PID Parameter Tuning Using Modified BAT Algorithm

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***Abstract*—In this original work, we compare different optimization techniques and demonstrate the most favorable one for tuning PID parameters. This paper demonstrates effectively how to efficiently search for Optimal PID Controller Parameters for 3 different Plant functions using Bat Algorithm. Different types of optimization method are studied which are then compared with Ziegler-Nichols Algorithm. Our work shows that if parameters population and maximum iteration are kept constant, the proposed Bat-Ziegler-PID algorithm has the best performance criterion amongst different nature inspired meta-heuristic algorithms.**

***Index Terms*—PID controllers, Bat-Ziegler-PID, optimization, ACO, PSO, HAS, Z-N**

I. Introduction

PID is the most ubiquitous form of feedback in today's Industrial Control scheme. Digital PID controllers boast of more user friendly access along with additional features in attaining stability, which is one of the reasons for their popularity [1]. Bio inspired algorithms provide a ready remedy to solve Optimization problem occurring in our day to day lives[2]. In this paper, the performance of each described meta-heuristic method is evaluated and compared in order to observe the overshoot and undershoot and accuracy towards universal optimum and in turn compared with Ziegler-Nichols Algorithm. This optimization comparison throws new light on designing methods for engineering and Industrial Automation. The Bat Algorithm has several advantages over other meta-heuristic algorithm, such as faster convergence from exploration to exploitation. It provides easier solution to non-linear problems in far more efficient manner and faster than other algorithms [3]. Recently Optimization techniques have received much attention for achieving better efficiency and finding global optimal solution [4]. New methods, like Genetic algorithm (GA) [5], fuzzy logic [6] and Ant Colony Optimization Algorithm [7] are used for tuning PID controllers. In this work, we have successfully demonstrated the best optimization scheme for tuning the parameters of PID controllers.

II. PID Design

The transfer function of a PID controller is defined as

$$G_{PID}(s) = K_p + \frac{K_I}{s} + K_D{*}s \quad (1)$$

where K_P, K_I, and K_D are the proportional, integral and derivative gains respectively. As shown in Fig. 1, the K_P, K_I and K_D of the PID controller G_{PID} are generated by the Bat Algorithm for a given plant P(t).

The output Out (t) of the PID controller is

$$\text{Out}(t) = K_p{*}err(t) + K_I\int_0^t err(\delta)d\delta + K_D{*}err(t) \quad (2)$$

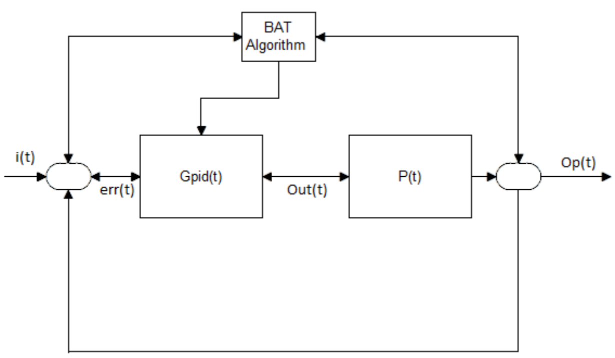

Figure 1. PID control system.

where, err(t) is the error between the output of the PID Control System op(t)and the reference input to the PID system i(t) at a particular moment of time t. The rest of

Manuscript received September 3, 2015; revised November 23, 2015.

doi: 10.18178/joace.4.5.347-352

the paper is divided into the following Parts: Section III describes the Bat Algorithm; Section IV describes Bat-Ziegler-PID Algorithm; Section V describes the Simulation and Section VI describes the Conclusions of our paper.

III. BAT ALGORITHM

Bat Algorithm is a meta-heuristic algorithm first presented by Xin She Yang which exploits the echolocation behavior of the Bats which they use to find their prey. There are around 1000 different species of bats and each bat has a different rate of emission of pulses and their respective pulse amplitude. The following are the approximations regarding bat behavior [8].

