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Evolutionary algorithms based design of multivariable PID controller

M. Willjuice Iruthayarajan *, S. Baskar

Department of EEE, Thiagarajar College of Engineering, Madurai 625 015, Tamilnadu, India

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ABSTRACT

In this paper, performance comparison of evolutionary algorithms (EAs) such as real coded genetic algorithm (RGA), modified particle swarm optimization (MPSO), covariance matrix adaptation evolution strategy (CMAES) and differential evolution (DE) on optimal design of multivariable PID controller design is considered. Decoupled multivariable PI and PID controller structure for Binary distillation column plant described by Wood and Berry, having 2 inputs and 2 outputs is taken. EAs simulations are carried with minimization of IAE as objective using two types of stopping criteria, namely, maximum number of functional evaluations (Fevalmax) and Fevalmax along with tolerance of PID parameters and IAE. To compare the performances of various EAs, statistical measures like best, mean, standard deviation of results and average computation time, over 20 independent trials are considered. Results obtained by various EAs are compared with previously reported results using BLT and GA with multi-crossover approach. Results clearly indicate the better performance of CMAES and MPSO designed PI/PID controller on multivariable system. Simulations also reveal that all the four algorithms considered are suitable for off-line tuning of PID controller. However, only CMAES and MPSO algorithms are suitable for on-line tuning of PID due to their better consistency and minimum computation time.

1. Introduction

Proportional-integral-derivative (PID) control offers the simplest and yet most efficient solution to many real-world control problems. Three-term functionality of PID controller covers treatment of both transient and steady state responses. The popularity of PID control has grown tremendously, since the invention of PID control in 1910 and the Ziegler–Nichol's straight forward tuning method in 1942. With the advances in digital technology, the science of automatic control now offers a wide spectrum of choices for control schemes such as adaptive control (Astrom & Wittenmark, 1995), neural network control (Fukuda & Shibata, 1992) and fuzzy logic control (Lee, 1990). However more than 90% of industrial controllers are still implemented based around PID control algorithms, as no other controllers match the simplicity, clear functionality, applicability and ease of use offered by the PID controllers (Ang, Chang, & Li, 2005).

Several approaches have been reported in literature for tuning the parameters of PID controllers. Ziegler–Nichols and Cohen–Coon are the most commonly used conventional methods for tuning PID controllers and neural network, fuzzy based approach, neuro-fuzzy approach and evolutionary computation techniques are the recent methods (Astrom & Hagglund, 1995).

Many researches have already reported the optimal design of PID controller parameters using various EAs such as GA (Chen, Cheng, & Lee, 1995), MPSO (Gaing, 2004; Ghoshal, 2004; Mukherjee & Ghoshal, 2007; Wang, Zhang, & Wang, 2006) and DE (Bingul, 2004) for SISO system. In general, EAs are robust search and optimization methodology, able to cope with ill-defined problem domain such as multimodality, discontinuity, time-variance, randomness and noise. GA approach for tuning of PID controllers for multi-input multi-output (MIMO) process is also reported (Chang, 2007; Zuo, 1995).

In Chang (2007), decoupled multivariable PI controller tuning using GA with multi-parent crossover approach was presented. Simple three-parent differential crossover and uniform mutation operators have been employed. The better performance of three-parent crossover RGA over BLT and traditional two-parent crossover based RGA was demonstrated in the paper.

Recently, several modifications are carried out in crossover and mutation mechanisms of RGA such as SBX crossover, PCX crossover and non-uniform polynomial mutation to improve the performance of RGA. Self-adaptive simulated binary crossover (SBX) based RGA was successfully applied to various engineering optimization problems (Deb, 2001). SBX crossover is self-adaptive in nature which creates children solutions in proportion to the difference in parent solutions. The near parent solutions are monotonically more likely to be chosen as offspring than solutions distant from parents.

* Corresponding author. Tel.: +91 94434 87093.
E-mail address: willjuice@tce.edu (M.W. Iruthayarajan).

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Another EA, namely, covariance matrix adaptation evolution strategy (CMAES) with the ability of learning of correlations between parameters and the use of the correlations to accelerate the convergence of the algorithm is recently proposed. Due to the learning process, the CMAES algorithm performs the search independent of the coordinate system, reliably adapts topologies of arbitrary functions, and significantly improves convergence rate especially on non-separable and/or badly scaled objective functions. CMAES algorithm has been successfully applied in varieties of engineering optimization problems (Baskar, Alphones, Suganthan, Ngo, & Zheng, 2005).This algorithm outperforms all other similar classes of learning algorithms on the benchmark multimodal functions (Kern et al., 2004).

Covariance matrix adaptation evolution strategy algorithm and also recent modifications in other EAs were not applied for the tuning of PID controllers. Also, all the reported papers for EA based PID controller design, have considered one or two algorithms for the purpose of comparison.

