, 2014; Mirzaei and Moattar, 2015; Purnama *et al*., 2019). Classical techniques or Metaheuristic techniques are the two main methods commonly used for PID tuning (Shaista *et al*., 2018). When PID controllers are implemented in communication networks, tuning their parameters can be challenging with classical methods due to the delays introduced by the network.

Numerous PID tuning methods for first-order-plus-delay-time systems have been proposed over the years. Among these methods are Ziegler-Nichols, Cohen-Coon, constant open loop transfers function, synthesis, and internal model controller (Kadua and Patil, 2016; Anusha, 2017).

Over time, a diverse array of metaheuristic algorithms has been created, and numerous metaheuristics are gaining popularity (Yang, 2011). These techniques have been utilized in control systems, with results indicating a considerable improvement compared to traditional methods (Rajpoot *et al*., 2021; Mohammed *et al*., 2021; Sabir and Khan 2014; El-Deen *et al*., 2015; Olympia, 2013; Agnihotri *et al*., 2018; Asif, 2019; Ashraf *et al*., 2022). Transit Search (TS) is an optimization strategy developed from a well-known exoplanet detection method. Based on data gathered from space telescopes, over three thousand eight hundred (3,800) planets have been identified using the transit technique.

The transit search method has demonstrated greater effectiveness than the second widely recognized method (radial velocity), which has resulted in the discovery of 915 planets. Detecting planets can be challenging due to their small size on a cosmic scale. Given the high effectiveness of the transit technique in astrophysics and its potential, it has been adapted to create an optimization technique for this research (Ahmed 2024). In this study, a method that integrates the Transit Search Optimization technique with PID (TSO PID) controllers will be utilized for controlling DC motors. The primary objective of implementing the TSO-PID controller for a DC motor is to provide an effective, robust, progressive, distinctive, and straightforward framework for analyzing and synthesizing control for optimal system performance, thanks to the simplicity and enhanced effectiveness of the TSO-based tuning method. The TSO-PID tuning approach offers the advantage of allowing a clear trade-off between closed-loop performance and robustness against model uncertainties with just a single user-defined tuning parameter.

REVIEW OF RELATED WORK

This section deduced the review of related works about the optimal tuning of the proportional integral derivative controller for the speed control of the direct current motor using the TSO-PID controller.

Mustafa *et al*., 2024 work on the algorithm-based multilevel inverter optimizer using the gold rush and dandelion optimizers, as well as their application in power control systems. The outcome provides insight into how to apply intelligent optimization algorithms to multilayer inverters (MLIs) to minimize total harmonic distortion (THD) and produce optimal switching angles. However, the main drawback of this strategy is that it is selective.

Mohamed *et al*., 2024, in their work Development of Automatic Voltage Regulator (AVR) controller performances using exponential distribution and transit search optimization techniques. The result of this approach shows that the Integrated Square Error (ISE) is minimized and it also minimizes the error voltage for improved stability and response but the limitation to this is that this particular method is not applied to all the multi-area power systems to prove their efficiency.

Choon *et al*., 2023, worked on the Development of an optimized travel route system for Tourist Transit Optimized. The result shows that the operational cost is minimized and the efficiency maximized in the highly competitive travel and tourism industry. However, understanding the local area and its topology, as the basics of operations management and optimization algorithms is very important to know and is limited.

Gang *et al*., 2023, worked on an adaptive hybrid dandelion optimizer for engineering optimization with the Application of combined three strategies of adaptive tent chaotic mapping. The result shows that the Differential evolution (DE) strategy and adaptive t-distribution perturbation address the shortcomings of weak DO development. However, the Application of combined three strategies of adaptive tent chaotic mapping, differential evolution (DE) strategy, and adaptive t-distribution perturbation to address the shortcomings of weak DO development was minimal.

Masoomeh *et al*., 2022, in their paper Transit search: an exoplanet exploration-based optimization technique. He applied the Transit Search (TS) optimization algorithm, which is based on exoplanet exploration, a meta-heuristic optimization technique. When compared to other effective algorithms, the results showed that the suggested algorithm's overall average error for the benchmark problems was the lowest. However, a number of factors, including the problem's size, acceptable time, number of constraints, and type of constraints, must be implemented. While these methods do not ensure that the optimal answer will be found, they do lead to control.