- All bats differentiate between food and obstacles via echolocation, and measure distance using the same mechanism.
- The i^{th} bat will fly with a velocity V_i at a position ρ_i and emits a frequency pulse F_i varying between F_{min} to F_{max}.
- The loudness of the bats (A_i) varies from Amplitude A_{max} when they start the hunt and reaches A_{min} as they near the prey. The range of the Amplitudes is [0, 1].
- The pulse emission rate R_i varies from a minimum of R_{min} to a maximum of R_{max}. The rate of pulse emissions increase as the bat nears its prey.

In these simulations virtual bats are utilized to demonstrate the application of BAT Algorithm and for i^{th} bat the following equations are followed [9]:

$$F_i=F_{min}+(F_{max}-F_{min})*\alpha \tag{3}$$

$$V_i^{t+1}=V_i^t+(\rho_i-\rho_{best})*F_i \tag{4}$$

$$\rho_i^t=\rho_i^{t-1}+V_i^t \tag{5}$$

here α is a random vector drawn from range [0,1]. ρ_i is the current solution of the i^{th} bat and ρ_{best} is the best solution for all bats across all iterations.

A local search is carried out if the rate of pulse emission by the i^{th} bat R_i is less than a randomly generated number, a new solution is generated for each bat via a Random Walk to improve the variability of the possible solutions [9]

$$\rho_{new}=\rho_{old}+eps*\text{mean}(A^t) \tag{6}$$

where mean(A^t) is the Mean of all the Amplitudes of pulses emitted by each bat at time step t and eps is the bat parameter utilized for random local search. The solutions ρ_{new} are accepted if the Amplitude A_i of the bat is more than a randomly generated number and ρ_{new} is better than ρ_{old}.The Amplitudes and the pulse emissions of the i^{th} bat are updated according to the formulae.

$$A_i^{t+1}=\theta*A_i^t \quad \text{and} \quad R_i^t=R_i^0\{1-\exp(-\gamma t)\}$$

where θ and γ are Bat Parameters in the range [0 1], θ is similar to the cooling factor in simulated annealing, $\theta=\gamma$ is chosen for simplicity [9].

IV. BAT-ZIEGLER-PID

A. Ziegler Nichols Method

Ziegler and Nichols gave a method to determine K_P, K_I, K_D for the PID Controller [10], which we utilize to minimize the search space. We must find K_P, K_I, K_D via Zeigler Nichols formulae and then try to find the optimum solution by developing a search space around these parameters . Elaborating on the above, we first determine critical gain K_c by keeping T_I =infinity and T_D=0.Then we increase the value of K_U (Proportional gain) slowly till oscillations are obtained for critical gain K_C and the time period T_U. Utilizing the formulae in Table I, we calculate T_I and T_D. K_I and K_D can then be calculated from K_P, T_I, T_D.

TABLE I. ZIEGLER-NICHOLS PARAMETERS

Name	Symbol	Value
loop gain	K_P	0.6 * K_C
integral time constant	T_I	0.5 * T_U
derivative time constant	T_D	0.125 * T_U

The Speed of the algorithm is inversely proportional to the bat population i.e. as the population increases, the speed decreases and vice versa.

B. Application to PID Problem

Optimum tuning parameters (K_P, K_I, K_D) can be found out via Bat Algorithm by a hybrid tuning technique where initial parameters are determined using the Ziegler Nichols Algorithm.

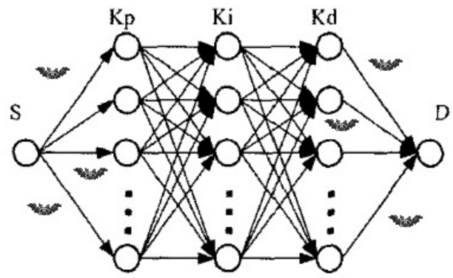

Figure 2. Bat tours

In this simulation as shown in Fig. 2 above, there are n nodes each of K_P, K_I, K_D, the Start node and the End node. The virtual bat starts from the Start node (S) and ends its tour at the End node (D). Each tour of the virtual Bat Represents a Cost Function (Performance Index) for a parameter set (K_P, K_I, K_D).

The initial population of Bats consists of m bats spread randomly over n nodes. Initialize the Amplitude (A_q), pulse rate (R_q), frequencies (F_q) and Velocities (V_q) for the q^{th} bat.

