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Fractional Order PI$^{\lambda}$D$^{\mu}$ Control Design for a Class of Cyber-Physical Systems with Fractional Order Time-Delay models:

Fractional PIλDμ Design for CPS with Time-Delay models

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ABSTRACT

The control of cyber-physical systems (CPS) is a great challenge for researchers in control theory and engineering mainly because of delays induced by merging computation, communication, and control of physical processes. Consequently, control solutions for time-delay systems can be applied efficiently for many CPS system configurations. In this article, a fractional order PI$^{\lambda}$ and PI$^{\lambda}$D$^{\mu}$ control design is investigated for a class of fractional order time-delay systems. The proposed control design approach is simple and efficient. The controller parameter's adjustment is achieved in two steps: first, the relay approach is used to compute satisfactory classical PID coefficients, namely k_p, T_i and T_d. Then, the fractional orders λ and μ are optimized using performance criteria. Simulation results show the efficiency of the proposed design technique and its ability to enhance the PID control performance.

KEYWORDS

Cyber-Physical System, Fractional Order Control, Fractional PI$^{\lambda}$ Controller, Fractional PI$^{\lambda}$D$^{\mu}$ Controller, Optimization, Parameters Adjustment, Performance, Relay Method, Time-Delay Systems

1. INTRODUCTION

Fractional calculus (FC) is an old mathematical analysis concept which is attracting great interest nowadays (Ladaci et al., 2008; Ladaci and Charef, 2012; Rabah et al., 2017). Initially introduced pure mathematics, recently, FC has invested various engineering domains (Ladaci and Charef, 2006; Petráš, 2011). Fractional order models have proven to better represent many physical systems, like dielectric polarization, semi-infinite transmission lines, viscoelasticity, etc. (Schmidt and Gaul, 2002). In the automatic control engineering field, an important effort is done towards design and development and application of fractional order controllers with various control strategies (Khettab et al., 2019; Vafaei et al., 2019).

At the other hand, time delay systems (TDS) are focusing many research actions for their multiple potential applications. In particular, cyber-physical systems (CPS) are generally modelized as TDS because they involve communication network delays with embedded control and signal processing

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systems. Usually, the control unit gathers sensor data over a communication network and sends the calculated control value in order to regulate the physical system. Such distributed regulators are highly sensitive to induced delays. The problem of control of TDS system for CPS application has gathered many researches with various control approaches (Lou et al., 2016; Shen et al., 2014; Xia et al., 2011). The originality of this work is addressing the class of fractional order time-delay systems which generalizes the CPS control problem modelization.

Recently, a great number of researchers focused their work on the stability analysis of fractional order time-delay systems (Lazarević, 2011; Zhang et al., 2016; Li et al., 2014; He et al., 2018). Finite-time stability has been investigated in (Lazarević and Spasić, 2009; Chen et al., 2014; Naifar et al., 2019), while different stability criteria for this class of systems have been proposed in literature (Hwang and Cheng, 2006; Merrikh-Bayat and Karimi-Ghartemani, 2009; Shi and Wang, 2011; Fioravanti et al., 2012; Gao, 2014). Stability of linear fractional order systems with delays has been studied in many papers (Busłowicz, 2008), also fractional-order nonlinear systems with delay (Lazarević and Debeljković, 2008; Wang and Li, 2014), neutral fractional-delay systems (Bonnet and Partington, 2002; Xu et al., 2016) and fractional-order time-varying delay systems (Boukal et al., 2016).

In the field of control engineering, the introduction of fractional operators and systems has proven certain ability for performance enhancement Li and Chen (2008). One of the pioneering works was developed by Podlubny in 1999 who has proposed a generalized form for PID controllers, namely $PI^{\lambda}D^{\mu}$ controllers, using an integrator of order λ and a differentiator of order μ (where λ and μ have real values) (Podlubny, 1999). He showed that the fractional order PID control improves the control system performance in comparison with the classical PID controller because of the extra real parameters λ and μ involved. The implementation of this fractional controller needs these non-integer operators to be approximated, using frequency domain approximations such as Oustaloup's method (Oustaloup et al., 2000) and Charef's method (Charef et al., 1992).

However, the problem of PID controllers' tuning remains an important issue (Rabah et al., 2018; Bourouba et al., 2018). There exist many adjusting techniques that do not require any model of the plant to control. All that is needed to apply such rules is to have time response of the plant. Examples of such sets of rules are those due to Ziegler and Nichols, Cohen and Coon, and the Kappa-Tau rules (Valério and Costa 2006). In particular, the Ziegler-Nichols method (Ziegler et al., 1942) still remains popular, particularly in industry. An interesting similar modern approach is based on the relay auto tuning (Atherton et al., 2014).

In this paper, a fractional order PI^{λ} and $PI^{\lambda}D^{\mu}$ control design technique is proposed for a class of fractional order Time-Delay systems. The controller parameter's adjustment is achieved in two steps: first, the relay approach is used to compute satisfactory classical PID coefficients, namely k_p, T_i, and T_d. Then, the fractional orders λ and μ are optimized using performance criteria.

This paper is organized as follows: In Section 2, the design of both integer order PI and PID controllers with relay feedback method is given. Charef's approximation method for fractional order systems is introduced in Section 3, whereas the proposed design methodology for fractional order PI and PID controllers is given in Section 4. In Section 5, simulation examples about integer and fractional time delay systems are presented. Concluding remarks are given in Section 6.

2. DESIGN OF INTEGER ORDER PI AND PID CONTROLLERS FOR TIME-DELAY SYSTEMS

The transfer function of an integer order PI controller and the integer order system are given respectively by:

$$C\left(s\right) = k_p\left(1 + \frac{1}{T_i s}\right) \tag{1}$$

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