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Tuning of an optimal fuzzy PID controller with stochastic algorithms for networked control systems with random time delay

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ABSTRACT

An optimal PID and an optimal fuzzy PID have been tuned by minimizing the Integral of Time multiplied Absolute Error (ITAE) and squared controller output for a networked control system (NCS). The tuning is attempted for a higher order and a time delay system using two stochastic algorithms viz. the Genetic Algorithm (GA) and two variants of Particle Swarm Optimization (PSO) and the closed loop performances are compared. The paper shows that random variation in network delay can be handled efficiently with fuzzy logic based PID controllers over conventional PID controllers.

1. Introduction

Fuzzy logic controllers (FLC) have become more common in recent control applications to handle complex nonlinear processes [1,2]. It has been shown by many contemporary researchers that application of FLC enhances the closed loop performance of a PID controller in terms of handling change in an operating point for nonlinear processes by online updating the controller parameters [3,4]. FLCs generally work with a set of control rules, derived from experts' knowledge. Various fuzzy logic controller structures which are analogous to the conventional PID controllers are analyzed by Mann et al. [5] and Golob [6] using single or multiple input conditions (viz. error, change of error and rate of change of error). The universal approximation property as in [2] states that there is a way to implement fuzzy controllers for almost all types of nonlinear processes but there is no mathematical formulation to decide what would be the appropriate choice of fuzzy parameters in implementing them. Hence empirical rules are used for the choice of various fuzzy parameters as discussed in [7]. The fuzzy tuning parameters may be the choice of inputs, scaling factors, membership functions (number or type or both), rule base, fuzzification–defuzzification and inferencing techniques [7].

It has been shown in [2–4,8] that a change in input–output scaling factors (SF) affects the control performance of the FLC to a greater extent compared to the choice of the type of membership functions (MF). Also, the output SFs act like the controller gains and hence directly affect the stability of the closed loop system. So, the output SFs have greater importance than the input SFs on the closed loop performance of a process and hence should be chosen very carefully. The FLC tries to mimic the operator's expertise by incorporating a nonlinear relationship between the error and the derivative of error and that of the output control signal [1,2]. Often, fixed SFs and predefined MFs become insufficient for achieving an optimal performance and need to be tuned online. It has been shown by Woo et al. [8] that a change in input and output scaling factors (SF) affects the control performance to a higher extent than variation in overlap of the fuzzy membership functions. Hence, in the present study, only input–output SFs are tuned to find out the optimal parameters of a FLC based PID controller to handle random variation in network delay.

In recent past, fuzzy logic based PID controllers have become more common to handle complex dynamic processes. Diverse linear and nonlinear plants have been tuned by Mudi and Pal [3,4] and Bhattacharya et al. [9] with a fuzzy gain tuning mechanism and implemented along with a two input-one output FLC. Various improvements in conventional PID controllers using

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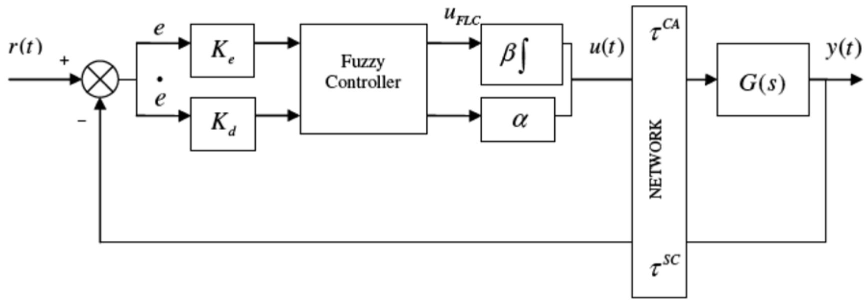

Fig. 1. Optimal fuzzy PID structure with random network delays.

a fuzzy inferencing mechanism have been investigated in [10–13]. Various tuning methods have also been proposed for tuning the fuzzy controller parameters as in [14] and others involving the Genetic Algorithm etc. [10,14–16]. Mathematical quantification using non symmetrical fuzzy sets for a generalized class of controllers has been discussed by Mohan and Sinha [17] and the applicability of various types of fuzzy controllers from control perspective are analyzed. Performances of fuzzy PIDs are compared with normal PIDs and model predictive control in [18]. In [18] the fuzzy parameters are tuned using the Nelder–Mead downhill simplex method. Also various performance indices [18–20] for the cost function are compared in [18]. PID controller parameters have been tuned by a fuzzy system by Kazemian [21]. Fuzzy logic coupled with neural networks has also been used to tune PID parameters in [19].

