Expert Systems with Applications 37 (2010) 5775–5781

Contents lists available at ScienceDirect

Expert Systems with Applications

journal homepage: www.elsevier.com/locate/eswa

Covariance matrix adaptation evolution strategy based design of centralized PID controller

M. Willjuice Iruthayarajan *, S. Baskar

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

ARTICLE INFO

Keywords:
PID control
CMAES
Real coded Genetic Algorithm
MIMO system
Controller tuning

ABSTRACT

In this paper, design of centralized PID controller using Covariance Matrix Adaptation Evolution Strategy (CMAES) is presented. Binary distillation column plant described by Wood and Berry (WB) having two inputs and two outputs and by Ogunnike and Ray (OR) having three inputs and three outputs are considered for the design of multivariable PID controller. Optimal centralized PID controller is designed by minimizing IAE for servo response with unit step change. Simulations are carried out using SIMULINK-MATLAB software. The statistical performances of the designed controllers such as best, mean, standard deviations of IAE and average functional evaluations for 20 independent trials. For the purpose of comparison, recent version of real coded Genetic Algorithm (RGA) with simulated binary crossover (SBX) and conventional BLT method are used. In order to validate the performance of optimal PID controller for robustness against load disturbance rejection, load regulation experiment with step load disturbance is conducted. Also, to determine the performance of optimal PID controller for robustness against model uncertainty, servo and load response with +20% variations in gains and dead times is conducted. Simulation results reveal that for both OR and WB systems, CMAES designed centralized PID controller is better than other methods and also it is more robust against model uncertainty and load disturbance.

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. 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). 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).

Compared to the SISO system, the control of multivariable systems has always been a challenge to control system designers due to its complex interactive nature. In last several decades, designing controllers for MIMO systems has attracted a lot of research interests and many multivariable control approaches have been proposed (Luyben, 1986, 1990; Monica, Yu, & Luyben, 1988; Wang, Zou, Lee, & Qiang, 1997). Many researchers have already reported the optimal design of PID controller for MIMO system using Evolutionary Algorithms (EA) such as Genetic Algorithm (Chang, 2007; Zuo, 1995), Particle Swarm Optimization (Su & Wong, 2007).

Recently, 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 proposed (Kern et al., 2004). Owing 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). In general, EAs are robust search and optimization methodologies, able to cope with ill-defined problem domains such as multimodality, discontinuity, time-variance, randomness and noise. Willjuice and Baskar (2009) have demonstrated the application of various EAs for the design of decentralized PID controller of WB system. Effect of load disturbance and parameter variation has not been studied for the designed optimal decentralized PID controller.

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

0957-4174/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.eswa.2010.02.031

This paper focuses mainly on the design of centralized PID controller using CMAES algorithm for distillation column plant of WB and OR systems and also validates performance of controller over robustness against load disturbance rejection and model uncertainty.

For the purpose of comparison, conventional BLT method (Monica et al., 1988) and recent version of RGA with Simulated Binary Crossover (SBX) and non-uniform polynomial mutation is used (Deb, 2001).

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 CMAES algorithm. Section 4 introduces the MIMO systems considered for PID controller tuning. Section 5 describes the CMAES implementation details of multivariable PID controller. 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 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,

$$\begin{aligned}
&\text{where, desired output vector: } Y_d = [y_{d1}, y_{d2}, \ldots, y_{dn}]^T;\\
&\text{Actual output vector: } Y = [y_1, y_2, \ldots, y_n]^T;\\
&\text{Error vector: } E = Y_d - Y = [y_{d1} - y_1, y_{d2} - y_2, \ldots, y_{dn} - y_n]^T\\
&\qquad = [e_1, e_2, \ldots, e_n]^T;\\
&\text{Control input vector: } U = [u_1, u_2, \ldots, u_n]^T;
\end{aligned}$$

$n \times n$ Multivariable process:

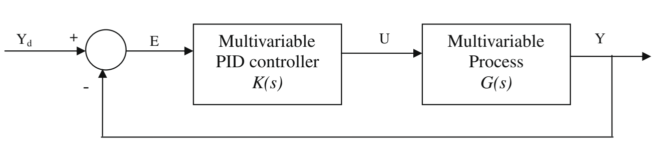

Fig. 1. A multivariable PID control system.

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

$n \times n$ Centralized PID controller:

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

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

$$k_{ij}(s) = k_{P_{ij}} + \frac{k_{I_{ij}}}{s} + k_{D_{ij}} s. \tag{5}$$

For convenience, let $\theta_{ij} = [k_{P_{ij}}, k_{I_{ij}}, k_{D_{ij}}]$, represents the gains vector of ith row and jth column sub PID 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 (6) is considered as the objective in this paper.

$$\mathrm{IAE} = \int_0^\infty (|e_1(t)| + |e_2(t)| + \cdots + |e_n(t)|)\, dt. \tag{6}$$

3. Covariance matrix adaptation evolution strategy (CMAES)

CMAES is a class of continuous EA; it generates new population members by sampling from a probability distribution that is constructed during the optimization process. CMAES is derived from the concept of self-adaptation in evolution strategies, which adapts the covariance matrix of a multivariate normal search distribution. One of the key concepts of this algorithm involves the learning of correlations between parameters and the use of the correlations to accelerate the convergence of the algorithm. Owing 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. This algorithm outperforms all other similar classes of learning algorithms on the benchmark multimodal functions (Hansen, 2006). The adaptation mechanism of CMAES consists of two parts:

(i) The adaptation of the covariance matrix **C** and
(ii) The adaptation of the global step size.

The covariance matrix **C** is adapted by the evolution path and vector difference between the μ best individuals in the current and previous generation. The detailed CMAES algorithm is explained in following steps:

Step 1: Generate an initial random solution.
Step 2: The offspring at $g + 1$ generation x_k^{g+1} are sampled from a Gaussian distribution using covariance matrix and global step size at generation g.

$$x_k^{(g+1)} = z_k, \quad z_k = N(\langle x\rangle_\mu^{(g)}, \sigma^{(g)^2}\mathbf{C}^{(g)}) \quad k = 1, \ldots, \lambda, \tag{7}$$