METHODOLOGY

Model Description

DC motors are used to generate rotational speed and linear position control. Brushless Direct Current (BLDC) motors have speed control capability which implies that speed, torque, and direction of rotation can be controlled at any time to meet new conditions. In other to represent the DC motor mathematical model, the construction and working should be presented n similar and simpler than the DC motor system. Generally, the DC motor models are composed of two parts: electrical and mechanical equations. The electrical equation shows the main parameters, which are armature resistance (R_a) and inductance (L_a). On the other hand, the main parameter of the mechanical equation is the moment of inertia (J) and the friction coefficient (B_m) (Hassan *et al.*, 2017).

R_a :armature resistance

L_a : armature inductance

i_a :armature current

i_f :field current

v_a : input voltage

e_b : back electromotive force (e.m.f)

T_m : motor torque

θ : rotor angular speed

w : rotor angular velocity

J : moment of inertia

b : viscous friction coefficient of the motor

The armature voltage equation is given by (Ahmed *et al.*, 2020):

$$V_a = R_a l_a(t) + L_a \frac{dl_a(t)}{dt} + e_b(t) \qquad (1)$$

The equation for the back e.m.f. of the motor will be:

$$e_b = K_b W(t) \qquad (2)$$

$V_a(s)$ represents the input voltage to the DC motor armature control system while $w(s)$ representing the output angular velocity.

The Mathematical Design of Brushless Dc Motor

The Mechanical time constant of the DC motor is

$$\tau_{mech} = \frac{RJ}{K_S K_z} \qquad (3)$$

Electrical time constants

$$\tau_e = \frac{L}{R} \qquad (4)$$

For the BLDC motor, the constant takes the form

$$\tau_{mech} = \frac{RJ}{K_{(S)}K_{(z)}} = \frac{J\sum R}{K_S K_z} \qquad (5)$$

$$\tau_e = \sum \frac{L}{R} = \frac{L}{\sum R} \qquad (6)$$

Since there is a symbolical arrangement between mechanical and electrical time constant and also that the phase is three; It becomes equations 7 and 8

$$\tau_{mech} = \frac{J.3R}{K_{(S)}K_{(z)}} \qquad (7)$$

$$\tau_e = \frac{L}{3.R} \qquad (8)$$

Taking the phase effect into consideration

$$\tau_{mech} = \frac{3R\emptyset J}{\left(\frac{K_S(L-L)}{\sqrt{3}}\right)K_z} \qquad (9)$$

$$\tau_{mech} = \frac{3R\emptyset J}{K_{(S)}K_{(z)}} \qquad (10)$$

Ks is the phase valve of the e.m.f. constant

$$K_S = \frac{K_S(L-L)}{\sqrt{3}} \qquad (11)$$

Since there is a relationship between Ks and Kz, Eqn 10 and 11 therefore becomes:

$$\sqrt{3} \times E \times I = \frac{2\pi}{60} \times N \times \tau_s \qquad (12)$$

Where: K_P = Proportional gain, K_D = Derivative gain, K_I = Integral gain and $e(t)$ = Tracking error, U(s) and E(s) are the Laplace transforms of the control signal U(t) and the error signal e(t).

$$\frac{E}{N} = \frac{T}{\tau} \times \frac{2\pi \times I}{60 \times \sqrt{3}} \qquad (13)$$

$$K_S = K_z \times \frac{2\pi \times I}{60 \times \sqrt{3}} \qquad (14)$$

$$K_S = K_z \times 0.0605 \quad (15)$$

$K_S = \left[\frac{V-sec}{m_d}\right]$, is the electrical torque and

$K_t = \left[\frac{N-m}{A}\right]$ is the mechanical torque and considering the effects of the time constant and its phase, the BLDC equation can now be written as:

$$G(s) = \frac{1/K_S}{\tau_{mech}.\tau_e S^2 + \tau_{mech} S + 1} \quad (16)$$

The Mathematical Design of the PID Controller

The block diagram of the PID controller is shown in Figure 1 while its basic equation is shown in Equation (18). The variable represents the tracking error, which is the difference between the desired input value and the actual output.

