Improved Closed Loop Performance and Control Signal Using Evolutionary Algorithms Based PID Controller

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Abstract—**Proportional-Integral-Derivative (PID) controllers are the most widely used controllers in industry because of their simplicity and robustness. Different values of PID parameters make different step response, so an increasing amount of literature is devoted to proper tuning of PID controllers. The problem merits further investigation as traditional tuning methods make large control signal that can damage the system but evolutionary algorithms based tuning methods improve the control signal and closed loop performance. In this paper three tuning methods for PID controllers have been studied namely Ziegler and Nichols, which is traditional tuning method and evolutionary algorithms based tuning methods, that are, genetic algorithm (GA) and particle swarm optimization (PSO). To examine the validity of PSO and GA tuning methods a comparative analysis of DC motor plant is studied. Simulation results reveal that evolutionary algorithms based tuning method have improved control signal amplitude and quality factors of the closed loop system such as rise time, integral absolute error (IAE) and maximum overshoot.**

Keywords—evolutionary algorithm, genetic algorithm, particle swarm optimization, PID controller.

I. INTRODUCTION

As it is well known, PID controllers are the most popular controllers in process control because of their simplicity of architecture, easy theoretical analysis and implementation [1]. PID controllers have three adjustable parameters, i.e. K_p as proportional gain, K_i as integral gain and K_d as derivative gain. The performance of the control system undeniably depends on adjusting these three parameters, correspondingly, adjusting proper values can make a good performance and improper values can make the closed loop system unstable [1]. Through the years several methods have been proposed for tuning of PID controller parameters such as:

- Traditional methods
- Evolutionary Algorithms based methods

There are several traditional methods for tuning of PID controllers such as Ziegler and Nichols tuning method and damped oscillation tuning method [1]. But using traditional tuning methods the performance of the closed loop system cannot be optimized. There are some evolutionary algorithms based tuning methods such as Genetic Algorithms (GA) [2], Ant Colony Optimization (ACO) [3] and Particle Swarm Optimization (PSO) [4]-[6].

Genetic algorithm briefly called GA is inspired by Darwin's theory about evolution. Genetic Algorithms (GAs) were invented by John Holland [7], while Particle Swarm Optimization (PSO) is a method, which searches through the n-dimensional space of a problem to find the parameters that minimize a special objective function. PSO is developed by an American psychologist Dr. Kennedy and electrical engineer Dr.Eberhart in 1995 [8], inspired by the behavior of birds searching for food, which in every iteration knowing each birds best position and best position of all birds algorithms updates the velocity and position of each bird. In all traditional and evolutionary algorithms based tuning method proposed up to now, optimization of control signal have been neglected. In this paper using GA and PSO based tuning methods in addition to reducing output error, making a faster response and optimizing quality factors of the system like rise time, maximum overshoot and settling time, control signal of the system is optimized.

The remainder of this paper is organized as follows, in section 2 Ziegler and Nichols tuning method which is a traditional method of PID tuning, genetic algorithms and particle swarm optimization as evolutionary algorithms based tuning methods are discussed; in section 3 results and discussions will be taken where traditional methods and evolutionary algorithms based tuning methods are compared, and finally this paper is concluded in section 4.

II. TUNING METHODS

A. Ziegler and Nichols Tuning Method

One of the most important traditional tuning methods is Ziegler and Nichols tuning method. This tuning method which is based on closed loop system first was proposed by Ziegler and Nichols in 1942 [9]. In this method initially a proportional controller is set and its value is increased slowly to oscillate the system, this value of proportional controller and period of its oscillation respectively is called K_u and P_u. Using K_u and P_u the parameters of controller can be tuned as shown in Table I:

TABLE I
ZIEGLER AND NICHOLS CLOSED LOOP TUNING METHOD

Controller	Parameters
P	$K_p = \frac{K_u}{2}$
PI	$K_p = 0.45 * K_u$, $\tau_i = \frac{5}{6} * P_u$
PID	$K_p = 0.6 * K_u$, $\tau_i = \frac{P_u}{2}$, $\tau_d = \frac{P_u}{8}$

where τ_i and τ_d are respectively called integral time constant and derivative time constant and $K_i = \frac{K_P}{\tau_i}$ and $K_d = K_p * \tau_d$.