For q=1: m do the following steps

1. The Q^{th} bat moves randomly across the three parameters, making one tour.

2. Calculate the cost function of each of the Q^{th} bat of the population, which may be amongst IAE, ISE, ITAE and ITSE (Table II).

3. Compare each individual's cost value ρ_q with the existing ρ_{best} of the group

4. Modify the velocity of every Q^{th} bat according to the equations (7), (8), (9)

$$V_{q,P}^{t+1} = w*V_{q,P}^{t} + (\rho_q-\rho_{best})*F_q \quad (7)$$

$$V_{q,I}^{t+1} = w*V_{q,I}^{t} + (\rho_q-\rho_{best})*F_q \quad (8)$$

$$V_{q,D}^{t+1} = w*V_{q,D}^{t} + (\rho_q-\rho_{best})*F_q \quad (9)$$

here $V_{q,P}$, $V_{q,I}$, $V_{q,D}$ are the change in velocities of the Q^{th} bat at Proportional, Integral and Derivative PID controller parameters of the Q^{th} bat. The weight w is a random inertial weight, this weight is akin to the inertial weight used in Particle Swarm Optimization(PSO) [11] used to accelerate the search for the optimum tour and has the range $[W_{min}\ W_{max}]$.

5. Update the position of each Q^{th} bat with the equations (10), (11), (12).

$$K_{q,P}^{(t+1)} = K_{q,P}^{(t)} + V_{q,P}^{(t+1)} \quad (10)$$

$$K_{q,I}^{(t+1)} = K_{q,I}^{(t)} + V_{q,I}^{(t+1)} \quad (11)$$

$$K_{q,D}^{(t+1)} = K_{q,D}^{(t)} + V_{q,D}^{(t+1)} \quad (12)$$

where $K_{q,P}$, $K_{q,I}$, $K_{q,D}$ refer to the Proportional, Integral and Derivative PID controller parameters of the Q^{th} bat.

6. Develop a local solution around the existing bat solution if it satisfies the criteria (rand>R_q) with the formula (6)

7. Check if (rand <A_q&&$\rho_q<\rho_{best}$).Accept the new solutions and Update the Amplitude A_q and the rate of pulse emission R_q for each bat using formulae

$$A_q^{t+1} = \theta * A_q^{t} \quad \text{and} \quad R_q^{t} = R_q^{0}\{1 - \exp(-\gamma t)\}$$

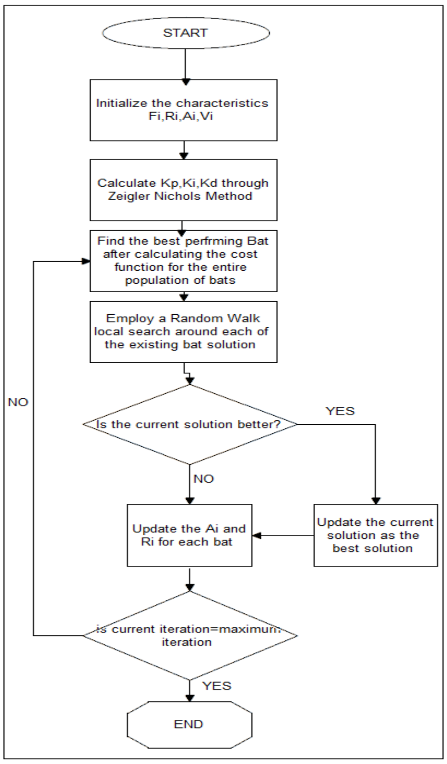

Figure 3. Bat algorithm flowchart

The flowchart describing the above algorithm has been given in Fig. 3 on the right.

