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Cuckoo search algorithm based design of interval Type-2 Fuzzy PID Controller for Furuta pendulum system

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ABSTRACT

The Interval Type-2 Fuzzy Logic Controller (IT2FLC) is an advanced version of Type-1 Fuzzy Logic Controller (T1FLC) that improves the control strategies by using the advantage of its footprint of uncertainty of the Fuzzy Membership Function (MF). Numerous experimental investigations have shown the superiority of IT2FLC over T1FLC, particularly in high level of uncertainties and nonlinearities. Nevertheless, the systematic design of IT2FLCs remains an attractive problem because of the difficulty in finding the parameters associated with IT2FLCs. In this study, a novel application of Cuckoo Search (CS) algorithm in the design of an optimized cascade Interval Type-2 Fuzzy Proportional Integral Derivative Controller (IT2FPIDC) is presented. The PID gains and the parameters of the antecedent MFs of IT2FPIDC are optimized using CS algorithm. Considering the higher number of parameters to be optimized in cascade IT2FPIDC, the CS method was employed due to its high convergence speed and less computational cost. The proposed CS based cascade optimized IT2FPIDC is compared with CS-based Type-1 Fuzzy Proportional Integral Derivative Controller (T1FPIDC). The present research presents a new application of proposed CS based cascade optimized IT2FPIDC for the balancing control and trajectory tracking control of the Furuta pendulum (FP) which is a nonlinear, non-minimum phase and unstable system. Furthermore, the disturbance rejection ability of the proposed controller is analyzed. The proposed control strategies are evaluated on FP produced by Quanser through numerous experimentations in the real world as well as simulation. The performance characteristic considered for these controllers are settling time (t_s), steady state error (E_{ss}), rise time (t_r) and maximum overshoot (M_p). Both the simulation and real world experiments results demonstrated the robustness and effectiveness of the proposed CS based IT2FPIDC with respect to parameter variation, noise effects and load disturbances, with an improved performance of 27.1%, 5.7% and 20.8% for t_r, t_s and M_p respectively over its CS based T1FPIDC counterpart.

1. Introduction

The real industrial systems exhibit a significant level of uncertainties and nonlinearities (Castillo and Melin, 2012). Looking at this from the control viewpoint, it poses some difficulties in controller design (Sanchez et al., 2015). Numerous controller architectures have been proposed by researchers to overcome these difficulties (Oh et al., 2011). Modern control strategies, such as adaptive, variable structure, nonlinear and optimal have been used in the past decades (Krstic et al., 1995; Hung et al., 1993). Even though these control approaches exhibit good performance, they are relatively complex and difficult to implement (Caraveo et al., 2016). Recently, the unprecedented interest of the control engineering community was focused on the applications of Type-2 Fuzzy Logic Controller (T2FLC) to nonlinear systems (Castillo and Melin, 2012; Hamza et al., 2015a; John and Coupland, 2007). Various records of successful applications of T2FLC have been published with the expectation of generalizing such strategies to many challenging control issues efficiently (Castillo et al., 2016; Yassin et al., 2016; Zeghlache et al., 2015; Li et al., 2015a, 2015b).

The T2FLC is of two types, namely, Interval Type-2 Fuzzy Logic Controller (IT2FLC) that uses Interval Type-2 Fuzzy Sets (IT2FSs) and General Type-2 Fuzzy Logic Controller (GT2FLC) that uses general type-2 fuzzy sets (Sanchez et al., 2015). IT2FLC is employed in this research because it is more practicable and has less computational complexity (Kumbasar and Hagras, 2014). In addition, IT2FLC can implement a very complex control surface that cannot be achieved by a T1FLC using the same rule base (Tai et al., 2016). This is due to the advantage of Footprint of Uncertainty (FOU) present in the corresponding MF of IT2FLC. The IT2FS construction methods can be roughly categorized into two. The first method is to construct the IT2FS

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from an existing T1FS, and the second is the direct design of IT2FSs from either collected experimental data by employing clustering methods or artificial neural network structures. There are several experimental pieces of evidence indicating substantial improvements in terms of efficiency and accuracy of IT2FLC over T1FLC counterpart (Sanchez et al., 2015; Raju and Pillai, 2016; Li et al., 2015c).