B. Genetic Algorithms

In the case of genetic algorithm solutions of the optimization problem which is K_p ,K_i ,K_d are encoded to 0 and 1 bits. In the first generation a population of chromosomes are generated initially and in each generation GA searches for the best solutions in the solution space. In each generation three main operators which are mutation, crossover and selection operates on the algorithm. Selection operator moves the best solutions of the generation which have the minimum value of cost function f to the next generation so it helps the algorithm to converge the optimum solution of the algorithm.

$$\text{Cost function} = \min f(K_p, K_i, K_d) \tag{1}$$

Note that in (1) f is a general function in terms of Integral Absolute Error, Integral Square Error, Maximum Overshoot and control signal. In section three, f is introduced in three forms of minimizing ISE, ISE + Mp and ISE + Mp + Control signal. Crossover combines two individuals and produces two new individuals and moves them to the next generation while mutation operates on one individual to produce a single new individual. In each generation after operating mutation, crossover and selection operator, the solutions are applied to the specified cost function.

C. Particle Swarm Optimization

In particle swarm optimization initially a set of random solution is generated, each solution has a velocity and position, then searches for optima by updating velocity and position of particle in each iteration using (2) and (3):

$$V^{j+1} = \omega * V^j + c_1 * (\mathrm{P} - \mathrm{x}^j) + c_2 * (G - \mathrm{x}^j) \tag{2}$$

$$x^{j+1} = x^j + V^{j+1} \tag{3}$$

Which " V^{j+1} " is updated velocity of particle , " V^j " is velocity of particle , " P " is each particle's best position (best fitness), " G "is best position of all particles in one iteration, " x^{j+1} " is updated position of particle, " x^j " is particle position, " ω " is inertia weight in range of 0 and 1 , " c_1 " and " c_2 " are acceleration constants in range of 0 and 1. PSO similar to GA uses cost function f introduced in (1).

Actually in classical PSO values of ω , c_1 and c_2 are constants. But in improved PSO algorithms some variable values for ω , c_1 and c_2 are presented, Knowing that inertia weight is better to be linearly decreasing, c_1 decreasing and c2 increasing [10], for example as shown in (4) an improved formula for PSO parameters is presented [11]:

$$\begin{aligned} \omega &= 0.4 \\ c_1 &= \exp(-0.05t) \\ c_2 &= \frac{\exp(0.05t)}{1 + 0.05\exp(0.05t)} \end{aligned} \tag{4}$$

As shown in (4) the inertia weight is supposed to be constant while as shown in (5) Inertia weight also can be linearly decreasing [12]:

$$\omega(i) = \omega_{\max} - (\frac{\omega_{\max} - \omega_{\min}}{i_{\max}})i \tag{5}$$

Where $\omega_{\max}$ and $\omega_{\min}$ two small constants in the interval of zero and one, i is the current iteration and $i_{\max}$ is the maximum number of iteration. So we can use variable parameters instead of constant parameters.

In each iteration after updating velocity and position of each particle, the resulted value are applied to the specified cost function.

In Fig. 1 flow chart of the evolutionary algorithms based tuning of PID controller is plotted.