C. *Fitness Function*

In order to judge the efficacy of the proposed Bat Algorithm, we need to choose the appropriate cost function which helps us arrive at an optimal solution. They are:

TABLE II. DIFFERENT COST PARAMETERS

Error	Name	Characteristics
$\int^{t} \lvert e(t)\rvert dt$	IAE: Integral Absolute Error	Pertinent for highly damped monotonic step response. Minimization can result in small overshoot but long settling time
$\int^{t} e^2(t)dt$	ISE: Integral Square Error	Pertinent for non-monotonic step response, Slower response but less oscillation than IAE.
$\int^{t} t * \lvert e(t)\rvert dt$	ITAE: Integral Time Absolute Error	Errors are penalized with a greater severity when t is high as compared to when t is small.
$\int^{t} t * e^2(t)dt$	ITSE: Integral Time Squared Error	Less sensitive and computationally more intensive than ITAE

V. SIMULATION

The parameters and specifications for the Simulation of the Bat-Ziegler-PID Algorithm are given in Table III below.

TABLE III. BAT ALGORITHM PARAMETERS

Parameter	Description	Value
M	No. of Bats	10
Max_Iteration	Maximum Iterations	100
N	Problem Dimension	3
Eps	Random no. for local search	-0.45
Θ	Bat Parameter theta	0.5
Γ	Bat Parameter gamma	0.5
$[W_{min}\ W_{max}]$	Inertial weight	[0.4 0.9]

Experimental results in this section conclusively prove the proposed Bat Ziegler-PID Algorithm's effectiveness in optimization of performance characteristics. The simulations were performed using Matlab/Simulink on an Intel Core i5 processor with 4 Gb RAM and 2.66 Ghz speed having Windows 7 OS (32 bit).

$$\text{Plant 1} = \frac{4.2228}{(s+0.5)*(s^2+1.64s+8.456)} \quad (13)$$

$$\text{Plant 2} = \frac{27}{(s+1)*(s+3)^3} \quad (14)$$

$$\text{Plant 3} = \frac{\exp^{-3s}}{(s+1)^2*(1+2s)} \quad (15)$$

The Plant functions Plant 1, Plant 2 [7] and Plant 3[12] are utilized to demonstrate the efficacy of Bat Algorithm.

We have compared different cost functions with each other for a single plant and also compared step response for different Algorithms keeping the cost function and parameters Max_Iteration and population constant.

TABLE IV. CHARACTERISTICS FOR DIFFERENT COST FUNCTIONS

	Plant 1		Plant 2		Plant 3	
	RiseTime(s)	Overshoot(%)	RiseTime(s)	Overshoot(%)	RiseTime(s)	Overshoot(%)
IAE	0.3795	5.398	0.7837	25.2706	4.8501	6.3458
ISE	0.3782	4.6417	0.5276	14.1299	2.9924	13.8459
ITAE	0.9083	12.1878	0.8826	21.2054	4.7777	3.0435
ITSE	0.5282	9.6579	0.5778	10.745	3.6429	7.8102
	SettlingTime(s)	Peak	SettlingTime(s)	Peak	SettlingTime(s)	Peak
IAE	9.0386	1.0511	4.6224	1.2547	23.3724	1.0659
ISE	5.7158	1.0468	5.189	1.1423	31.4848	1.1321
ITAE	6.2102	1.1185	4.7711	1.213	23.054	1.0283
ITSE	7.3465	1.092	3.6037	1.1114	21.1601	1.0762

In Fig. 4 We observe that the step response to the four cost functions for Plant 1, we can observe that the cost function ISE has the smallest rise time, smallest settling time and the least overshoot and peak.

In Fig. 5 We observe that the step response to the four cost functions for Plant 2, we can observe that the cost function ITSE has the smallest settling time and the least overshoot and peak and performs second best in the four cost functions in having least rise time.

