Engineering Applications of Artificial Intelligence 25 (2012) 430–442

Contents lists available at SciVerse ScienceDirect

Engineering Applications of Artificial Intelligence

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

A novel fractional order fuzzy PID controller and its optimal time domain tuning based on integral performance indices

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ARTICLE INFO

Article history:
Received 4 November 2010
Received in revised form
14 July 2011
Accepted 6 October 2011
Available online 3 November 2011

Keywords:
Fractional order controller
Fuzzy PID
FLC tuning
Integral performance indices
Genetic algorithm
Optimal PID tuning

ABSTRACT

A novel fractional order (FO) fuzzy Proportional-Integral-Derivative (PID) controller has been proposed in this paper which works on the closed loop error and its fractional derivative as the input and has a fractional integrator in its output. The fractional order differ-integrations in the proposed fuzzy logic controller (FLC) are kept as design variables along with the input–output scaling factors (SF) and are optimized with Genetic Algorithm (GA) while minimizing several integral error indices along with the control signal as the objective function. Simulations studies are carried out to control a delayed nonlinear process and an open loop unstable process with time delay. The closed loop performances and controller efforts in each case are compared with conventional PID, fuzzy PID and $PI^{\lambda}D^{\mu}$ controller subjected to different integral performance indices. Simulation results show that the proposed fractional order fuzzy PID controller outperforms the others in most cases.

1. Introduction

So far the focus of the engineering community had been primarily on expressing systems with integer order differential equations and using a multitude of analytical and numerical solutions to optimize the formulation and analysis procedure. However recent developments in hardware implementation (Das, 2008; Podlubny et al., 2002; Charef, 2006) of fractional order elements have brought a renewed wave in the modeling and analysis of new class of fractional order systems, which look at natural phenomenon from a whole new perspective. The theory for fractional order systems have existed for the last 300 years (Das, 2008). These extend our common notion of integer order (IO) differential equations to include fractional powers in the derivative and integral terms and have been shown to model natural processes more accurately than IO differential equations. However the mathematical analysis behind these kinds of FO systems is naturally more involved than IO systems.

From classical control engineering perspective the stress has always been to obtain linearized model of a process and the controller as the control theory for these types of systems are already well formulated. With the advent of fuzzy set-theory there is perhaps some more flexibility in designing systems and expressing the observations in a more easy to follow linguistic notation. The fuzzy logic controller in a closed loop control system is basically a static non-linearity between its inputs and outputs, which can be tuned easily to match the desired performance of the control system in a more heuristic manner without delving into the exact mathematical description of the modeled non-linearity. Traditional PID controllers work on the basis of the inputs of error, the derivative and the integral of error. An attempt can be made to justify the logic of incorporating a fractional rate of error as an input to a controller instead of a pure derivative term. Assuming that a human operator replaces the automatic controller in the closed loop feedback system, the human operator would rely on his intuition, experience and practice to formulate a control strategy and he would not do the differentiation and integration in a mathematical sense. However the controller output generated as a result of his actions may be approximated by appropriate mathematical operations, which have the required compensation characteristics. Herein lies the applicability of FO derivatives or integrals over their IO counterparts as better approximation of such type of control signals, since it gives additional flexibility to the design. The rationale

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0952-1976/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engappai.2011.10.004

behind incorporating fractional order operators in the FLC input and output can be visualized like an heuristic reasoning for an observation of a particular rate of change in error (not in mathematical sense) by a human operator and the corresponding actions he takes over time, which is not static in nature since the fractional differ-integration involves the past history of the integrand and as if the integrand is continuously changing over time (Das, 2008). Since the human brain does not observe the rate of change of a variable and its time evolution as pure numerical differentiation and integration, the fractional orders of differ-integration perhaps put some extra flexibility to map information in a more easily decipherable form. Our present day's mathematical modeling techniques, motivated by integer order differ-integrals do not give this flexibility and fails to describe it adequately. It is investigated in the present study that the fractional rate of error perhaps is capable of providing extra flexibility in the design of conventional FLC based PID controllers (Mudi and Pal, 1999) which works with error and its rate in a pure mathematical sense (IO). It is logical that the fractional rate of error introduces some extra degree of flexibility in the input variables of FLC and can be tuned also like the input–output scaling factors as the FLC gain and shape of the membership functions (MF) to get enhanced closed loop performance. The present study investigates the effectiveness of the proposed fuzzy FOPID controller at producing better performance compared to classical PID, fuzzy PID and even $PI^{\lambda}D^{\mu}$ controllers due to higher degrees of freedom for tuning. However, the objectives to be fulfilled by different controller structures must be chosen judiciously.