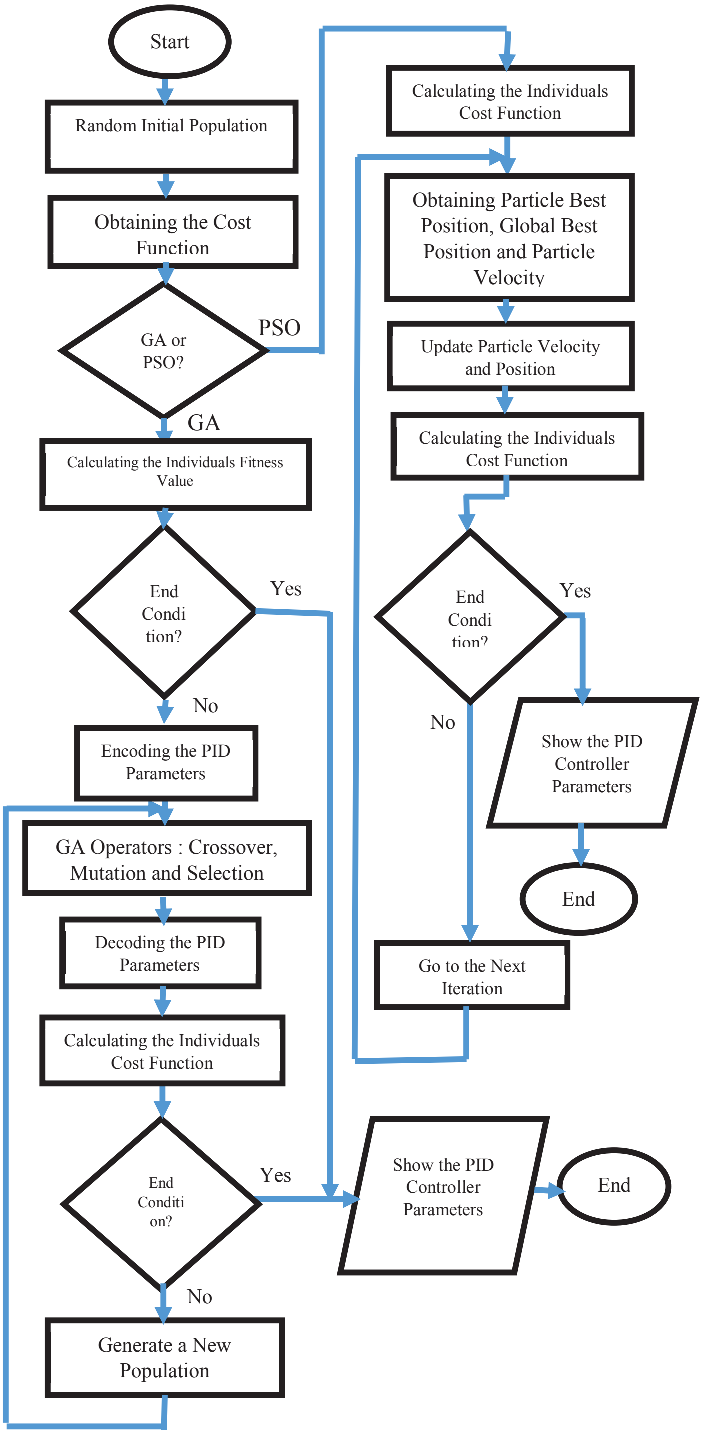

Fig. 1 Flow Chart of the Evolutionary Algorithms Based Tuning of PID Controller

III. RESULTS AND DISCUSSIONS

A frequently cited case study i.e. DC motor is considered in this paper that its transfer function is represented in (6) ([13, 14]):

$$G(s) = \frac{\theta(s)}{V(s)} = \frac{0.9}{0.00105s^3 + 0.2104s^2 + 0.8913s} \quad (6)$$

The following PID coefficient is calculated by Ziegler and Nichols tuning method:

$$K_p = 119.07$$

$$K_i = 1102.5$$

$$K_d = 3.22$$

In genetic algorithms and particle swarm optimization case we have chosen three different cost functions which are:

- Optimizing Integral Square Error (ISE)

$$f = \sum_{i=1}^{\text{inf}} (y(i) - y_{sp})^2 \quad (7)$$

- Optimizing Integral Square Error and Maximum Overshoot (ISE + Mp)

$$f = c_1 * \sum_{i=1}^{\text{inf}} (y(i) - y_{sp})^2 + c_2 * \text{abs}(\max(y) - y_{sp}) \quad (8)$$

- Optimizing Integral Square Error, Maximum Overshoot and Control Signal (ISE + Mp + Control Signal)

$$f = c_3 * \sum_{i=1}^{\text{inf}} (y(i) - y_{sp})^2 + c_4 * \text{abs}(\max(y) - y_{sp}) + c_5 * \sum_{i=1}^{\text{inf}} (u(i) - u_{sp})^2 \quad (9)$$

Where c_1, c_2, c_3, c_4 and c_5 are constant weights.

In Fig. 2 output signal of the system optimized with the first cost function is plotted.

