

Feedforward control of a class of hybrid systems using an inverse model

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Received 28 January 2010; accepted 14 October 2010

Available online 26 October 2010

Abstract

In this paper we describe the design of a control algorithm for MISO systems, which can be modelled as *hybrid fuzzy models*. Hybrid fuzzy models present a convenient approach to modelling nonlinear hybrid systems.

We discuss the formulation of a hybrid fuzzy model, its structure and the identification procedure. This is followed by a derivation of the inverse model and its implementation in the control algorithm. The control scheme we are discussing splits the control algorithm in two parts: the feedforward part and the feedback part. In the paper, we deal with the feedforward part of the control algorithm, which is based on an inverse of a hybrid fuzzy model. Next, a batch-reactor process is introduced. The modelling of the batch reactor is tackled and the results of the simulation experiments using the proposed control algorithm are presented. The experiments involved controlling the temperature of a batch reactor using two on/off input valves and a continuous mixing valve.

The main advantage of the proposed approach is that the feedforward part of the control algorithm can bring the system close to the desired adjusted feasible trajectory, which avoids the need for a very complex feedback part of the algorithm. Therefore, the control algorithm presents a low computational burden, particularly comparing to the standard model predictive control algorithms. These usually require a considerable computational effort, which often thwarts their implementation on real industrial systems. Nevertheless, we show that using the proposed control approach the hybrid fuzzy model framework presents a convenient option for modelling complex systems for control purposes in practice.

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Keywords: Hybrid fuzzy model; Inverse-model-based control; Hybrid systems; Nonlinear systems; Batch reactor

1. Introduction

Dynamic systems that involve continuous and discrete states are called *hybrid systems*. Most industrial processes contain both continuous and discrete components, for instance, discrete valves, on/off switches, logical overrides, etc. The continuous dynamics are often inseparably interlaced with the discrete dynamics; therefore, a special approach to modelling and control is required. At first this topic was not treated systematically [20]. In recent years, however, hybrid systems have received a great deal of attention from the computer science and control community.

The principle of *model predictive control* (MPC) is based on forecasting the future behavior of a system at each sampling instant using the process model. The complex hybrid and nonlinear nature of many processes that are met

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in practice causes problems with both structure modelling and parameter identification; therefore, obtaining a model that is suitable for MPC is often a difficult task. Hence, the need for special methods and formulations when dealing with hybrid systems is very clear.

MPC methods for hybrid systems employ several model formulations. Often the system is described as *mixed logical dynamical* (MLD) [3]. A lot of interest has also been devoted to *piecewise affine* (PWA) formulation [17], which has been proven to be equivalent to many classes of hybrid systems [7]. What is more, MLD models can be transformed to the PWA form. The optimal control problem for discrete-time PWA systems can be converted to a mixed-integer optimization problem and solved online [11]. On the other hand, in [10] the authors tackle the optimal control problem for PWA systems by solving a number of multi-parametric programs offline. In such manner, it is possible to obtain a solution in the form of a PWA state feedback law that can be efficiently implemented online.

The aforementioned methods mainly consider systems with continuous inputs, despite the fact that solutions based on (*multiparametric*) *mixed integer linear/quadratic programming* (mp-MIQP/MILP) can be applied to systems with discrete inputs as well. However, the computational complexity increases drastically with the number of discrete states, and so these methods can become computationally too demanding. An algorithm for the efficient MPC of hybrid systems with discrete inputs only is proposed in [13].

Most of the previous work related to the MPC of hybrid systems is based on (piecewise) linear and equivalent models. However, such approaches can prove unsuccessful when dealing with distinctive nonlinearities. Since a PWA formulation can only represent piecewise affine systems, further segmentation is required in order to suitably approximate the nonlinearity. The new segments introduce new discrete auxiliary variables in the MILP/MIQP optimization program, which causes a higher complexity, often resulting in programs that are computationally too demanding.

A nonlinear modelling approach for MPC purposes is presented in [16]. The authors introduce an analytical predictive-control-law for fuzzy systems. The modelling and identification methodology is usable for plain nonlinear systems, but not for the structurally more complex class of hybrid systems. A hierarchical identification of a fuzzy switched system [21] is introduced in [12]. Furthermore, two structure-selecting methods for nonlinear models with mixed discrete and continuous inputs are presented in [5]. In [14] a fuzzy control method is implemented in the low control-level for a class of hybrid systems based on hybrid automata.

In this paper we focus on using the hybrid fuzzy model formulation presented in [9]. The framework is suitable for modelling nonlinear hybrid systems and can be implemented in model predictive control design. The basic idea of this paper is to present the feedforward part of a control algorithm suitable for controlling MISO systems, which can be modelled by a hybrid fuzzy model.

The outline of the paper is as follows. Section 2 introduces the hybrid fuzzy model. In addition, in Section 3 the identification procedure for a hybrid fuzzy model is introduced. Next, in Section 4 the basic control scheme and the idea of the feedforward part of the control algorithm is presented. We also discuss the inclusion of a feedback part in the control algorithm. This is followed by Section 5, which deals with derivation of the inverse model and its implementation in the control algorithm. In the following section, a batch-reactor process is introduced. The modelling of the batch reactor is tackled and the results of the simulation experiments using the proposed control algorithm are presented. Finally, we give some concluding remarks.

2. Modelling of a hybrid fuzzy model

Dynamic systems are usually modelled by feeding back delayed input and output signals. In the discrete-time domain a common nonlinear model structure is the NARX (Nonlinear AutoRegressive with eXogenous inputs) model [15], which gives the mapping between the past input–output data and the predicted output.

$$\hat{y}_p(k+1) = F(y(k), y(k-1), \dots, y(k-n+1), u(k), u(k-1), \dots, u(k-m+1)) \quad (1)$$

Here, $y(k), y(k-1), \dots, y(k-n+1)$ and $u(k), u(k-1), \dots, u(k-m+1)$ denote the delayed process output and input signals, respectively. Hence, the model of the system is represented by the (nonlinear) function F .

In this paper, a special class of systems is addressed, i.e., nonlinear hybrid systems with discrete inputs. Therefore, in Eq. (1) u stands for the discrete input.

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