$$U(t) = K_P e(t) + K_i \int_0^t e(t)\,dt + K_d \frac{de(t)}{dt} \quad (17)$$

$$G_{PID}(S) = \frac{U(s)}{E(s)} = K_p + \frac{k_i}{s} + K_d s \quad (18)$$

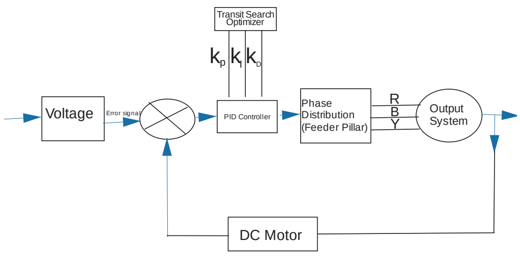

Figure 1: PID Controller

Tuning of PID Controller

PID controller has three principal effects, the proportional (P) action which gives a change in the input (manipulated variable) directly proportional to the control error, the integral (I) action which gives the change in the input that is proportional to the integrated error and its primary goal is to remove the offset point and the less frequently employed Derivative (D) action, which stabilizes the system or regulates the speed up response by providing an input change according to the derivative of the regulated error. The total of these three terms' contributions is the controller's overall output. In this research, the PID controller will be tuned using a transit search optimizer, a meta-heuristics optimization technique that is based on exoplanet exploration. In the design of a PID controller using meta-heuristic techniques for PID tuning, a cost function is required for error minimization (Bansal *et al.*, 2012). Integral absolute error (IAE), integral square error (ISE), integral time absolute error (ITAE), and integral time square error (ITSE) are the four most often utilized cost functions.

Transit Search Algorithm for Tuning PID Controller

The steps involved in the application of the TSO algorithm for the PID controller tuning are as follows:

Step 1: Initialize the TSO algorithm's parameter and decision variables, like the number of randomly generated search agents, the maximum number of iterations, upper and lower limits, and the number of independent runs.

Step 2. Enter the simulation parameters of the DC motor and define the fitness function using Equation 18

Step 3. Using the number of search agents, generate PID tuning parameters (and) at random. The galactic center is selected at random from the search space. Once this location has been established, locate the galaxy's habitable zones (life belt).

Step 4: Check the constraints limit during each iteration and update the solution within the lower and upper bound of the decision variables.

$$Obj = \left|1 - \frac{G_m(s) + G_{PID}(s)}{1 - G_m(s) + G_{PID}(s)}\right| \quad (19)$$

Where:

G_m And G_{PID} are the open-loop transfer functions

Subjected to the following constraints:

$0.0001 \leq K_p \leq 100$ (20)

$0.0001 \leq K_i \leq 100$ (21)

$0.0001 \leq K_d \leq 50$ (22)

$$X_{J+1} = \begin{cases} X_{J+1}, & X_{min} \leq X_{J+1} \leq X_{max} \\ X_{min}, & X_{J+1} < X_{min} \\ X_{max}, & X_{J+1} > X_{max} \end{cases} \quad (23)$$

Step 5. Store the best solution and modify this solution according to equation 23 based on the exploration and exploitation process by updating the parameter coefficients, T, r_1 *and* C_1 of the TSO algorithm.

$$X^{Current}_{Best,j+1} = \begin{cases} X^{new}_{Best,j+1} & if\ f(X^{new}_{Best,j+1}) < f(X^{Current}_{Best,j+1}) \\ X^{Current}_{Best,j+1} & Otherwise \end{cases} \quad (24)$$

Step 6. Check the boundary condition for size and location and update it according to equation 24.

$$X^{Current}_{O_{lr},Best} = \begin{cases} X^{new}_{O_{lr},Best} & if\ f(X^{new}_{O_{lr},Best}) < f(X^{Current}_{O_{lr},Best}) \\ X^{Current}_{O_{lr},Best} & Otherwise \end{cases} \quad (25)$$

$O_{lr} = 1,2,3, \ldots$ (26)

Step 7: After each iteration, compare the solutions; if the new solution had a minimum value of the goal function, it would replace the old solution; if not, it would be discarded, keeping the old answer as the best one.

Step 8: If termination criteria ($J > J_{max}$) are achieved, record the so far best solution, and increment the independent run of the algorithm for the new value of K_p, K_i and K_d.

Step 9: After a certain number of independent runs, select the best solution with a minimum fitness function value.

Step 10. Record the best solution and display the optimal value of $K_p K_i K_d$ and for PID tuning.

Step 11: Stop.

RESULTS AND DISCUSSION

The effectiveness of the TSO-PID controller for optimal DC motor speed control was assessed based on rise time, settling time, and percentage overshoot. The outcomes obtained are detailed, analyzed, and compared with Nelder-Mead-based PID (referred to as SA-NM-PID). The DC motor was simulated in the MATLAB R2021a environment using equations 1-8. Figure 2 illustrates the open loop step response of the DC motor, and Table 1 presents its performance metrics without a controller, including rise time, settling time, overshoot, and undershoot. From the open loop response of the DC motor, before the implementation of the tuned controller, it is evident that the motor required 38.26 seconds to ascend from a stationary position and reach its maximum value. This duration is excessive for a system that necessitates immediate responsiveness. In terms of settling time, the modeled DC motor took 68.60 seconds to stabilize, which could negatively impact a system that is sensitive to damping. The system exhibited zero percentage overshoot and undershoot.

