ISA Transactions 53 (2014) 732–743

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research Article

Interval type-2 fuzzy PID controller for uncertain nonlinear inverted pendulum system

Mohammad El-Bardini, Ahmad M. El-Nagar *

Department of Industrial Electronics and Control Engineering, Faculty of Electronic Engineering, Menofia University, Menof 32852, Egypt

A R T I C L E I N F O

Article history:
Received 5 December 2012
Received in revised form
29 January 2014
Accepted 16 February 2014
Available online 21 March 2014
This paper was recommended for publication by A.B. Rad

Keywords:
Fuzzy PID controllers
Interval type-2 fuzzy logic system
Interval type-2 fuzzy PID controller
Inverted pendulum system
Uncertain system

A B S T R A C T

In this paper, the interval type-2 fuzzy proportional–integral–derivative controller (IT2F-PID) is proposed for controlling an inverted pendulum on a cart system with an uncertain model. The proposed controller is designed using a new method of type-reduction that we have proposed, which is called the simplified type-reduction method. The proposed IT2F-PID controller is able to handle the effect of structure uncertainties due to the structure of the interval type-2 fuzzy logic system (IT2-FLS). The results of the proposed IT2F-PID controller using a new method of type-reduction are compared with the other proposed IT2F-PID controller using the uncertainty bound method and the type-1 fuzzy PID controller (T1F-PID). The simulation and practical results show that the performance of the proposed controller is significantly improved compared with the T1F-PID controller.

1. Introduction

The conventional PID controllers are still the most widely used control structure in most of the industrial processes. This is mainly because PID controllers have simple control structures, affordable price, and effectiveness for linear systems [1–6]. Due to their linear structure, the conventional PID controllers are usually not effective if the system 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 [7]. For these reasons, many researchers have attempted to combine a conventional PID controller with a fuzzy logic controller (FLC) in order to achieve a better system performance over the conventional PID controller.

The fuzzy PI controller [8] and the fuzzy PD controller [9] are developed to improve the system performance rather than conventional PID controllers. The fuzzy PI controllers are preferred more than the fuzzy PD controllers as the fuzzy PD controllers are not able to eliminate the steady state errors [10]. However, the fuzzy PI controllers show a poor performance during the transient phase for higher order processes due to their internal integration operation. The fuzzy PI and the fuzzy PD controllers are combined to get a fuzzy PID controller [11,12]. Its knowledge base consists of two-dimensional rule base for the PI and the PD controllers to obtain the overall improved performance. The fuzzy PI+D controller is developed which is a combination of a fuzzy PI controller and a fuzzy D controller [13]. The fuzzy P+ID controller is developed for tracking control of a two-link experimental direct arm [14]. There are different control structures for the fuzzy PID controller mentioned in [15–21], in order to improve the closed loop systems. Despite the significant improvement of system performance with the 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 structure uncertainties as the ordinary fuzzy controllers (type-1 FLCs) have limited capabilities to directly handle data uncertainties [22].

There are five sources of uncertainties in type-1 fuzzy logic systems (T1-FLSs) [23,24]: (1) uncertainties in the inputs to the FLS, which translate into uncertainties in the antecedents membership functions as the sensor measurements are affected by high noise levels from various sources. (2) Uncertainties in the control outputs, which translate into uncertainties in the consequents membership function of the FLS. (3) The meanings of the words that are used in the antecedents and consequents of rules can be uncertain (words mean different things to different people). (4) Uncertainties associated with the change in the operating conditions of the controller. Such uncertainties can translate into uncertainties in the antecedents and/or consequent membership functions. (5) The data that is used to tune the parameters of a T1-FLS may also be noisy. All of these uncertainties translate into uncertainties about fuzzy set membership functions. The T1-FLSs are not able to directly model such uncertainties because their membership functions are totally crisp.

* Corresponding author.
E-mail addresses: dralbardini@ieee.org (M. El-Bardini), Ahmed_elnagar@menofia.edu.eg (A.M. El-Nagar).

http://dx.doi.org/10.1016/j.isatra.2014.02.007
0019-0578/

On the other hand, the type-2 fuzzy sets (T2-FSs) that were introduced by Zadeh in 1975 are able to model such uncertainties because their membership functions are themselves fuzzy; they are very useful in circumstances where it is difficult to determine an exact membership function for a fuzzy set [25]. The concept of a T2-FS is an extension of the concept of ordinary fuzzy sets (type-1 fuzzy sets; T1-FSs). A T2-FS is characterized by a fuzzy membership function (i.e., the membership grade for each element of this set is a fuzzy set in [0, 1]), unlike a T1-FS where the membership grade is a crisp number in [0, 1] [25]. Therefore, a T2-FS provides additional degrees of freedom that make it possible to model and handle the uncertainties directly [26]. Both the T1-FLS and T2-FLS have the same four components, which are a fuzzifier, a rule base, a fuzzy inference engine, and an output processor. Furthermore, unlike a T1-FLS, the output processor generates a T1-FS output using the type-reducer or a crisp number using the defuzzifier. A T2-FLS also is characterized by IF–THEN rules, but its antecedent or consequent sets are type-2. A T2-FLS can be used when the circumstances are too uncertain to determine membership grades exactly and they have been used in many applications, especially in the control systems [27–34]. The IT2-FLS is a special case of the T2-FLS [24]. These are simpler to work with than general T2-FSs and distribute the uncertainty evenly among all admissible primary memberships [35]. The IT2-FLSs have been applied to various fields with great success [36–43].

