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Data-driven predictive control of Hammerstein–Wiener systems based on subspace identification[☆]

Xiao-Suo Luo, Yong-Duan Song[*]

School of Automation, Chongqing University, Chongqing 400044, China

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ABSTRACT

It poses significant challenge to control Hammerstein–Wiener systems involving modeling nonlinearities. In this paper, a novel data-driven predictive control method based on the subspace identification of Hammerstein–Wiener systems is presented. By reformulating the open- and closed-loop Hammerstein–Wiener model, subspace predictions of the outputs are derived using recursive substitution of the Hankel matrices. The output nonlinearity is presented by polynomial representation and the subspace predictors are obtained using the QR decomposition, together with additional algebra manipulations, where Q is an orthogonal matrix and R is an upper triangular matrix. The predictors are applied to the model predictive controller, wherein the integrated action is successfully incorporated. The effectiveness and feasibility of the proposed controller is also verified by numerical simulation on a fermentation bioreactor system.

1. Introduction

In recent years, nonlinear systems have garnered widespread attention, resulting in a rich collection of technical reports [32,33,48] and further enticing an increased interest for the Hammerstein, Wiener, and Hammerstein–Wiener systems, which present the nonlinear systems models [7,12,18,25,26,30,31,40]. The Hammerstein–Wiener model can be represented as a set of two static nonlinear elements that surround a linear dynamic block. The Hammerstein–Wiener model could be successfully used to describe a number of processes [45]. Recently, many Hammerstein–Wiener models have been developed, for instance: the micro-scale polymerase chain reaction reactor [13], the continuous stirred tank reactor [8], the DC motor [21], model for temperature variations in a silage bale [19], the neutralization reactor [23], and the photovoltaic system [24].

The model predictive control (MPC) is a powerful model-based control technique which optimizes the overall performance of the controlled system [2,28]. The most important features of the MPC are: it can handle multivariable control problems, it considers input and output constraints, and it adapts to structural changes [17]. The Hammerstein–Wiener system may be implemented in the MPC for the control purpose. Direct application of the nonlinear model in the MPC requires a nonlinear optimization which must be proceeded instantly at each time moment. The most common solution for that is to use inverse steady-state blocks algorithms in control which compensate for the process nonlinearity [1].

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[*] Corresponding author.
E-mail addresses: luoxiaosuo@cqu.edu.cn (X.-S. Luo), ydsong@cqu.edu.cn (Y.-D. Song).

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Subspace identification is an algorithm commonly used for state-space modeling. It does not require the use of the tedious modeling mechanism because the certain state-space model is obtained just once and there is enough input-output data for the processing [6,14]. Moreover, the subspace matrices obtained by the subspace identification algorithm can be used to derive the predictor for predictive controllers, eliminating the intermediate step of process model identification and providing a method of data-driven predictive control which has been applied in some industrial processes and has achieved favorable results [15,29,34,43].

At present time, most studies are focused on the subspace identification for the Hammerstein and Wiener systems, while the Hammerstein–Wiener systems are neglected. A two-step procedure for the Hammerstein–Wiener system identification, intended for magnetosphere data and based on the subspace algorithm and a least squares, was employed in [22]. Moreover, the Hammerstein–Wiener system identification method presented in [5] is the linear subspace intersection algorithm extension based on the kernel canonical correlation analysis (KCCA) which is used to calculate the present state as the intersection between past and future states. Wingerden and Verhaegen [41] used two steps to identify the multiple-input multiple-output Hammerstein–Wiener systems for closed-loop condition; the first step represents the reformulation of the linear regression problem, and the second step represents the state sequence estimation. Note that these methods only address the problem of system identification, leaving the control problem untouched. Here in this work, we propose a truly data-driven approach for predictive control of Hammerstein–Wiener systems operating in either open-loop or close-loop mode.

Because of the useful feature of subspace identification, efforts have been made on using subspace identification based MPC for either Wiener or Hammerstein systems. For example, in [10], it first needs to identify the state-space Wiener model and then the model was incorporated into an MPC scheme. It is not a data-driven method but has two steps increasing computation. Song et al. [27] employed the linear input/output data-based prediction model to design a Wiener input/output data-based predictive controller. But the relatively harsh condition is given that the measurement and process noises influence the linear time invariant (LTI) part only. Kulcsar et al. [11] proposed a closed-loop subspace predictive control algorithm for the Hammerstein LTI systems. It should be noted that the aforementioned predictive control is more complex because it needs to estimate Markov parameters. Moreover, most existing methods are either not fully data-driven and impose restrictive conditions, or involve Markov parameters, and the results are only valid for either Hammerstein or Wiener systems. In this work, we consider the more complex MPC control problem for Hammerstein–Wiener systems using truly data-driven method without the need for Markov parameters. The proposed solution just makes use of some common algebra calculation tools, making resultant algorithms less demanding for design and simpler for computation. This method is directly applicable for single Wiener or Hammerstein systems. The salient features and the main contribution of the proposed method can be summarized as:

- It is a truly data-driven method. Only input and output data (present and past recent data stored in the system) are used to generate the required predictive control action, and there is no need for precise mathematical model e.g. (A, B, C, D) for control design;
- It is applicable for open- and closed-loop systems, both are transformed into the uniform forms in order to obtain the subspace predictions of the outputs via recursive substitution;
- It contains several key and easily derived subspace predictors. The subspace predictors obtained through the QR factorization are employed to make the method simple and robust;
- It provides an attractive way to establish nonlinear MPC cost function. Here the incremental nonlinear function is directly integrated into the MPC cost function, significantly facilitating the design procedures and simplifying the online computations.

The rest of the paper is organized as follows. In Section 2 the Hammerstein–Wiener system model is described. In Section 3 the subspace prediction of outputs is explained and discussed. In Section 4 the subspace predictors are analyzed in detail. In Section 5 the design of data-driven predictive control method is presented. In Section 6 the results of the simulation experiments are provided. Lastly, a brief conclusion is given in Section 7.

2. The Hammerstein–Wiener system model

2.1. The open-loop system model

The open-loop Hammerstein–Wiener system model can be defined as [41]:

$$x_{k+1} = Ax_k + BF(u_k) + K\xi_k \tag{1}$$

$$g^{-1}(y_k) = Cx_k + DF(u_k) + \xi_k \tag{2}$$

where $u_k \in \mathbb{R}^m$, $y_k \in \mathbb{R}^l$, and $x_k \in \mathbb{R}^n$ are input, output, and state vectors, respectively; $\xi_k \in \mathbb{R}^l$ is a zero-mean white innovation sequence; $K \in \mathbb{R}^{n\times l}$ is the Kalman filter gain and the Kalman filter is a more simplified white noise processor compared with the filtering schemes in [37] and [39]; (A, B, C, D) are system matrices where $A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times m}$, $C \in \mathbb{R}^{l\times n}$, $D \in \mathbb{R}^{l\times m}$;