The main difficulty in IT2FLC design is that the searching for the suitable values of its parameters and structure is time consuming and difficult (Castillo and Melin, 2014). This problem serves as the driving force that motivated this research. Some researchers proposed the use of bio-inspired optimization algorithms to help in the automatic design of IT2FLC (Hamza et al., 2015a; Castillo and Melin, 2014). The bio-inspired optimization algorithms that have been applied to the design of IT2FLC include genetic algorithm (GA) (Lu, 2015), Ant Colony Optimization (ACO) (Juang and Hsu, 2009), Particle Swarm Optimization (PSO) (Oh et al., 2011), Big-bang big-crunch optimization (Kumbasar and Hagras, 2014), biogeography optimization (Sayed et al., 2013), Bacterial foraging optimization (Kiani et al., 2013), Chemical optimization (Melin et al., 2013), simulated annealing (Doostparast Torshizi and Fazel Zarandi, 2014), Tabu Search optimization (Almaraashi and Hedar, 2014), firefly (Nguyen Cong and Meesad, 2013), bee colony optimization (Amador-Angulo et al., 2016) and hybrid algorithms (Hamza et al., 2015a). These algorithms have the ability to obtain near optimal parameters of IT2FLC, but the computational time required is quite high. None of these methods were declared as the best so far (Castillo and Melin, 2012; Hamza et al., 2015a).

An observer-based adaptive output tracking control for nonlinear systems under input saturation and unknown time delay was investigated in Zhou et al. (2017). The fuzzy logic system (FLS) was used to approximate the system unknown function. The IT2FLS based stability and stabilization of nonlinear discrete-time switched systems under average Dwell time was studied in Liu et al. (2017). The IT2FLS was used for modelling and stability of system. The adaptive sliding mode control for discrete-time Takagi-Sugeno (T-S) fuzzy systems with external disturbances and actuator faults was consider in Wang et al. (2016). The application of the bio-inspired optimization algorithms to optimized the parameters associated with FLS was not considered in the investigations presented in Zhou et al. (2017), Liu et al. (2017), Wang et al. (2016).

In this study, a novel application of the bio-inspired optimization algorithms optimize the scaling factors and Membership Functions (MFs) parameters of cascade Interval Type-2 Fuzzy Proportional Integral Derivative Controller (IT2FPIDC) called cuckoo search (CS) is proposed. The CS algorithm has been chosen because it has a relatively high convergence speed and a low computational cost compared to most of the mentioned state-of-art bio-inspired optimization algorithms (Yang and Deb, 2014; Gonzalez et al., 2014). The T-S type-2 fuzzy systems with center-of-set type reduction will be used in this investigation (Li et al., 2014). The T-S fuzzy system is an effective method that can handle complex nonlinear systems (Li et al., 2015a). The rules base and consequent MFs will not be optimized in the design of IT2FPID controller. Only the antecedent MFs parameters and the scaling factors are optimized. This is to clearly show the effect of the extra degree of freedom (DOF) of IT2FPIDC provided by its FOU.

This research proposes the cost function in time domain that is comprised of four important performance indexes namely: steady state error, settling time, rise time and maximum overshoot. It is demonstrated that IT2FPIDCs provide the opportunity for CS algorithm to search for more optimal solution which translates to a better controller compared to T1FPIDC with regards to the proposed cost function. The cascade structure is used for both IT2FPIDC and T1FPIDC. The cascade control strategy is effective for systems with large time error and high level of disturbances (Oh et al., 2011). The hardware-in-loop (HIL) structure that is available in QUARC targets libraries of MATLAB is used to provide a real-time controller interface for validation of the proposed IT2FPIDC and T1FPIDC.

