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ICT Express xxx (xxxx) xxx

www.elsevier.com/locate/icte

A new fitness function for tuning parameters of Peripheral Integral Derivative Controllers

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Received 27 July 2021; received in revised form 27 September 2021; accepted 13 October 2021

Available online xxxx

Abstract

In recent years, the need for greater effectiveness and efficiency in industrial processes and procedures has made control system engineering a favored area of scientific investigation, especially the proper tuning of the parameters of Peripheral Integral Derivative (PID) Controllers. This paper critically examines some issues with the present fitness functions being used by different researchers involved in metaheuristic tuning of PID Controllers. It concludes with the introduction of a fitness function called the Inverse Integrated Squared Absolute Error whose experimental outcome using the African Buffalo Optimization algorithm was able to obtain zero (0) steady state error, zero (0) overshoot, 1.77 s rise time and 2.87 s steady time which is quite competitive. The paper opines that further appropriate investigations of the metaheuristic tuning of PID Controllers using this latest fitness function are highly recommended since it is very simple to both implement and use.

Keywords: Control systems engineering; Metaheuristic-tuning; PID Controllers; Fitness function; Inverse Integral Squared Error; Computational Intelligence

1. Introduction

The world is ever thinking of better ways of getting the existing technologies to function. The development of electric motors, feed forward technologies were received with excitement, the world over [1]. However, after a few years, researchers began working on feedback systems following a clamor for more effective, efficient and robust machines [2]. These research efforts led to the development of Proportional Integral Derivative (PID) and Proportional Integral Derivative (PID) Controllers [3,4]. Basically, PID is, simply, the abbreviation of Proportional, Integral, and Derivative. It is a three-step technique used in engineering and industrial procedures to bring a process to a previously agreed set-point, and further attempts to hold the set-point at the pre-set position. On the other hand, a PID Controller, as the name implies, is used to control the process with the aid of three variables/parameters, namely, the Proportional (P), the Integral (I), as well as the Derivative (D). Please note that these three variables/parameters can be tuned or weighted to assert their individual and collective effect on the engineering or industrial process.

In the past few decades, Proportional Integral Derivative (PID) Controllers have been gaining increasing popularity in control engineering worldwide. Application areas of PID Controllers include electric motors, process control, autonomous vehicles, flight control, instrumentation, Automatic Voltage Regulators [5] etc. Researchers have adduced several reasons for this phenomenal popularity of PID Controllers: simplicity, user-friendliness, effectiveness, wide-applicability and efficiency etc. Another outcome of the popularity of PID Controllers in industrial, engineering design and scientific environments is that it has awakened the researchers' interests in PID Controllers [6].

Most of the current research focus towards improving the tuning of PID components of Controllers is in evaluating the tuning techniques. In a previous work [1], there was an implementation comparing two tuning methods: Ziegler–Nichols and Iterative Method. In that study, much attention was concentrated on compensating the effect of delays in systems' stability of both methods. There are a few other efforts investigating the effectiveness and efficiency of different heuristic and meta-heuristic methods [7–9]. In this study, our

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Peer review under responsibility of The Korean Institute of Communications and Information Sciences (KICS).

https://doi.org/10.1016/j.icte.2021.10.006

2405-9595/

Please cite this article as: J.B. Odili, A. Noraziah and A.E. Babalola, A new fitness function for tuning parameters of Peripheral Integral Derivative Controllers, ICT Express (2021), https://doi.org/10.1016/j.icte.2021.10.006.

concern is the consideration of a new fitness function used in calculating the efficiency and effectiveness of the different metaheuristic techniques used in tuning the parameters of PID Controllers since there is a paucity of literature in this regard. This study introduces the novel fitness function: Inverse Integrated Squared Absolute Error to the body of existing fitness functions in parameter-tuning of PID controllers.

The rest of this paper is structured in the following way: section two presents the review of relevant literature; section three describes the proposed fitness function, section four presents the theory/calculations and section five discusses the results obtained while section six draws conclusions from the study.

2. Literature review

The popularity of PID among researchers could be as a result of the auto-tuning facility embedded in the design of most modern PID Controllers resulting in easy tuning by just any user: not necessarily expert users. Most auto-tuning techniques follow the Ziegler–Nichols Frequency Tuning Method (ZNFTM) that starts by first turning off the integral and derivative coefficients, then gradually increasing the values of the Proportional coefficient until the system reaches oscillating point. At this point, the tuner triggers off the Derivative component and then the Integral coefficient [10]. Available literature [11,12] indicate that the standard PID Equation is

$$G(s) = G(1 + \frac{1}{sTi} + sTd) \tag{1}$$

The other basic PID Controller has the following equation:

$$G(s) = G(Gp + \frac{Ki}{S} + sGd) \tag{2}$$

From Eq. (1), harmonizing the two prominent equations for a PID, we have:

$$\begin{aligned} GP &= G \\ Gi &= \frac{G}{Ti} \\ Gd &= GTd \end{aligned} \tag{3}$$