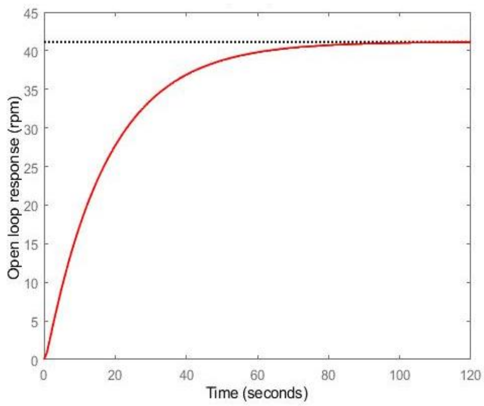

Figure 2: Open loop step response of DC motor without controller

Table 1: Step information of DC motor without controller

Performance metrics	Value

Rise Time	38.2458
Settling Time	68.6029
Overshoot	0

TSO-PID controller for DC motor speed control

The PID parameters, including Kp, Ki, and Kd were optimally adjusted using TSO to create the TSO-PID controller. The TSO-PID controller developed was employed to manage the speed of the DC motor, with the optimal PID parameter values recommended by TSO shown in Table 2. The system's closed-loop response when utilizing the TSO-PID controller for DC motor speed control is illustrated in Figure 3. The performance metrics of the DC motor with the TSO-PID controller, as presented in Table 3, indicated that the rise time decreased from 0.6641 seconds to 0.6457 seconds, representing a 98.30% reduction in rise time. Similarly, the settling time experienced a 98.53% decrease compared to when no controller was in use. Additionally, the system's percentage overshoot was determined to be zero, indicating that the developed controller did not negatively impact the system.

Table 2: Step information of DC motor with the

Performance metrics	Value
Rise Time (secs)	0.6491
% Rise Time Reduction	98.30
Settling Time (secs)	1.0060
% Settling Time Reduction	98.53
Percentage Overshoot	0

developed TSO-PID controller

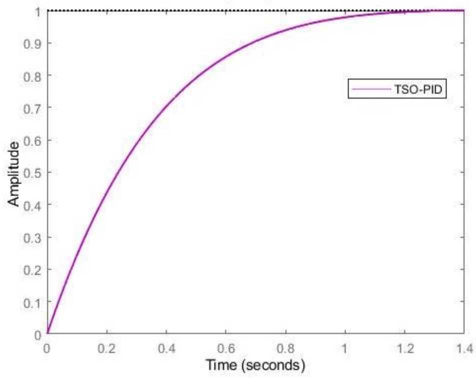

Figure 3: Closed Loop Step Response of DC Motor with TSO-PID Controller

Table: 3: Comparison of the performance of TSO-PID with classical methods

Methods	Rise time (secs)	Settling time (secs)	Overshoot (%)
SA-NM-PID	0.6641 (96.50%)	0.9999 (98.54%)	0.3773 (-0.38%)
TSO-PID	0.6457 (98.30%)	1.0185 (98.53%)	0

The performance of the TSO-PID controller in optimal speed control of the BLDC motor was evaluated in terms of rise time, setting time, and percentage overshoot. The results are presented, discussed, and compared with Simulated-Annealing and Nelder-Mead-based PID (i.e. SA-NM-PID). For rise time (secs) TSO-PID has a value of 0.6457 (98.30%) compared to SA-NM-PID with 0.6641 (96.50%) and for settling time (secs) TSO-PID has a value of 1.0185 (98.53%) compared to SA-NM-PID with 0.9999(98.54%) and the percentage overshoot as compared to TSO-PID was 0% and SA-NM-PID was 0.3773(-0.38%) respectively. The outcome of this study shows the best performance of the TSO in tuning the PID parameters for effective DC motor speed control. It can therefore be concluded that TSO can be used for optimal tuning of PID controller parameters for the speed control of DC motors.

CONCLUSION

This research carried out the optimal tuning of the PID controller's parameters using Transit Search Optimization (TSO) to control the speed of the DC motor so as to enhance optimum performance. The outcome of this study shows the best performance of the TSO in tuning the PID parameters for effective DC motor speed control. It can therefore be concluded that TSO can be used for optimal tuning of PID controller parameters for the speed control of DC motors.

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