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Computational intelligence approach to PID controller design using the universal model

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ABSTRACT

Despite the popularity of PID (Proportional-Integral-Derivative) controllers, their tuning aspect continues to present challenges for researches and plant operators. Various control design methodologies have been proposed in the literature, such as auto-tuning, self-tuning, and pattern recognition. The main drawback of these methodologies in the industrial environment is the number of tuning parameters to be selected. In this paper, the design of a PID controller, based on the universal model of the plant, is derived, in which there is only one parameter to be tuned. This is an attractive feature from the viewpoint of plant operators. Fuzzy and neural approaches – bio-inspired methods in the field of computational intelligence – are used to design and assess the efficiency of the PID controller design based on differential evolution optimization in nonlinear plants. The numerical results presented herein indicate that the proposed bio-inspired design is effective for the nonlinear control of nonlinear plants.

1. Introduction

Despite many efforts to find an alternative, the PID (Proportional-Integral-Derivative) controller continues to be the main component in industrial control systems, included in the following forms: embedded controllers, programmable logic controllers, and distributed control systems. From the viewpoint of simplicity and effectiveness, the PID controller represents a good solution for controlling many practical applications. However, the control literature still shows different tuning structures for the PID control in order to overcome the complex dynamics and limitations [5,6].

Since the 1990s, many methodologies for setting the gains of PID controllers have been proposed. In this context there are classical (Ziegler/Nichols, Cohen/Coon, Abas, pole placement and optimization) and advanced (minimum variance, gain scheduling and predictive) techniques [5,6,3,52]. Some disadvantages of these control techniques for tuning PID controllers are: (i) excessive number of rules to set the gains, (ii) inadequate dynamics of closed-loop responses, (iii) difficulties associated with nonlinear processes, and (iv) mathematical complexity of the control design [50]. Therefore, the tuning aspect of PID controllers is of great interest to academic and industrial communities, especially in relation to obtaining a reduced number of parameters to be selected and a good performance when dealing with complex processes [3].

Another possible solution to deal with complex processes is the implementation of PID control systems based on knowledge and learning. These systems collect process information and select values for the control variable from heuristic rules to

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achieve and maintain the process output at the desired operating point [16]. Recently, a wide variety of fuzzy logic Proportional-Integral-like controllers and fuzzy logic PID-like controllers [27,36,37], as well as PID-like neural controllers [32,53,58] have been developed.

Being composed of control rules comprising conditional linguistic statements that state the relationship between input and output variables, the fuzzy logic PID-like controllers have the ability to emulate human knowledge and experiences and to deal with model uncertainty. PID neural controllers accommodate poorly modeled, nonlinear, dynamic systems; however, it is important to note that neurocontrol is not a suitable method for linear or linearizable systems, where it can result in poorer performance in terms of computation time and controller convergence.

Several hybrid methodologies based on computational intelligence approaches including fuzzy, neural models and evolutionary algorithms have been developed [4,22,33]. In this context, the use of differential evolution is an emerging approach in fuzzy and neural design. The differential evolution algorithm is a greedy evolutionary algorithm that incorporates an efficient means of self-adapting mutation using small populations. The potentialities of differential evolution are its simple structure, easy use, convergence property, quality of solution and robustness [14]. In this study, fuzzy and neural methods based on differential evolution optimization are presented to improve the PID controller design.

The contribution of this paper is the analysis of the intelligent tuning and design aspects of a PID controller based on the universal model of the plant where there is only one design parameter to be selected. The proposed controller has the same structure as a conventional three-term PID controller. The design is based on a version of the generalized minimum variance control of Clarke and Gawthrop [13] using new tuning approaches based on computational intelligence with hybrid structures including fuzzy and neural paradigms with differential evolution optimization. Simulation tests are shown for nonlinear plants (continuous stirred-tank reactor and heat exchanger).

The remainder of this paper is organized as follows. The idea design of the PID controller, based on the universal model, is derived in Section 2. Tuning and analysis aspects of the proposed approach are shown in Section 3. Applications and conclusions are given in Sections 4 and 5, respectively.

2. Controller design

In this section a PID controller design is proposed based on an alternative representation for dynamic systems [34,39]. The system output can be approximated by the universal model defined as follows:

$$\hat{y}(k+d) = \sum_{i=0}^{N} \Delta^i y(k) + (d-1) \cdot b \cdot \sum_{i=0}^{N} \Delta^i u(k-1) + b \cdot \left\{ u(k-1) - \sum_{i=0}^{N-1} \Delta^i u(k-2) \right\}, \tag{1}$$

where Δ is the backward difference, d is the dead time, $y(k)$ is the output, $u(k)$ is the input, and $\hat{y}(k)$ is an estimate of the system output.

It can be observed that the universal model is simple and has only one parameter, b, which contains the system information. Considering the approach presented in Park et al. [34] the dimension of the universal model, N, can be chosen. The parameter b can be derived from the previous measurements of the system, i.e., if the values of $y(k)$, $\sum_{i=0}^{N} y(k-1)$ and $\Delta^N u(k-1-d)$ are given, b can be calculated from Eq. (1) as follows:

$$b = \frac{\left\{ y(k) - \sum_{i=0}^{N} \Delta^i y(k-1) \right\}}{\Delta^N u(k-1-d)}. \tag{2}$$

Using the universal model, Eq. (1), and the generalized minimum variance control law, Eq. (2), it is possible to obtain the desired PID structure as follows [14]:

$$u(k) = \frac{1}{Q(z^{-1})} \left\{ \Lambda(z^{-1}) y_r(k) - [\Gamma(z^{-1}) \hat{y}(k+d)] \right\}, \tag{3}$$

$$u(k) = \frac{1}{H(z^{-1})} \left[\Lambda(z^{-1}) y_r(k) - \Gamma(z^{-1}) \sum_{i=0}^{N} \Delta^i y(k) \right], \tag{4}$$

where $y_r(k)$ is the reference and

$$H(z^{-1}) = Q(z^{-1}) + \Gamma(z^{-1}) \cdot b \cdot \left\{ \left[1 + (d-1) \sum_{i=0}^{N} \Delta^i \right] z^{-1} - \sum_{i=0}^{N-1} \Delta^i z^{-2} \right\}, \tag{5}$$

Next, $N = 2$, $\Gamma = 1$, $d = 1$ and $\Lambda = 1$ are applied to Eqs. (4) and (5). Since Q is free to be chosen, then it is possible to tune $Q = q_0 \Delta - \widetilde{Q}$, (in order to guarantee offset elimination for setpoint and load changes), where $\widetilde{Q}$ is a polynomial defined as

$$\widetilde{Q}(z^{-1}) = \Gamma(z^{-1}) b \left\{ \left[1 + (d-1) \sum_{i=0}^{N} \Delta^i \right] z^{-1} - \sum_{i=0}^{N-1} \Delta^i z^{-2} \right\}. \tag{6}$$

Therefore, the law for a digital PID controller that has the same structure as a conventional PID controller is given by