In each of the above equations, G denotes the Gain coefficient of the PID Controller parameters, the s represents the step function, p represents the proportional parameter, i, the integral parameter and d, the derivative parameter. In spite of the observable good results from the ZNFTM, experts agree that this tuning method cannot be applied to all industrial plants [13]. Moreover, adjusting the Proportional Controller until oscillation point (a necessary requirement in ZNFTM) is difficult to determine because oscillation point is dangerously close to instability point that could damage the entire power set-up [14]. To solve this problem, some experts recommend that the PID Controllers use a relay/sensor to set up an alarm signal [15].

In any case, in spite of any suggested modifications that can be done to the ZNFTM, the ZNFTM remains a manual method with the attendant human and mechanical errors leading to system' instability, hence the need for metaheuristic tuning. This situation led to the emergence of several metaheuristic tuning techniques of PID Controllers as opposed to the existing manual tuning. Some of the popular metaheuristic tuning techniques include PSO-Tuner, GA-Tuner and ACO-Tuner, PID-Tuner [16]. Recently a few more tuners have been developed; some of these are CS-Tuner, BFO-Tuner and ABO-PID [17,18]. In spite of the good results obtained with the use of metaheuristic tuning, the need for better results necessitated a deeper investigation that revealed some lapses with the existing fitness function leading to this present study.

Literature in meta-heuristic tuning of PID Controllers reveal that it has proven to be a more efficient and effective tuning technique, thus, providing more stability in power systems [19]. Moreover, metaheuristic tuning is simple, cost-effective and user-friendly. Another major characteristic of metaheuristic tuning is that, in general, it deploys any of the following fitness functions: the integrated absolute error (IAE):

$$\int_0^\infty |e|\, \Delta t \tag{4}$$

or the integrated of time-weighted-squared-error (ITSE):

$$\int_0^\infty te^2 \Delta t \tag{5}$$

or the integrated absolute squared error (IASE):

$$\int_0^\infty \left|e^2\right| \Delta t \tag{6}$$

where e denotes the error whether in absolute or real term; Δt denotes changes in time 't' as the integral process goes from zero to infinity. The use of any of the above fitness functions is simply because any of those fitness functions can be analytically evaluated in the time or frequency domains [20].

It is important to note that the three common integral performance evaluation criteria, otherwise called fitness function in the frequency domain have their individual merits and demerits. For instance, a major demerit of IASE is that though deploying this fitness function results in small overshoot, it takes such a long time to settle. A similar problem is associated with the IAE. This is because both fitness evaluation methods first embark on the measurement cum calculation of all existing errors before sending the feedback. On its part, the ITSE appears very effective in handling settling time issues of the ISE and the IAE but finds itself entangled in the Derivative coefficient where it embarks on the complex evaluation of the system's performance leading to the emergence of Steady State Errors [21].

Again, most metaheuristic tuning approaches require the introduction of search boundaries for the PID Controller in order to obtain good results [22]. To solve this problem, algorithm-users usually assign arbitrary values as the search minimum and extremum boundaries, resulting in further complication of the search process which sometimes leads to instability, especially in complex industrial plants.

3. Material and method

In the light of the above observations, it is expedient to propose a new performance indicator otherwise called fitness function that will take cognizance of the weaknesses of the existing methods. This study aims at this objective. It is our belief that with the right parameter-set for the Proportional, Integral and Derivative gains (Gp, Gi and Gd) respectively coupled with a more efficient performance criterion measurement such as the one being proposed, the control engineering in industries will be enhanced. In view of the observed weaknesses of the previous fitness functions, we propose the following as the performance indicator:

$$\int_0^{\infty} t \frac{1}{|e^2|} \Delta t \tag{7}$$

It is our belief that with the introduction of the integration of inverse of the squared error multiplied by the time-coefficient, the issues raised with the existing performance indices (fitness functions) will be addressed. In addition, this study will stimulate more research interests in fitness functions and control engineering, in general. To validate the effectiveness of the new fitness function being introduced in this study (see Eq. (7)), we tuned the peripheral, integral and derivative parameters of an Automatic Voltage Regulator.

3.1. African buffalo optimization methodology for tuning PID controllers

In tuning the parameters of PID Controllers, ABO chooses the objective function that is used to evaluate fitness of each buffalo. Some previous studies used performance locations of each individual in the herd as the objective functions [23]. Some other works used any of the established fitness functions: Integral of Absolute Magnitude of the Error (IAE), Integral of Time multiplied by Absolute Error (ITAE), Mean of the Squared Error (MSE) and the Integral of the Squared Error (ISE). In this study, we used the Inverse Integral Squared Error (ISE) to minimize the error signal E(s) and compare them to find the most suitable one.