The structure of the IT2-FLS has four components, viz. a fuzzifier, a rule base, a fuzzy inference engine, and an output processor. The output sets of the IT2-FLS 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-FLS to a T1-FS, this operation is called a type-reduction and calls the type-1 set so obtained a type-reduced set [44]. The type-reduced set is a collection of the outputs of all of the embedded T1-FLSs [25]. The type-reduction is usually performed by iterative Karnik–Mendel (KM) algorithms [45], which are computationally intensive. However, the IT2-FLS has a computational overhead associated with the computation of the type-reduced fuzzy sets using the KM algorithms [46]. This computational overhead reduces the real-time performance of the IT2-FLS, 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-FLSs in industrial embedded controllers. Wu and Mendel [47] proposed a method called uncertainty bounds (UB) to approximate the type-reduced set, thus avoiding the use of the iterative KM algorithms. In this study, we propose a new method of type-reduction called the *simplified type-reduction method* which is able to reduce the computation cost of the type-reduction and also, reduces the memory required for the IT2-FLS when implemented in embedded systems.

As reported in [48,49], the T1F-PID controller is proposed to improve the system performance where the fuzzy rules and reasoning are utilized on-line to determine the PID controller parameters based on the error signal and its first difference. The main drawback of the T1F-PID controller [48,49] is the limitation capabilities to directly handle data uncertainties. For these reasons, the main objective of this paper is developing an IT2F-PID controller using the proposed type-reduction method which combines the conventional PID controller with the IT2-FLS to improve the system performance compared with the T1F-PID controller. The proposed controller has the ability to minimize the effect of structure uncertainties and external disturbance. The proposed controller is used for controlling the uncertain nonlinear inverted pendulum on a cart system. The results are compared with the T1F-PID controller to test the robustness of the proposed controller to provide some improvements in system performance over the T1F-PID controller under the effect of the system uncertainties and the external disturbance.

The major contributions of this study are (1) the successful development of fuzzy PID controller to IT2F-PID controller. (2) The successful application of the proposed IT2F-PID controller for controlling the uncertain inverted pendulum on a cart system. (3) The success of the proposed method of type-reduction to minimize the memory required and reduces the time of computation for the type-reduction process. (4) The success of the proposed controller to minimize the effect of the system uncertainties and the external disturbance.

This paper is organized as follows. In Section 2, the IT2F-PID controller is included. The description of the mathematical model of the uncertain inverted pendulum is presented in Section 3. Section 4 presents the simulation and practical results followed by the conclusions and the relevant references.

2. Interval type-2 fuzzy PID controller

The prime objective of the controller design is to achieve a better control performance in terms of the stability and the robustness for the system uncertainties and the environmental disturbances. The proposed control structure consists of a simple upper-level intelligent controller and a lower-level classical controller. The upper level controller provides a mechanism to select the gains of a classical PID controller, whereas the lower-level controller should deliver the solutions to a particular situation. In the proposed control structure, a rule-based Mamdani-type-2 fuzzy controller is used in the upper level and a conventional PID controller is selected for the lower level. The structure of the IT2F-PID controller is shown in Fig. 1. In usual practice, the error (e) and the change of error (Δe) parameters were preferred to the designing of the antecedent of the fuzzy rules for control applications [50]. So, in this proposed controller the error signal and the change in error signal are used for the antecedent part of the rule based.

The PID controller is usually implemented as follows:

$$u(t) = k_p e(t) + k_i \int e(t)dt + k_d \frac{de(t)}{dt}$$
$$e(t) = y_r(t) - y_m(t) \quad (1)$$

where k_p, k_i, and k_d are the proportional, the integral, and the derivative gains respectively. The controller output, the process output, and the set point are denoted as u, y_m, and y_r, respectively. In the classical PID controller, the values of k_p, k_i, and k_d in Eq. (1) are adjusted by the operator according to the changes in the process condition. By developing a rule-based intelligent type-2 fuzzy controller structure, these parameters can be modified online, according to the changes in the process condition without much intervention of an operator and further it will enhance the conventional controller performance over a wide operating range.

The structure of upper-level IT2-FLS contains four components: a fuzzifier, an inference engine, a rule base, and an output processing

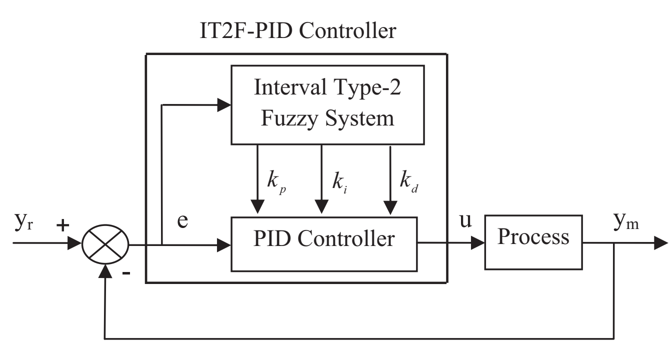

Fig. 1. Interval type-2 fuzzy PID controller structure.