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Fractional-order PID controller optimization via improved electromagnetism-like algorithm

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ABSTRACT

Based on the electromagnetism-like algorithm, an evolutionary algorithm, improved EM algorithm with genetic algorithm technique (IEMGA), for optimization of fractional-order PID (FOPID) controller is proposed in this article. IEMGA is a population-based meta-heuristic algorithm originated from the electromagnetism theory. It does not require gradient calculations and can automatically converge at a good solution. For FOPID control optimization, IEMGA simulates the "attraction" and "repulsion" of charged particles by considering each controller parameters as an electrical charge. The neighborhood randomly local search of EM algorithm is improved by using GA and the competitive concept. IEMGA has the advantages of EM and GA in reducing the computation complexity of EM. Finally, several illustration examples are presented to show the performance and effectiveness.

1. Introduction

Evolutionary computation technique has become gradually popular to obtain global optimal solution in many areas. Several algorithms have been proposed by the observation of real-world systems, such as genetic algorithm, evolutionary algorithm, particle swarm optimization, immune algorithm, differential evolution, and so on (ACPA, 2002; Cao & Cao, 2006; Cao, Liang, & Cao, 2005; Fan, Sun, & Zhang, 2007; IEE, 2002; IFAC, 2001; Lee, 2004a, 2004b; Lee & Teng, 2002, 2003; Nataraj & Tharewal, 2007; Podlubny, 1999; Yamato & Hashimoto, 1991). Recently, a novel meta-heuristic algorithm, electromagnetism-like (EM) mechanism, for global optimization was proposed (Biswas, Das, Abraham, & Dasgupta, 2009; Clerc & Kenney, 2002; Farag, Quintana, & Germano, 1998; Goldberg, 1989; Podlubny, 1999b). EM algorithm is originated from the electromagnetism theory in physics, which simulated the electromagnetism theory by considering each particle to be an electrical charge. Subsequently, the movement of attraction and repulsion is introduced by Coulomb's law, i.e., the force is inversely propositional to the distance between the particles and directly proportional to the product of their charges. Obviously, it has advantages of multiple search, global optimization, and faster convergence procedure and simultaneously evaluates many points in the search space; researchers are more likely to find a better solution (Biswas et al., 2009; Clerc & Kenney, 2002; Farag et al., 1998; Goldberg, 1989; Podlubny, 1999b). However, the local search procedure of EM is stochastic. Hence, the major drawback of EM is high computation complexity. To improve the performance of EM, a modified local search phase and the competition concept are adopted.

The proportional-integral-derivative (PID) controller is perhaps the most widely used controller in the world; it is easy to design and implement and has been applied well in most control systems. While control theory has been developed significantly, the PID controllers are used in a wide range of process control, motor drives, magnetic and optic memories, automotive control, flight control, instrumentation, and so on. In industrial applications, more than 90% of all control loops are PID type (Gudise & Venayagamoorthy, 2003; Hong & Yuan, 2002; Juang, 2004; Kim, 2002; Price, Storn, & Lampinen, 2005; Srinivas & Patnaik, 1994; Xu, Wei, & Xu, 2000; Yao, 1999). Feedback control systems form one such area, as witnessed in part by recent special issues on the subject (Gudise & Venayagamoorthy, 2003; Hong & Yuan, 2002; Juang, 2004). The concept of fractional-order processes or controllers has been studied considerably (ACPA, 2002; Birbil & Fang, 2003; Birbil, Fang, & Sheu, 2004; Chang, Chen, & Fan, 2009; Tsou & Kao, 2007; Wu, Yang, & Wei, 2004). This is due to the fact that many real-world systems are characterized by fractional-order differential equations (ACPA, 2002; Birbil & Fang, 2003; Birbil et al., 2004; Chang et al., 2009; Tsou & Kao, 2007; Wu et al., 2004). Hence, Podlubny proposed a generalization of the PID controller, namely the fractional-order PID controller (FOPID or $PI^{\lambda}D^{\delta}$), where λ and δ are integers (Tsou & Kao, 2007; Wu et al., 2004). Fractional calculus is usually used to design the FOPID controller. Various studies have demonstrated that the FOPID controller enhances performance and robustness (Birbil et al., 2004; Chang et al., 2009). However, it is difficult and complicated to design the FOPID controller by analytical meth-

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od because of using fraction calculus. In this article, a hybrid optimization method for FOPID controller is presented by the evolutionary algorithm IEMGA.

This article proposes an evolutionary algorithm IEMGA for FOPID controller optimization. IEMGA is a population-based meta-heuristic algorithm originated from the electromagnetism theory. For FOPID control optimization, IEMGA simulates the "attraction" and "repulsion" of charged particles by considering each controller parameters as an electrical charge. The neighborhood random local search is implemented by GA and the competitive concept, which reduces the computation complexity. The IEMGA has the capability of multiple searches, global optimization, and less computation complexity. Furthermore, IEMGA does not need any gradient information for the optimization process. As a result of these advantages, we use IEMGA to solve optimization of FOPID controller design.

The article is organized as follows. Section 2 introduces the fractional-order PID controllers. In Section 3, the EM algorithm is introduced. The hybrid algorithm IEMGA for PID controller optimization is introduced in Section 4. Section 5 shows the simulation and comparison results of optimization of FOPID controller. It demonstrates the performance of the proposed IEMGA. The final section offers the conclusion.