In general, there are a number of variables that are used to measure systems performance in a PID Controller. Specifically, the systems' input step helps to evaluate the systems health. Similarly, the output signal characterized by a couple of standard performance measures, namely, rise time, percentage overshoot, error signal, settling time, peak time, and stability margin. These output signal performance measures are defined in the time domain which is the focus of this study.

Please note that the Percentage overshoot is defined as the point where the system response reaches its peak and then exceeds it as it tends to settle to a stable position. The Settling Time is measured as the time needed by systems to move from 0 to 100% of the final value. Similarly, the peak time refers to that point where the maximum value is reached as the search progresses. Finally, the error signal refers to the difference between the magnitude of input signal and the magnitude of system response. The error signal is obtained:

$$\mathrm{G(s)} = 1/\mathrm{s} + 1 \tag{8}$$

'*s*' here is the step function.

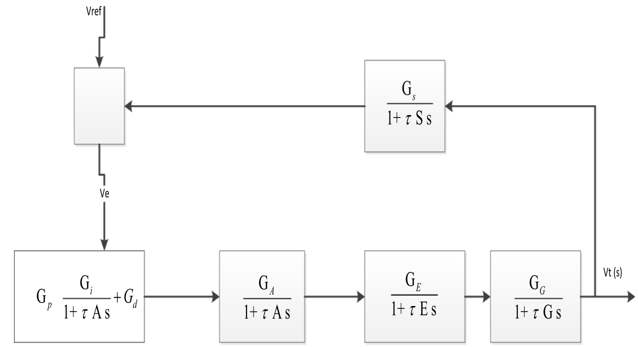

Fig. 1. Block diagram of ABO-PID for AVR.

4. Theory/calculation

The tuning technique of the ABO-PID using the new fitness function is:

1. Initialize the buffalo population within the solution space in sets of three buffalos per set. Set s which represents the step function as 2
2. Calculate each buffalo's exploitation fitness:

$$mk' - mk + lp1\,(bg - wk) + lp2\,(bp.k - wk) \tag{9}$$

$$wk' = \frac{wk + mk}{\gimel} \tag{10}$$

3. Calculate $Gp\ Gi\ and\ Gd$ for each set of buffalos using Eq. (1).
4. Plot the $Gp\ Gi\ and\ Gd$ into the PID transfer function using Eq. (2):
5. Identify the set of buffalos with the best outcome and set as bg with Eqs. (9) and (10)
6. Plot the values of x/y. If the output is 1 which represents the steady state, go to Step 7, else go back to Step 2
7. Plot the output into a MATLAB tool to determine the rise time, settling time, percentage overshoot and the steady state error.

In order to investigate the capacity of the proposed fitness function, the new fitness function was implemented in MATLAB using the African Buffalo Optimization algorithm. The experiments were performed using a PC with the following configurations: Intel Duo Core i3, 5005U at 2.00 GHz, 2.00 GHz, 4 GB RAM, WOS 10. The block diagram of the African Buffalo Optimization-PID (ABO-PID) for an Automatic Voltage Regulator (AVR) is presented in Fig. 1 and the outcome of this investigation is presented in Fig. 2.

5. Results

From earlier studies, the outcome of the proposed fitness function is impressive as it compares favorably with the established fitness functions for the tuning of Proportional Integral Derivatives of an Automatic Voltage Regulators (AVR). As can be seen in Fig. 2, the simulation output of the Parameter-tuning of PID Controller of an AVR using proposed fitness function