This paper focuses mainly on the performance evaluation of various EAs such as Self-adaptive RGA, MPSO, DE and CMAES on optimum design of multivariable PI and PID controllers for binary distillation column plant described by Wood and Berry (Chang, 2007). The essence of the paper lies in the determination of suitable EA method for the tuning of PID controller for MIMO system.

The remaining part of the paper is organized as follows. Section 2 introduces PID controller structure for SISO and MIMO systems. Section 3 describes the various EAs methods. Section 4 introduces the MIMO system considered for PID controller tuning. Section 5 presents the implementation of EA based multivariable PID controller design. Section 6 reveals the simulation results. Finally, conclusions are given in Section 7.

2. PID controller structure

A standard PID controller structure is also known as the "three-term" controller, whose transfer function is generally written in the ideal form in (1) or in the parallel form in (2)

$$G(s) = K_P\left(1 + \frac{1}{T_I s} + T_D s\right) \tag{1}$$

$$G(s) = K_P + \frac{K_I}{s} + K_D s \tag{2}$$

where K_P is the proportional gain, T_I is the integral time constant, T_D is the derivative time constant, $K_I = K_P/T_I$ is the integral gain and $K_D = K_P T_D$ is the derivative gain.

The "three-term" functionalities are highlighted below.

- The proportional term – providing an overall control action proportional to the error signal through the all pass gain factor.
- The integral term – reducing steady state errors through low frequency compensation by an integrator.
- The derivative term – improving transient response through high frequency compensation by a differentiator.

For optimum performance, K_P, K_I (or T_I) and K_D (or T_D) are tuned by EAs by minimizing the performance measures such as IAE, ISE and ITAE.

2.1. PID controller for MIMO system

Consider a multivariable PID control structure as in Fig. 1, where, desired output vector: $Y_d = [y_{d1}, y_{d2}, \ldots, y_{dn}]^T$;

Actual output vector: $Y = [y_1, y_2, \ldots, y_n]^T$;

Error vector: $E = Y_d - Y = [y_{d1} - y_1, y_{d2} - y_2, \ldots, y_{dn} - y_n]^T = [e_1, e_2, \ldots, e_n]^T$;

Control input vector: $U = [u_1, u_2, \ldots, u_n]^T$;

$n \times n$ Multivariable processes:

$$G(s) = \begin{bmatrix} g_{11}(s) & \cdots & g_{1n}(s) \\ \vdots & \ddots & \vdots \\ g_{n1}(s) & \cdots & g_{nn}(s) \end{bmatrix} \tag{3}$$

$n \times n$ Multivariable PID controller:

$$K(s) = \begin{bmatrix} k_{11}(s) & \cdots & k_{1n}(s) \\ \vdots & \ddots & \vdots \\ k_{n1}(s) & \cdots & k_{nn}(s) \end{bmatrix} \tag{4}$$

In this work, decoupled multivariable PID controller is considered. So $K(s)$ becomes

$$K(s) = \begin{bmatrix} k_1(s) & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & k_n(s) \end{bmatrix} \tag{5}$$

The form of $k_i(s)$ is either in (1) or (2). In this work, "parallel form" of PID controller in (2) is used and can be rewritten as

$$k_i(s) = k_{P_i} + \frac{k_{I_i}}{s} + k_{D_i} s, \tag{6}$$

For convenience, let $\theta_i = [k_{P_i}, k_{I_i}, k_{D_i}]$, represents the gains vector of ith diagonal sub PID controller in $K(s)$ .For multivariable PI controller, $k_i(s)$ in (6) can be rewritten as

$$k_i(s) = k_{P_i} + \frac{k_{I_i}}{s} \tag{7}$$

$\theta_i = [k_{P_i}, k_{I_i}]$ represents the gains vector of the ith diagonal sub PI controller in $K(s)$.

2.2. Performance index

In the design of PID controller, the performance criterion or objective function is first defined based on the desired specifications such as time-domain specifications, frequency domain specifications and time-integral performance. The commonly used time-integral performance indexes are integral of the square error (ISE), integral of the absolute value of the error (IAE) and integral of the time-weighted absolute error (ITAE). Minimization of IAE as given in (8) is considered as the objective of this paper

$$\mathrm{IAE} = \int_0^\infty (|e_1(t)| + |e_2(t)| + \cdots + |e_n(t)|)\mathrm{d}t \tag{8}$$

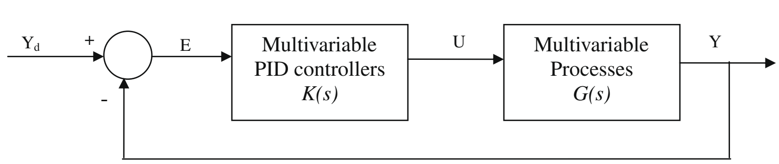

Fig. 1. A multivariable PID control system.