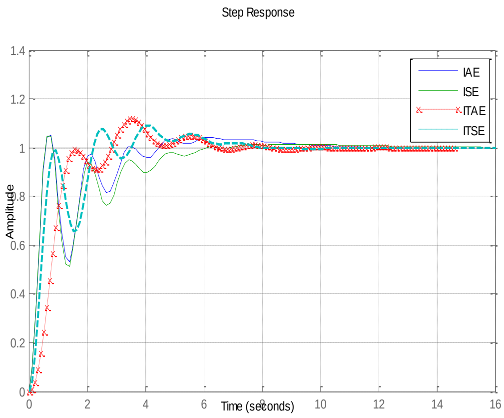

Figure 4. Step response of Plant 1 for different cost functions

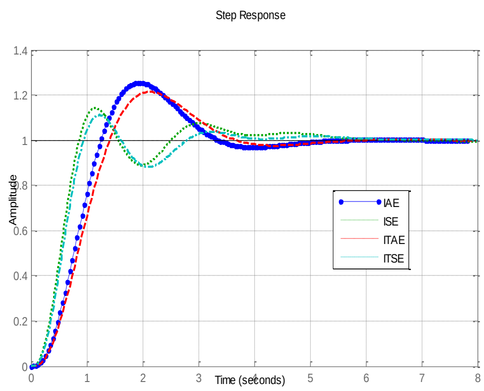

Figure 5. Step response of Plant 2 for different cost functions

In Table IV we have compared the step response characteristics amongst 4 different cost functions. Characteristics such as Rise Time, Settling Time, Overshoot and Peak of a particular Plant have been compared.

The Bat-Ziegler-PID is then compared to other meta-heuristic Algorithms such as Ant Colony Algorithm(ACO) [7], Ziegler Nichols Algorithm(Z-N) [10], Particle Swarm Optimization (PSO) [11] and Harmonic Search Algorithm(HSA) [13].

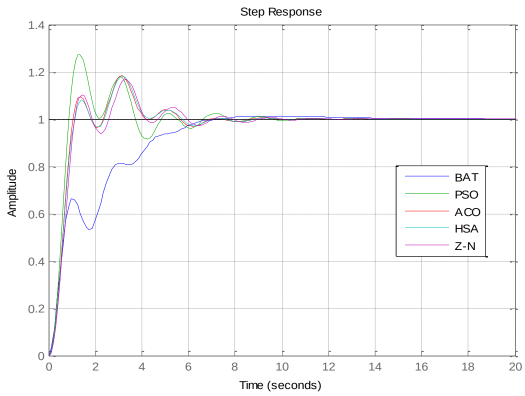

Figure 6. Step response of different algorithms for plant 1

As it can be seen from the step response of Plant 1 in Fig. 6, Bat Algorithm consists of the smallest over shoot and correspondingly has the smallest peak response characteristic as compared to the other algorithm. It also has the least “ringing” of all the algorithms.

That is, it settles faster than other comparative meta-heuristic Algorithm to a steady state value.

The Comparison of all the characteristics is given in the Table V and depicted in Fig. 6 and Fig. 7.

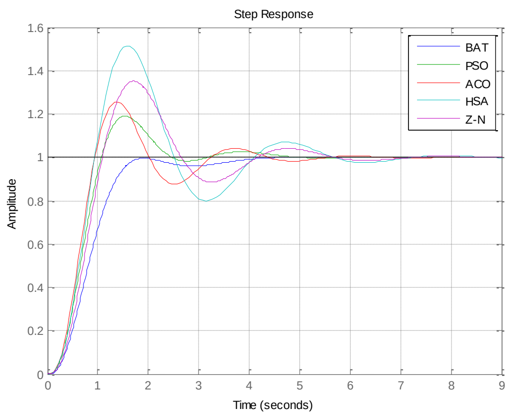

Figure 7. Step response of different algorithms for plant 2

TABLE V. CHARACTERISTICS OF DIFFERENT ALGORITHMS

	Plant 1		Plant 2		Plant 3	
	RiseTime(s)	Overshoot(%)	RiseTime(s)	Overshoot(%)	RiseTime(s)	Overshoot(%)
BAT	4.1188	1.2745	1.0059	0	4.9846	6.5959
PSO	0.5777	27.3913	0.6585	19.1398	4.6818	15.7005
ACO	0.6929	18.7031	0.5776	25.0721	4.7498	8.4757
HAS	0.7189	18.1646	0.5708	51.171	3.1003	45.1074
Z-N	0.719	17.3822	0.6665	8.7611	2.815	33.9173
	SettlingTime(s)	Peak	SettlingTime(s)	Peak	SettlingTime(s)	Peak
BAT	6.1865	1.0128	3.6357	1	23.5871	1.0685
PSO	7.3893	1.2717	4.2463	1.1901	26.2998	1.1557
ACO	6.4827	1.1842	4.9807	1.2555	24.1578	1.0879
HAS	6.5234	1.1793	6.6563	1.5145	39.2684	1.446
Z-N	6.5967	1.1682	5.2799	1.352	45.8704	1.3432

As illustrated in Fig. 7, the Bat-Ziegler-PID has zero overshoot as well as the least settling time.