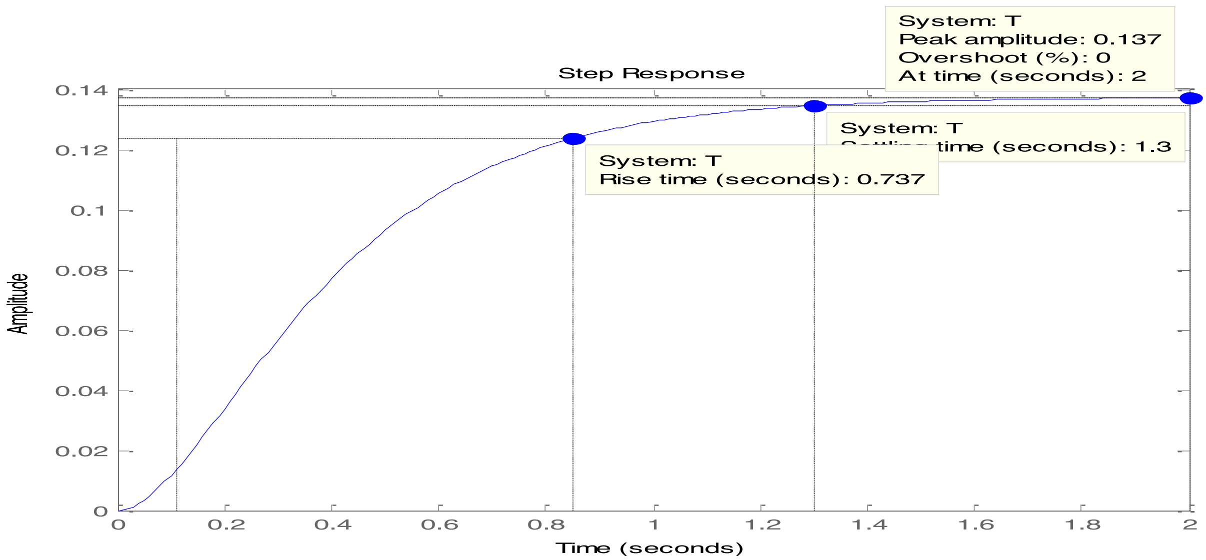

Fig. 2. Implementation simulation output of ABO-PID using the new fitness function.

Table 1
Comparative tuning results.

Gain overshoot (%)	Types of controller	PID parameters			Rise time	Settling time	Steady state error
		Gp	Gi	Gd	(s)	(s)	
0	**ABO-PID**	**3.007**	**1.0734**	**0.4304**	**1.77**	**2.85**	**0**
8.99	PID_PSO	0.6125	0.4197	0.2013	0.684	3.087	0.06
2.44	LQR-PID	1.0100	0.5000	0.1000	0.500	2.335	0.02
0	GA-PID	3.1563	0.9463	0.4930	0.493	8.900	0.005
0.487	ACO-PID	2.9917	1.1053	0.3085	0.493	7.100	0
0	PSO-PID	3.3172	0.8993	0.2814	0.4993	10.200	0.008
0.288	BFO-PID	3.0725	1.1054	0.2601	0.4993	6.800	0

produced a 0% gain overshoot and a Steady State Error of 0.137% which is quite competitive. Similarly, the rise time of 0.737 s is also good for an emerging fitness function. The same can be said of the settling time of 1.3 s,

The new fitness function was effective and efficient in producing competitive output (see the output of ABO-PID in Fig. 2 and Table 1) when compared with the results obtained from using the other fitness function as can be seen in Table 1. GA-PID produces good results using integral of the time weighted squared error; PSO-PID, integral of time multiplied by absolute-error value; LQR-PID, integrated of time-weighted-squared-error.

Comparing the output of the ABO-PID using the new approach with an earlier implementation using the popular fitness function in an earlier study [5] (see Table 1), visible improvements can be seen. For instance, while both shares 0% Gain Overshoot, the new approach produces a Steady State Error of 0.137% visa-a-vis the 0%, the new approach improved on the Rise Time (0.737 s as opposed to 1.77 s of the old approach).

Similarly, the new fitness function produced a Settling Time of 1.3 s while using the old approach, the settling time was achieved at 2.85 s. This is a mark of the efficiency of the new approach bearing in mind that the longer the system takes to settle the more computer resources are utilized leading to more time and greater economic costs to the end-users.

Furthermore, when the outcome of the new approach (See Fig. 2) is compared with the output of the other PID tuners, the new approach has an edge. While it takes the new approach just 0.737 s to settle, it took Bacteria Foraging Optimization-PID (BFO-PID), (6.800 s), Particle Swarm Optimization-PID (PSO-PID) (10.200 s), Ant Colony Optimization-PID (ACO-PID) (7.100 s) etc. The performances of Genetic Algorithm-PID (GA-PID) and Linear Quadratic Regulator-PID (LQR-PID) are below par. In view of the competitive results produced using the newly-introduced Inverse Integral Squared Error fitness function, it may be safe to conclude that this new approach is a worthy contribution to the existing literature on fitness functions.

6. Conclusion

This paper introduces a new fitness function to the parameter-tuning of PID Controllers called the Inverse Integral Squared Error. This study aims to improve on the existing fitness functions with the overall aim of designing a more efficient and effective fitness function for tuning parameters of control systems in robotics, electronic, mechatronics, mechanical and electrical engineering.

After a brief examination of the existing fitness functions, this paper examined the capacity of the newly-introduced

Inverse Integral Squared Error fitness function, the study concludes that the introduction of the emerging fitness function when fully developed holds a great promise for control systems engineering as it produces good result when implemented with the ABO. It is hoped that this introductory study will stimulate further research investigations into the proposed fitness function using other metaheuristics.

CRediT authorship contribution statement

Julius Beneoluchi Odili: Initiator of this research work, Implemented the new fitness function, Wrote the paper. **A. Noraziah:** Academic supervisor of the project. **Asegunloluwa Eunice Babalola:** Proof-read the manuscript, Formatted it to suit the journal requirement.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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