2. Fractional-order PID controllers

Proportional-integral-derivative (PID) controllers are widely used to build automation equipment in industries. They are easy to design, implement, and are applied well in most industrial control systems. Even though control theory has been developed significantly, the PID controllers are used for a wide range of process control, motor drives, magnetic and optic memories, automotive control, flight control, instrumentation, etc. In industrial applications, over 90% of all control loops are PID type (Gudise & Venayagamoorthy, 2003; Hong & Yuan, 2002; Juang, 2004; Price et al., 2005; Yao, 1999). As many real-world systems are characterized by fractional-order differential equations, the concept of fractional-order processes or controllers has been the subject of considerable research (ACPA, 2002; Birbil & Fang, 2003; Birbil et al., 2004; Cao & Cao, 2006; Chang et al., 2009; Tsou & Kao, 2007; Wu et al., 2004). In (Tsou & Kao, 2007; Wu et al., 2004), a generalization of the PID controller is introduced, namely the $PI^{\lambda}D^{\delta}$ controller, where λ and δ are the indices. Previous results have demonstrated that the $PI^{\lambda}D^{\delta}$ controller enhances performance and robustness (Birbil et al., 2004; Chang et al., 2009).

A block diagram of a simple feedback control system is shown in Fig. 1. The system comprises a process and a controller. The process has one input and one output, denoted u and y, respectively. The desired value y_r is called the set point or the reference one. The purpose of the system is to keep the process output y close to the desired one y_r in spite of disturbances.

Assume that the system is modeled by an nth-order process with time delay L:

$$G_p(s) = \frac{b_m s^m + b_{m-1}s^{m-1} + \cdots + b_1 s + b_0}{s^n + a_{n-1}s^{n-1} + \cdots + a_1 s + a_0} e^{-Ls}. \tag{1}$$

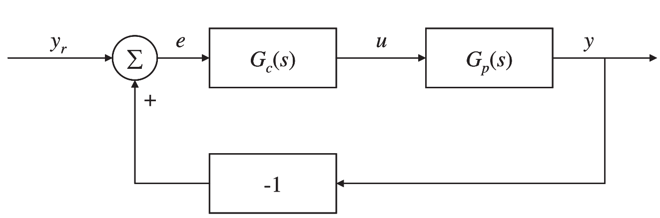

Fig. 1. Block diagram of a simple feedback control system.

Here, we assume $n > m$ and the system (1) is stable. For the PID controller, the transfer function is

$$G_C(s) = K_p + K_i s^{-1} + K_d s, \tag{2}$$

and the fractional-order PID controller-$PI^{\lambda}D^{\delta}$ is of the form:

$$G_C(s) = K_p + K_i s^{-\lambda} + K_d s^{\delta}, \tag{3}$$

where λ and δ are the orders of the fractional integral and derivative, respectively. Therefore, the PID controller parameters vector is (K_p, K_i, K_d) and the fractional-order PID controller parameters vector is $(K_p, K_i, \lambda, K_d, \delta)$. Obviously, the PID controller is a special case of FOPID. In addition, the expansion of fractional order of derivative and integral terms could provide much more flexibility in PID controller design.

3. Electromagnetism-like algorithm

This section introduces the EM algorithm for optimization problem. The EM algorithm was developed to simulate the electromagnetism theory of physics by each sample point to be a charge (or particle) Podlubny (1999b). The EM for optimization problems with lower and upper bound is in the form of:

$$\begin{aligned} &\text{Minimize} \quad f(x), \\ &\text{Subject to } x \in S, \end{aligned} \tag{4}$$

where $S = \{x \in \Re^n | l_k \leqslant x_k \leqslant u_k, l_k, u_k \in \Re, k = 1, \ldots, n\}$ and n, dimension of the problem; u_k, corresponding upper bound; l_k, corresponding lower bound; and $f(x)$, pointer to the function that is minimized. Herein, each particle x represents a solution with the corresponding fitness function $f(x)$. EM uses the mechanisms of attraction and repulsion to put the sample points toward to the optimum. By the Coulomb's law, the magnitude of force is proportional to the product of the particles and inversely proportional to the distance between two particles. The principles behind the algorithm are that inferior particles prevent a move in their direction by repelling other particles in the population and that superior particles facilitate moves in their direction.

The Pseudo code of EM algorithm is shown in Fig. 2. The following sections discuss each phase.

3.1. Initialization phase

For most applications of algorithm, the real-value coding technique is used to represent a solution for a given problem. In real-value coding implementation, each particle is encoded as a vector of real numbers, of the same lengths as the solution vector. In this article, each particle denotes a weighting vector $(K_p, K_i, \lambda, K_d, \delta)$, and the EM is used to find the optimum $(K_p^*, K_i^*, \lambda, K_d^*, \delta)$.

Typically, initial particles are randomly chosen from a feasible solution region. "Initialization phase" is used to generate m initial particles. At first, the feasible region of solution for tuning param-

```
P= initial population
While the termination criteria is not satisfied
    Fitness values calculation
    x^best=best particle of P
    Local search
    For each particle, calculate total force F
    For each particle, Movement
end while
```

Fig. 2. Pseudo code of the EM algorithm.