In this paper, the parameters of this new kind of fractional order fuzzy logic controller are optimally tuned with GA to handle a delayed nonlinear process and an open loop unstable process with time delay. Time domain performances of other controller structures viz. PID, fuzzy PID and $PI^{\lambda}D^{\mu}$ using Integral of Squared Control Signal (ISCO) along with various integral error indices like Integral of Time multiplied Absolute Error (ITAE), Integral of Time multiplied Squared Error (ITSE), Integral of Squared Time multiplied Error whole Squared (ISTES) and Integral of Squared Time multiplied Squared Error (ISTSE) are compared and the effectiveness of the different controllers are evaluated therein. Optimal tuning of FLC based PID can be found in few literatures. Hu et al. (1999) tuned the FLC MFs along with the input–output SFs using GA to minimize a weighted summation of Integral of Squared Error (ISE) normalized by maximum error, maximum percentage of overshoot and settling time normalized by simulation time. Woo et al. (2000) have shown that tuning of MFs have lesser effect on the closed loop performance than the input–output SFs of a fuzzy PID controller. Their relative impact can be viewed like changing the universe of discourse for fuzzy inference by the input SFs and amplifying the defuzzified control law by output SFs while acting as the conventional PID controller gains. Also, Pan et al. (2011a) designed an optimal fuzzy PID controller by minimizing the ITAE and ISCO to handle the effect of random delays in networked control systems (NCS). The present study assumes fixed MFs and rule base for the FLC as in its IO counterpart (Woo et al., 2000) and then tunes the fractional rate of error, fractional order integration of FLC output along with the input–output SFs to achieve optimum performance in time domain i.e. low control signal and error index.

The rest of the paper is organized as follows. Section 2 gives a brief review of the existing intelligent techniques for designing fractional order controllers and introduces the novelty of the proposition in the present study. Section 3 describes the structure of the fractional order fuzzy PID controller with the details of the rule base and the membership functions. The objective functions (time domain performance indices) along with genetic algorithm that has been used for the optimization are introduced in this section. Section 4 gives a comparison of the simulation results for two different classes of processes. The paper ends with the conclusions in Section 5, followed by the references.

2. Review of the existing intelligent tuning techniques of FO controllers

Classical notion of PID controllers has been extended to a more flexible structure $PI^{\lambda}D^{\mu}$ by Podlubny (1999) with the fractional differ-integrals as the design variables along with the controller gains. Several intelligent techniques have been proposed for efficient tuning of such fractional order $PI^{\lambda}D^{\mu}$ controllers. Dominant pole placement based optimization problems have been attempted to design $PI^{\lambda}D^{\mu}$ controllers using Differential Evolution in Maiti et al. (2008), Biswas et al. (2009) and Invasive Weed Optimization with Stochastic Selection (IWOSS) in Kundu et al. (2009). Maiti et al. (2008) also tuned a FOPID controller for stable minimum phase systems by minimizing ITAE criteria with Particle Swarm Optimization (PSO). A similar approach has been adopted for optimization of a weighted sum of Integral of Absolute Error (IAE) and ISCO to find out the controller parameters with GA by Cao et al. (2005) and with PSO by Cao and Cao (2006). Cai et al. (2009) tuned a $PI^{\lambda}D^{\mu}$ controller by minimizing the ITAE criteria using multi-parent crossover evolutionary algorithm. Luo and Li (2009) tuned a similar ITAE based $PI^{\lambda}D^{\mu}$ controller with Bacterial Foraging oriented by Particle Swarm Optimization (BF-PSO). Meng and Xue (2009) designed a $PI^{\lambda}D^{\mu}$ controller using a multi-objective GA, which minimizes the infinity-norm of the sensitivity (load disturbance suppression), and complementary sensitivity function (high frequency measurement noise rejection), rise time (t_r) and percentage of maximum overshoot (M_p) and additionally meets the specified gain crossover frequency (ω_{gc}), phase margin (ϕ_m) and iso-damping property rather than minimizing these as a single objective with a weighted summation like Zamani et al. (2009). Dorcak et al. (2007) proposed a frequency domain robust $PI^{\lambda}D^{\mu}$ controller tuning methodology using Self-Organizing Migrating Algorithm (SOMA), which is an extension of that proposed by Monje et al. (2008) using constrained Nelder–Mead Simplex algorithm. Zhao et al. (2009) tuned a $PI^{\lambda}D^{\mu}$ controller for inter-area oscillations in power systems by minimizing a weighted sum of the M_p, settling time (t_s) and error signal (e) using a GAPSO algorithm. Kadiyala et al. (2009) designed PSO based optimization problem for minimizing a weighted sum of t_r,M_p,t_s, steady-state error (e_{ss}) to design a $PI^{\lambda}D^{\mu}$ controller for aerofin control system. A PSO based similar approach can be found in Sadati et al. (2007) for SISO and MIMO systems. Sadati et al. (2008) designed a Neural Network based FOPID controller by minimizing the Mean Square Error (MSE) of the closed loop system while weights of the Neural Network and fractional orders are determined in the learning phase and the controller gains are adapted with change in the error. Ou et al. (2010) designed a FOPID controller for First Order Plus Time Delay (FOPTD) systems using Radial Basis Function (RBF) neural network where the controller gains and differ-integrals can be determined from the time constant and delay of the process after the neural network is trained with a large set of FOPID parameters and system parameters with available frequency domain robust tuning methods. Weighted sum of several time-domain and frequency-domain criteria based optimization approach has been used to tune a FOPID controller with PSO for an automatic voltage regulator by Karimi-Ghartemani et al. (2007) and Zamani et al. (2009, 2007). The approach in Zamani et al. (2007) also proposes an H_{∞}-optimal FOPID controller by putting the infinity norm of the weighted sensitivity