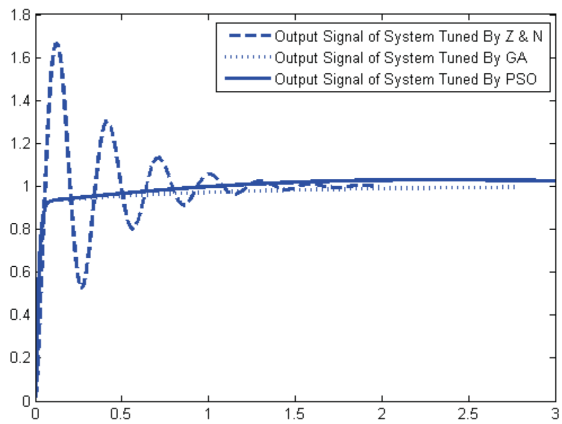

Fig. 2 Optimization Based on (7)

Based on Fig. 2 it is observed that Ziegler and Nichols tuning method make a large overshoot and settling time. On the other hand GA and PSO based tuning method have improved the overshoot and settling time of the control system and both GA and PSO based tuning methods make a fast response in comparison with Z&N tuning method.

In Table II the quality factors of the system optimized with the first cost function are listed.

TABLE II
OPTIMIZATION BASED ON (7)

	Kp	Ki	Kd	IAE	ISE	Mp	Rise Time	Settling Time
Z & N	119.07	1102.5	3.22	0.2204	0.0840	66.8 %	0.042 s	1.33s
GA	9.9968	0.0763	9.9997	0.1240	0.0177	0.02 %	0.0523s	1.38s
PSO	10	9.825	10	0.0689	0.0168	2.98 %	0.0521s	3.33s

According to Table II it is obvious that traditional tuning method had a larger IAE and ISE, evolutionary algorithms based tuning methods had made a small IAE, ISE and maximum overshoot. In PSO based tuning method because of larger values of K_p , K_i and K_d rather than GA control signal is larger. On the other hand GA based tuning method makes a smaller settling time which means that in this case GA is faster and has a smaller overshoot.

Now the system is optimized with the second cost function. In Fig. 3 output signal of the system optimized with the second cost function is plotted.

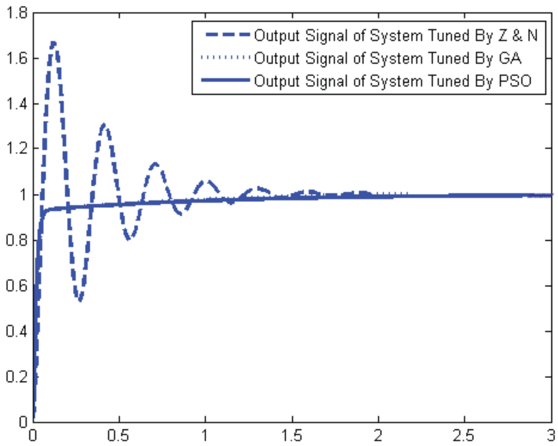

Fig. 3 Optimization Based on (8)

According to Fig. 3 similar to the last case Ziegler and Nichols tuning method have made a large overshoot and settling time while GA and PSO based tuning method are fast and perfectly optimize settling time, overshoot, IAE and ISE.

In Table III the quality factors of the system are shown.

TABLE III
OPTIMIZING BASED ON (8)

	Kp	Ki	Kd	IAE	ISE	Mp	Rise Time	Settling Time
Z & N	119.07	1102.5	3.22	0.2204	0.0840	66.8%	0.042 s	1.33s
GA	9.9926	1.5085	9.7575	0.1578	0.0181	0.0159%	0.0546	1.14s
PSO	10	0	10	0.0940	0.0176	0.5 %	0.0523s	1.4s

In Table III the quality factors of the system are compared. In this case in addition to ISE we have tried to optimize maximum overshoot, it is concluded that in comparison with traditional methods, evolutionary algorithms based methods make a smaller ISE and greatly reduced maximum overshoot. But in this case because of trying to minimize both ISE and overshoot its obvious that the value of ISE is some larger in comparison with the first case. Similar to the first method of optimization in this case GA based tuning method has a smaller settling time compared with PSO based tuning method, so GA based tuning method is faster. Rise time and maximum overshoot of GA and PSO based tuning method is in a same scale, but PSO had made a minimum value for IAE and ISE.