The experimental validation in the present work is similar to the one presented in Kumar and Ganapathy (2015). The main difference is in the proposed controller. The controller proposed in Kumar and Ganapathy (2015) is the hybrid fuzzy sliding mode controller which is more complex compared with our proposed controller. Also, only scaling factors are optimized using GA and PSO in Hamza et al., (2015b), which is differ from the present paper since the MF parameters was included in the optimization.

The Furuta pendulum (FP) is an inverted pendulum used in most control laboratories. In the past two decades, FP was used widely as an experimental setup for explaining and testing of different kinds of control algorithms (Acosta, 2010). The FP is nonlinear, non-minimum phase and unstable plant. Thus, the FP is used to validate the proposed controller in real world experiments. There are four main control objectives of FP which are: swing-up control, stabilization control, switching control and trajectory tracking control (Aranda-Escolástico et al., 2016).

The problem of stabilization control and the trajectory tracking control of the FP was solved using CS based cascade IT2FPIDC in this study. Additionally, the disturbance rejection ability of the proposed CS based cascade IT2FPIDC was analyzed. The present investigation starts with presenting the simulation studies comparing the performances of the optimized IT2FPIDC and optimized T1FPIDC structures. Subsequently, the real-world experiment using FP produced by Quanser was presented to validate the proposed cascade control strategies. The performance of the optimized IT2FPIDC and optimized T1FPIDC was compared through simulation and real time experiments. Experimental and simulation results indicated that the effectiveness and robustness of the proposed CS based IT2FLC on the FP control with respect to the parameter variation, load disturbances, and noise effects improved over state of the art method. It has been demonstrated that the reference tracking and the disturbances rejection performance of the optimized cascade IT2FPIDC is better in the presence of uncertainties, parameter variation, and noise, especially in experiments, compared with optimized cascade T1FPIDC. The experimental results agreed with the simulation results which justifies the availability of the proposed nonlinear model of FP and confirm the performance of the proposed control methods. The obtained results indicate that the CS based design strategy could achieve advanced quality solutions with fewer computational time. Hence, the CS can be used in future designs of more complex IT2FLCs with a higher number of inputs/outputs parameters in applications that require excellent optimization results in the shortest possible time.

2. Interval Type-2 fuzzy logic systems

Some important properties and definitions about IT2FSs is provided in this section. The idea of fuzzy logic systems and T2FS was pioneered by Zadeh in 1965 and 1975 respectively (Zadeh, 1974, 1965). All the secondary grades of the IT2FS are equal to 1 and it is completely described by upper MF (UMF) and lower MF (LMF). When $\mu_{\widetilde{A}}(x, u)$=1 for $\forall u \in J_x \subseteq [0, 1]$, an IT2FS is constructed as shown in Fig. 1.

A T2FS $\widetilde{A}$ is charaterised by T2-MF $\mu_{\widetilde{A}}(x, u)$, for $x \in X$ and $u \in J_x \subseteq [1,0]$, that is,

$$\widetilde{A} = \{((x, u), \mu_{\widetilde{A}}(x, u)) \mid \forall u \epsilon J_x \subseteq [0, 1]\}, \text{ in which} 0 \le \mu_{\widetilde{A}}(x, u) \le 1. \quad (1)$$

The primary membership of x can be represented as: $J_x \subseteq [0,1]$ and the secondary set is $\mu_{\widetilde{A}}(x, u)$ which is T1FS. Therefore, a T2-membership grade should lie between or be equal to 0 and 1 (Karnik et al., 1999a). Each primary membership has its corresponding secondary membership (also lies in [1,0]) that defined its possibilities. The uncertainty can be represented by the FOU region (Karnik and Mendel, 1998).

The T2FLC consists of the following blocks: Fuzzification, inference