Due to quantum leaps in communication systems, in recent years, it has become more normal to use a common communication channel like Ethernet or CAN bus etc. for transmission of the control signal and the measured output. This helps in reducing wiring costs and eliminates the necessity for maintaining dedicated communication channels for each control parameter [22,23]. However, this type of networked control system is not a panacea and has various unresolved issues like transmission delays and packet dropouts [24] which can degrade control performance. Hence these finer nuances over conventional control systems need to be delved into before actually implementing it in a real plant.

In recent NCS applications, fuzzy logic based controllers have been proved to be efficient in handling packet drop-out [25,26] and network induced delays [23]. Various improvisations over existing protocols have been proposed using fuzzy logic in [26–28] which help in congestion control and reduce delays and packet losses in the network. We, however intend to focus on existing transmission protocols and evaluate performances of various controllers for varying levels of transmission delays. Different models based on fuzzy logic have been proposed for the modelling of a NCS in [29,30]. Various nonlinear systems which can be represented by equivalent fuzzy models have been implemented over the network in [31–40] and their performance with respect to delays and packet dropouts have been analyzed. A Matlab based co-simulation tool called TrueTime which helps in analyzing controller task execution in real time kernels along with network transmissions and continuous plant dynamics has been used in the analysis of fuzzy PID controllers implemented over the network in [41–48]. Fuzzy logic controllers with their improvisations have been implemented to handle network induced delays and their performances over their conventional counterparts have been investigated in [49–52]. A fuzzy PID controller has been implemented for a network based cascade control system in [53,54]. However no optimization of the fuzzy PID parameters has been done to check for the optimum values of these parameters. Also time domain error indices like ITAE, Integral of Absolute Error (IAE) etc. based optimization have not been included in the analysis, and the saturation of controller output for these controllers has not been investigated. In the present work, we implement a fuzzy PID controller for a higher order plant and also a plant with time delay and optimize the fuzzy parameters with stochastic algorithms like the Genetic Algorithm and Particle Swarm Optimization, taking the random delays in the network into account. Also the effectiveness of the various stochastic algorithms and their variants for tuning are compared in the present study. Our cost function not only includes ITAE but also has the controller output taken into account to avoid controller saturation.

A practical networked control loop generally consists of a deterministic inherent system delay and two stochastic delays [23] viz. the controller to actuator delay (τ^{CA}) and the sensor to controller delay (τ^{SC}) as shown in Fig. 1. Under these conditions, the process to be controlled over a network can be considered as randomly varying with time. It has been suggested by Mudi and Pal [3,4] that FLCs have a higher capability of enforcing optimal performance in a control loop over conventional optimal PIDs for nonlinear and time-varying systems. In this paper, an optimal fuzzy PID controller has been tuned by minimizing the sum of ITAE and squared value of control signal considering random variation in network delay and the performance is compared with a conventional optimal PID controller, tuned with the same criteria.

The performance of the optimal controllers also depends on the choice of a suitable optimization algorithm, used for controller tuning. Many stochastic optimization algorithms have come up in control applications, especially in controller tuning [55–57]. In this paper, a PID and fuzzy-PID controller have been tuned with two stochastic optimization algorithms, namely the Genetic Algorithm and Particle Swarm Optimization with its two variants viz. *gbest* and *lbest* PSO [58,59].

The rest of the paper is organized as follows. Section 2 discusses the structure of the optimal fuzzy PID. A brief description of the two stochastic optimization methods used for controller tuning is discussed in Section 3. Section 4 presents the simulation results of two test plants with and without random network delay. The paper ends with the conclusion as Section 5 followed by the references.

2. Structure of the fuzzy PID controller and its optimal tuning

2.1. Fuzzy PID controller to handle random network delay

The fuzzy PID structure (Fig. 1) used in this paper is a combination of fuzzy PI and fuzzy PD controllers with K_e, K_d as input SFs and α, β as output SFs as discussed by Woo et al. [8], Yesil et al. [60], Qiao and Mizumoto [61], Li et al. [62], Mohan and Sinha [63] and Mann et al. [64]. This uses two-dimensional linear rule base (Fig. 2) for error (e), error derivative ($\dot{e}$) and FLC output (u_{FLC}) with standard triangular MFs (Fig. 3) and Mamdani-type inferencing.

In Figs. 2 and 3, the fuzzy linguistic variables NL, NM, NS, ZR, PS, PM, PL represent Negative Large, Negative Medium, Negative Small, Zero, Positive Small, Positive Medium and Positive Large respectively. The FLC output (u_{FLC}) is determined by using the center of gravity method by defuzzification.