In the last two past methods we have optimized IAE, ISE and maximum overshoot but control signal in them was not optimized, so control signal can damage the plant, now in this case in addition to quality factors of the system like ISE, control signal is optimized.

In Fig. 4 the output signal of the system optimized with the traditional and evolutionary algorithms based tuning methods according to the third cost function is plotted.

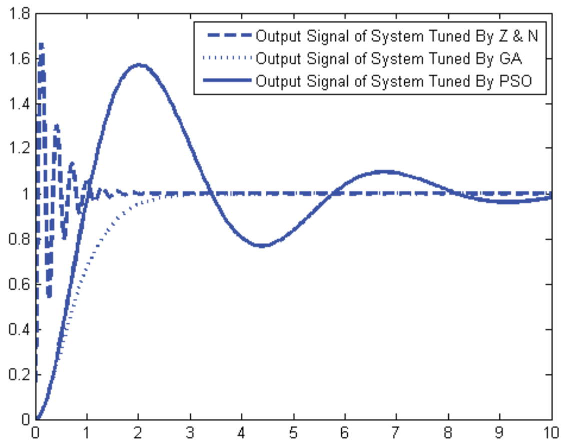

Fig. 4 Optimization Based on (9)

From Fig. 4 it is obvious that in the case of optimizing ISE, maximum overshoot and control signal PSO based tuning method is not a nice approach because it have made a large overshoot. But GA is still perfect in optimizing overshoot. GA based tuning method have made a faster response in comparison with PSO based tuning method. In Fig. 5 and Fig.

6 the control signal of the system optimized with the Z&N and GA and PSO based tuning method is plotted, respectively.

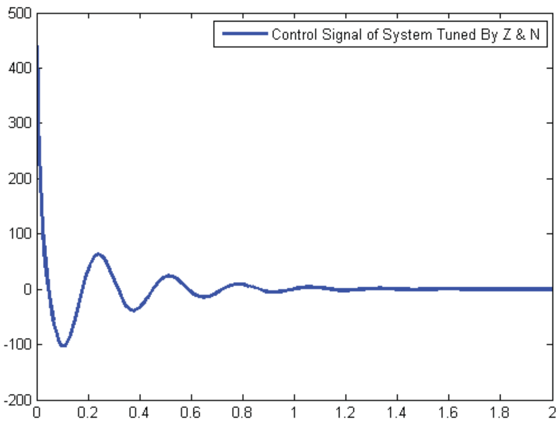

Fig. 5 Control Signal of System Tuned by Z&N

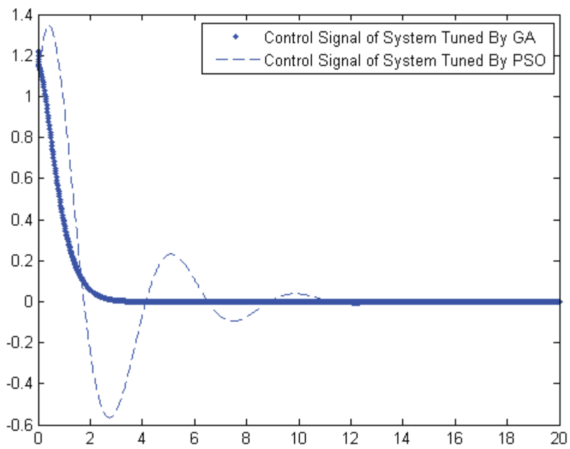

Fig. 6 Control Signal of system Tuned by GA and PSO

Fig. 5 shows that Z&N tuning method made a large control and its range of variation is about 500 which can damage the system so Z&N tuning method is poor in optimizing control signal while as shown in Fig. 6 the evolutionary algorithms based tuning method made a smooth control signal which its range of variation is about 2. Control signal of Z&N tuning method is 250 times larger than evolutionary algorithms based tuning method so evolutionary algorithms based methods can be used for optimizing control signal.

In Table IV the quality factors of this system are listed.

