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Identification and control of nonlinear system based on Laguerre-ELM Wiener model

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A B S T R A C T

In this paper, a new Wiener model is presented for identification and control of single-input single-output (SISO) nonlinear systems. The proposed Wiener model consists of a linear Laguerre filter in cascaded with an extreme learning machine (ELM) neural network (called Laguerre-ELM Wiener model). Laguerre filter can approximate a stable linear system to any degree of accuracy with a small number of Laguerre filters, which provides a parsimony structure and high level accuracy simultaneously. To determine the appropriated number of Laguerre filters in Laguerre-ELM Wiener model, Lipschitz quotient criterion is adapted to determine the order of linear part. A generalized ELM algorithm is proposed to estimate the parameters of Laguerre-ELM Wiener model. Once the unknown nonlinear system is identified using Laguerre-ELM Wiener model, a generalized predictive control (GPC) algorithm is designed for control of nonlinear system. The advantage of the proposed control method is that it transfers a nonlinear control problem to a linear one by inserting the inverse of static nonlinear section. Simulation results demonstrate the effectiveness of the proposed identification and control algorithms.

1. Introduction

System modeling and identification occupy an important place in scientific and engineered fields including simulation, fault tolerant analysis, prediction, automatic control, etc. [1–3]. The main task of system identification is to find a proper model with appropriate structure and parameters to characterize the dynamic behavior of real systems. Since many real systems are nonlinear in nature, nonlinear system identification has received more and more attention. In the past decades, many nonlinear modeling techniques have been developed such as nonlinear auto regressive moving average with eXogrnous input (NARMAX) model [1], artificial neural networks [2], fuzzy-logic based models [4], and some combinations of them like neuro-fuzzy models [5], etc.

In recent years, the so called block-oriented models have turned out to be effective models for characterizing nonlinear systems. In block-oriented models, various system characteristics, such as nonlinearities and dynamical response, are represented by separated blocks. Wiener model is a typical block-oriented model, which consists of a linear dynamic subsystem followed by a static nonlinear function. Wiener model has been applied to model many practical applications, such as fluid flow control system [6], pH control [7], separation process [8], as well as various biological systems [9], and so on.

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In identification of Wiener model, selecting an appropriate representation of linear dynamic part and static nonlinear function is a basic problem. In the literature, orthogonal filter networks such as Laguerre and Kautz filters [10–12] have been proven to be an effective and accurate representation for stable linear dynamic system. The advantages of orthogonal filters representation include: (1) the input–output equation can be written as a linear regression. (2) Even if the original data is truncated, the estimates of the model coefficients are unbiased. (3) It does not need any explicit knowledge about system time constant and time delay to develop orthonormal filter models. (4) A good approximation can be obtained with a small number of terms because of the orthogonal property. Due to these facts, many researchers have integrated orthonormal filters with some static nonlinear function to construct Wiener models. To name a few, Wiener proposed a Wiener model in [13] by using orthonormal Laguerre filters to represent the linear dynamic part and polynomials to represent the static nonlinear function. In [14], Hwang et al. proposed a method to use discrete Laguerre finite impulse response (FIR) and an inverse polynomial to form a Wiener model for nonlinear system identification. In [15], Tötterman and Toivonen presented a Wiener model identification method using Laguerre filters and support vector machine (SVM). In their method, the linear dynamic part of Wiener model is represented by Laguerre filters and the static nonlinear part by SVM. In [16], nonlinear model predictive controller was designed for pH neutralization process based on Laguerre-polynomial Wiener model, where the linear dynamic part and static nonlinear part were represented by Laguerre filters and polynomials, respectively. In [17], similar work as in [16] was conducted, where the nonlinear part of Wiener model was represented by least square support vector machine. In [10], a nonlinear system identification method was proposed based on Wiener type Laguerre-wavelet neural network (WNN) model.

On the other hand, finding an effective and simple representation of static nonlinear function is very important as well. A good representation should not only approximate the static nonlinear function accurately, but also simplify the identification process. In the literature, polynomials [18], artificial neural networks (ANNs) such as multi-layer feed-forward neural networks (MFNN) [19], radial basis function neural network (RBFNN) [20], non-uniform rational B-spline (NURB) neural network [21], WNN [10] and fuzzy systems (FSs) [22], had been adopted to characterize the static nonlinear function of Wiener model. Though these representation methods show effectiveness, there still exist some shortcomings, which may make the identification process more complex. A drawback of polynomials is that high degree polynomials have oscillatory behavior and parameter estimation is often numerically ill conditioned if the static nonlinear function is not polynomial form. For ANNs and fuzzy systems, large computation burden involves in the training phase and the training algorithm often traps into local optimal.

Recently, an effective and efficient algorithm, called extreme learning machine (ELM), was proposed by Huang to train single-hidden-layer feed-forward neural networks (SLFNs) [23]. In ELM, the input weights and hidden biases are randomly chosen of the training data, independently and only the output weights are calculated analytically using Moore–Penrose (M–P) generalized inverse. In other words, training is transformed into a standard least-squares problem, leading to a significant improvement in the learning speed [24]. In comparison with other traditional learning methods and even some evolutionary algorithms, the ELM algorithm has its unique advantages not only in faster learning speed with higher generalization performance, but also in avoiding many difficulties faced by other learning methods such as stopping criteria, learning rate, learning epochs, and local minima [25,26].

Motivated by the advantages of Laguerre filters and ELM, we propose a novel Wiener model, called Laguerre-ELM model. In Laguerre-ELM model, the linear dynamic part is represented by Laguerre filters, while the static nonlinearity of Wiener model is characterized by ELM neural network. It is found that ELM can not only provide an accurate approximation of static nonlinear function but also simplify the identification process. The proposed Laguerre-ELM model is used to identify nonlinear system, and then, a controller is designed for the nonlinear system according to the identified Laguerre-ELM model. To this end, the linear dynamic part, i.e., Laguerre filters must be carefully designed. In other words, *we must determine the appropriate number of filters as well as parameters of Laguerre filters.* However, this problem is always ignored in most literature relating to Laguerre filters based block-oriented models [10,14–18,22]. In these literature, the number of Laguerre filters are selected manually or trial and error. In this paper, we propose to use Lipschitz quotients criterion [27] to determine the appropriate number of Laguerre filters.

The rest of this paper is organized as follows. In Section 2, the proposed Laguerre-ELM model is given. In Section 3, the details about the identification of Laguerre-ELM model are presented. The controller design for nonlinear system based on Laguerre-ELM model is given in Section 4. Section 5 are the simulation examples. Finally, the conclusion remarks are given in Section 6.

2. Laguerre-ELM Wiener model

2.1. Laguerre filters

Function $G(z)$ is strictly proper ($G(\infty) = 0$), analytic in $|z| \geq 1$ and continuous in $|z| > 1$. Let $-1 < a < 1$, there exists a sequence $\{c_i\}$ such that

$$G(z) = \sum_{i=1}^{\infty} c_i L_i(z), \tag{1}$$