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Practical Implementation for the interval type-2 fuzzy PID controller using a low cost microcontroller

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Abstract In this study, we propose an embedded real-time interval type-2 fuzzy proportional – integral – derivative (IT2F-PID) controller which is a parallel combination of the interval type-2 fuzzy proportional – integral (IT2F-PI) controller and the interval type-2 fuzzy proportional – derivative (IT2F-PD) controller. The proposed IT2F-PID controller is able to handle the effect of the system uncertainties due to the structure of the interval type-2 fuzzy logic controller. The proposed IT2F-PID controller is implemented practically using a low cost PIC microcontroller for controlling the uncertain nonlinear inverted pendulum to minimize the effect of the system uncertainties due to the uncertainty in the mass of the pendulum, the measurement error in the rotation angle of the pendulum and the structural uncertainty. The test is carried out using the hardware-in-the-loop (HIL) simulation. The experimental results show that the performance of the IT2F-PID controller improves significantly the performance over a wide range of system uncertainties.

1. Introduction

Most of the industrial processes are still the conventional PID controllers due to their simple control structures, affordable price, and effectiveness for linear systems [1]. However, when the process to be controlled has a high level of complexity, such as, time delay, high order, modeling nonlinearities, vague systems without precise mathematical models, and structural uncertainties, the performance of a PID control system becomes unsatisfactory and fails to guarantee the requirements in most of the practical situations [2]. For these reasons, many researchers have attempted to combine a conventional PID controller with a fuzzy logic controller (FLC) in order to achieve better system performance over a conventional PID controller. The fuzzy PI controller [3] and the fuzzy PD controller [4] are developed to improve the system performance rather than the conventional PID controllers. The fuzzy PI and the fuzzy PD controllers are combined to get a fuzzy PID controller in order to improve the system performance [5]. It's knowledge base consists of two dimensional rule base for the PI and PD controllers to obtain overall improved performance. There are different control structures for the fuzzy PID controller mentioned in [6,7], in order to improve the

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closed loop systems. Despite the significant improvement of system performance with fuzzy PID controllers over their conventional counterparts, it should be noted that they are usually not effective if cases where the system to be controlled has system uncertainties as ordinary fuzzy controllers (type-1 fuzzy logic controllers; T1-FLCs) have limited capabilities to directly handle data uncertainties [8].

The concept of type-2 fuzzy set (T2-FS) is an extension and generalization of the type-1 fuzzy sets (T1-FSs) and it was first introduced by Zadeh [9]. FLCs that are described with at least one T2-FS are called type-2 fuzzy logic controllers (T2-FLCs) [10]. It has also been shown that T2-FSs are much more powerful to handle uncertainties and nonlinearities directly [11]. The major problem with T2-FLC is that the computations are much more complicated compared to T1-FLCs. Therefore, Mendel [10] has been proposed a special type of T2-FS called an interval type-2 fuzzy set (IT2-FS) in which the output of interval type-2 fuzzy is uncertain with an interval. The IT2-FLCs have been successfully implemented in controller design [12–25]. The structure of the IT2-FLC has four components, which are a fuzzifier, a rule base, a fuzzy inference engine, and an output processor. In the IT2-FLC, the output sets are interval type-2, so we have to use an extended version of type-1 defuzzification methods. The extended defuzzification operation with the type-2 case gives a T1-FS at the output. Since this operation takes us from the T2-FSs of the IT2-FLC to a T1-FS, this operation is called type-reduction and calls the type-1 set so obtained a type-reduced set [26]. The type-reduced set is a collection of the outputs of all of the embedded T1-FLCs [27]. The type-reduction is usually performed by iterative Karnik–Mendel (KM) algorithms [28], which are computationally intensive. However, the IT2-FLCs have a computational overhead associated with the computation of the type-reduced fuzzy sets using the KM algorithm [10]. This computational overhead reduces the real-time performance of the IT2-FLC, especially when operating on industrial embedded controllers which have limited computational and memory capabilities. So, the type-2 computational overhead can limit the application of the IT2-FLCs in industrial embedded controllers. Wu and Mendel [29] proposed a method to approximate the type-reduced set, thus avoiding the use of the iterative KM algorithm. This method calculates the inner- and outer-bound sets for the type-reduced set. These two sets can not only be used to estimate the uncertainty contained in the output of the IT2-FLC, but can also be used to directly derive the defuzzified output under certain conditions. Thus, the inner- and outer-bound sets have the potential to eliminate the computational bottleneck of an IT2-FLC.