TABLE IV
OPTIMIZING BASED ON (9)

	Kp	Ki	Kd	IAE	ISE	Mp	Rise Time	Settling Time
Z&N	119.07	1102.5	3.22	0.2204	0.0840	66.8%	0.042s	1.33s
GA	1.1455	2.31e-6	0.000781	0.8652	0.5511	0.2%	1.42s	2.42s
PSO	1.0524	1.537	0	2.0367	0.9200	56.8%	0.703s	9.97s

In the case of optimizing ISE, maximum overshoot and control signal PSO and GA did not optimized ISE because of focus on optimizing the control signal. PSO based tuning method had made a settling time over 4 times larger than GA, so GA based tuning method is faster than PSO based tuning method. PSO has a maximum overshoot absolutely larger than GA, values of IAE and ISE in GA based tuning method is smaller than PSO, so GA had optimized IAE and ISE greatly. It should be emphasized that the second one has a smaller settling time, so that second method of optimization is faster.

In this case the quality factors and control signal of the system tuned by Z&N is compared with the GA and PSO tuned parameters as the setpoint changes from 1 to 2 at time 16 seconds and an output disturbance at time 10 seconds. In Fig. 7 the output signal of the system is plotted.

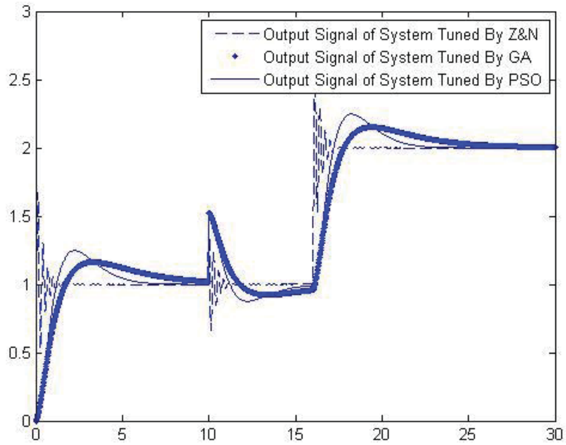

Fig. 7 Output Signal of the System as Setpoint Changes

As it is shown in Fig. 7 the GA and PSO based tuning methods make a smooth output as setpoint changes in comparison with traditional methods also in the presence of output disturbance the GA and PSO based PID controller quickly tries to eliminate the disturbance effect.

The control signal of the systems in the case of setpoint changing from 1 to 2 at time 16 seconds and inserting output disturbance at time 10 seconds is plotted in Fig. 8.

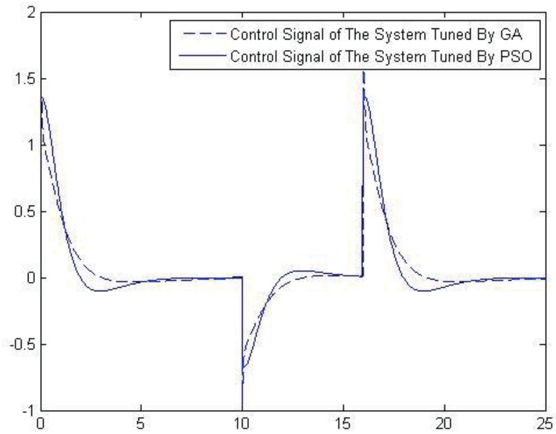

Fig. 8 Control Signal of system Tuned by GA and PSO

As shown in Fig. 8 as the setpoint changes from 1 to 2 at time 16 seconds and also in the presence of output disturbance it never make a large overshoot in control signal if our proposed tuning method have been used.

IV. CONCLUSIONS

Traditional methods and evolutionary algorithms methods based PID tuning have been investigated in this paper. Evolutionary algorithms based tuning methods use a high order plant model while in the traditional tuning methods a first order plus dead time (FOPDT) or a small order plant was needed. Using evolutionary algorithms based tuning methods focused attention on control signal that it was disregarded in previous research. Moreover, these methods improve response parameters like rise time, maximum overshoot and settling time. PSO-GA based tuning method make a faster response, reduce error of output as perfectly optimizing IAE and ISE and make a smooth control signal. Finally, it can be concluded that GA based tuning method provides better results compared to the traditional and PSO based tuning methods especially in terms of settling time and maximum overshoot.

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