The Step Response characteristics for Plant 1 and Plant 2 have been depicted in the Table V. From the above characteristics from Fig. 7 we can conclude that the in Plant 2 BAT Algorithm performs better than other algorithms by having the least overshoot, the fastest settling time and the correspondingly the lowest Peak response.

Dead Time Modeling: Dead Times manifest in different industries and processes, they may be caused by time lag in transferring goods and services, cascading of lower order systems leading to accumulation in time lag and computational time require for processes [14].

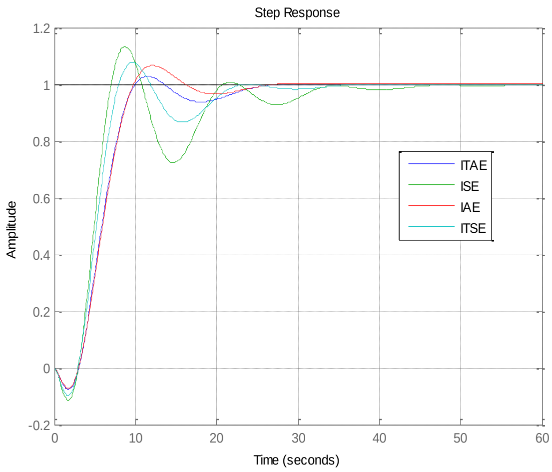

Figure 8. Step response for Plant 3 for different cost functions

Comparing Bat Algorithm to other meta-heuristic Algorithms. We get the following step response characteristics.

The undershoot observed in the Fig. 8 and Fig. 9 are due to the Plant 3 being a non-minimum phase function having a zero near time T=0 in the right half of the s-plane at s=0.667. In the above simulations, we observe that Bat-Ziegler PID, a memory less algorithm, outperforms comparative algorithms, this is an advantage as Bat Algorithm constantly looks for new paths, unhindered by the memory of the past paths, this can make it “forget” the paths which have high cost function and the performance of the K^{th} bat is not “biased” by the performance of other (K-1) bats.

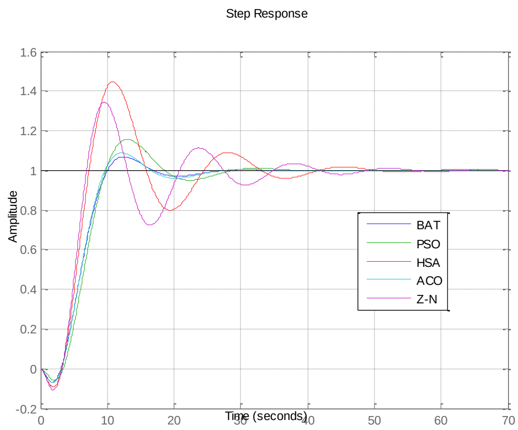

Figure 9. Step response for different algorithms for Plant 3

The Table VI as depicted below provides the PID parameters obtained from the simulation of Bat-Ziegler-PID Algorithm to each of the Plant 1, Plant 2 and Plant 3.

TABLE VI. PID CHARACTERISTICS OF BAT ALGORITHM

	K_P	K_I	K_D
Plant 1	1.2123	0.6153	0.9909
Plant 2	1.9681	1.1203	0.9447
Plant 3	0.6713	0.1606	0.4028

VI. CONCLUSIONS

In the Algorithm proposed above, we observe that the proposed BAT-Ziegler-PID Algorithm significantly outperforms similar meta-heuristic Algorithms when the parameters such as population and the number of iterations remain the same. The proposed changes in BAT-Ziegler-PID significantly narrow the search space and provide the optimum PID parameters faster than other algorithms.

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