As reported in [5,30], it is convenient to combine the fuzzy PI and the fuzzy PD controllers in a parallel structure to form a T1F-PID controller. Such a fuzzy PID structure is simple and can be theoretically analyzed. However, the main drawback of the T1F-PID controller is its limited capability to directly handle data uncertainties [8]. Thus, the main objective of this paper is developing and implementing an IT2F-PID controller taking into its consideration the advantages of using a parallel structure consisting of fuzzy PI and fuzzy PD controllers and the advantages of the type-2 fuzzy controllers to overcome the uncertainty problems. The proposed IT2F-PID controller using the Wu-Mendel type-reduction method and the Mamdani interval type-2 fuzzy rule base is implemented practically using a low cost PIC microcontroller (P18F4685) and its performance is tested using HIL simulation for controlling an uncertain nonlinear inverted pendulum. The main problem in an inverted pendulum system is the uncertainty which is divided into three groups; the uncertainty in the mass of the pendulum, the structural uncertainty which caused by parameters are difficult or impossible to get a precise measure or that the parameters tend to vary as a function of time, temperature, etc. and the uncertainty due to the measurement error in the rotation angle of the pendulum. The proposed IT2F-PID controller is designed and implemented to overcome the uncertainties in the inverted pendulum system. The rest of the paper is organized as follows. In Section 2, the IT2F-PID controller is included. The description of the mathematical model of the nonlinear inverted pendulum is presented in Section 3. Section 4, presents the hardware implementation of the IT2F-PID controller and practical results followed by the conclusions and the relevant references.

2. Interval type-2 fuzzy PID controller

Generally, an IT2-FLC is either a PD or a PI depending on the output of fuzzy control rules; if the output is the control signal it is said to be an IT2F-PD controller and if the output is the change of control signal it is said to be an IT2F-PI controller. An IT2F-PID controller may be constructed by introducing the third information besides error and derivative of the error, which is sum of error, with a 3-D rule base. Such an IT2F-PID controller with a 3-D rule base is difficult to construct because a 3-D rule base can be very complex when the number of quantizations of each rule dimension increases; in this case, the control rule number increases cubically with the number of quantizations. In this paper, we propose a parallel combination of an IT2F-PD controller and an IT2F-PI controller to achieve an IT2F-PID controller. The proposed IT2F-PID controller uses the Mamdani interval type-2 fuzzy rule and the Wu-Mendel type-reduction method for the IT2F-PI controller and the IT2F-PD controller. The proposed controller structure using the Wu-Mendel type-reduction method is suitable for real-time applications and implement in industrial embedded controllers, thus avoiding the use of the iterative KM algorithm which not suitable for real-time applications. The structure of the controller is first presented along with the interaction rules, followed by the description of the fuzzification, rule base and finally defuzzification involving type reduction.

2.1. The structure of the proposed controller

The overall structure of the proposed IT2F-PID controller is shown in Fig. 1. In Fig. 1, $e(k)$ and $\Delta e(k)$ represent the input variables and $u_{PID}(k)$ represents the output variable. For an IT2F-PI controller, two scaling factors G_{e1} and $G_{\Delta e1}$ are employed to scale $e(k)$ and $\Delta e(k)$, the error and the derivative error respectively, as follows:

$$\begin{aligned} E_{PI}(k) &= G_{e1}e(k) = G_{e1}(y_r(k) - y(k)) \\ \Delta E_{PI}(k) &= G_{\Delta e1}\Delta e(k) = G_{\Delta e1}(e(k) - e(k-1)) \end{aligned} \quad (1)$$

where $y_r(k)$ is the system output reference signal, $y(k)$ is the output of the system under control, and k is the sampling instance. The output variable of an IT2F-PI controller $u_{PI}(k)$ is