Information Sciences 294 (2015) 269–285

Contents lists available at ScienceDirect

Information Sciences

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

Single-hidden-layer fuzzy recurrent wavelet neural network: Applications to function approximation and system identification

Soheil Ganjefar *, Morteza Tofighi

Department of Electrical Engineering, Faculty of Engineering, Bu-Ali Sina University, Shahid Fahmideh Street, P.O. Box 65178-38683, Hamedan, Iran

ARTICLE INFO

Article history:
Received 25 March 2014
Received in revised form 19 September 2014
Accepted 28 September 2014
Available online 7 October 2014

Keywords:
Single-hidden-layer fuzzy recurrent wavelet neural network
Optimal learning rate
Genetic algorithm

ABSTRACT

When a fuzzy wavelet neural network (FWNN) has a large number of neurons in its consequent part, it may not be able to effectively follow fast variations in the process. This paper aims to develop a single-hidden-layer fuzzy recurrent wavelet neural network (SLFRWNN) for the function approximation and identification of dynamic systems. In the proposed framework, the consequent part of each fuzzy rule is developed by a single neuron with the capability of storing the past data of the network. To guarantee the convergence and to speed up the process of the on-line training algorithm, the optimal learning rate (OLR) is introduced based on Lyapunov stability theory. The modifications allow the SLFRWNN to be much faster than FWNN and hence it is more appropriate in real-time applications. The efficiency of the modified model is investigated using three different types of wavelet families in approximating a benchmark piecewise function. Furthermore, two nonlinear dynamic plants are considered to demonstrate the feasibility of the SLFRWNN in the system identification. The results indicate that SLFRWNN achieves higher accuracy and needs a lower number of parameters than the other models.

1. Introduction

Based on the Takagi–Sugeno–Kang (TSK) fuzzy model, researchers have proposed various structures for modeling and control of nonlinear systems. For example, in [10], an output feedback control problem for nonlinear discrete-time systems is represented using a class of T–S fuzzy systems with local nonlinear models. Using the sum-of-squares approach, the stability analysis of polynomial fuzzy model-based control systems is addressed in [27]. The stabilization problem of discrete-time two-dimension (2-D) Takagi–Sugeno (T–S) fuzzy systems is considered in [9], while the stability of fuzzy-model-based (FMB) control systems is investigated based on a fuzzy Lyapunov function in [26].

However, the major drawback of the TSK fuzzy model is that it cannot offer full mapping capabilities to the non-linear complex systems and thus a large number of rules are needed to obtain the desired mapping between inputs and outputs. As an alternative, many researchers have proposed to replace the consequent part of the TSK model with the wavelet neural network (WNN) [29,8,19,5,32,34,20,2]. The resulting network is a fuzzy wavelet neural network (FWNN) which contains the advantages of both the fuzzy systems and WNNs. As a result, the FWNN decreases the number of rules significantly, converges in a smaller number of iterations and is more efficient than the fuzzy systems and neural networks.

* Corresponding author.
E-mail addresses: s_ganjefar@yahoo.com (S. Ganjefar), tofighi_morteza@yahoo.com (M. Tofighi).

http://dx.doi.org/10.1016/j.ins.2014.09.054
0020-0255/

Several previous works have discussed the synthesis of a FWNN to solve such problems as forecasting, function approximation, sliding-mode control, fault diagnosis, system identification, and control problems [11,3,43,14,12,36]. In [11], an adaptive variable structure method is presented to design a fuzzy neural network for identification and control of a class of MIMO nonlinear systems. A five-layer architecture of a hybrid wavelet-neuro-fuzzy system is proposed in [3] based on multidimensional adaptive wavelet activation–membership functions. The constructed network can be utilized to solve the problems of emulation, diagnosis, forecasting and identification of nonlinear chaotic and stochastic non-stationary processes. In [43], using a wavelet neuro-fuzzy model, an intelligent signal processing method is explored for structural damage identification. Based on a combined wavelet transform and adaptive neuro-fuzzy inference system, a new fault diagnosis approach is presented for fault section identification, classification and location in a series compensated transmission line in [14]. In [12], using a combination of TSK fuzzy models with wavelet transform and a recursive orthogonal least square (ROLS) training algorithm, a fuzzy wavelet network is proposed with the aim of approximating arbitrary nonlinear functions. A fuzzy system coupled with a discrete wavelet network in a Takagi–Sugeno type model structure is proposed to form a fuzzy-wavelet network in [36]. The developed network was successfully applied to identify the maximum power points tracking (MPPT) voltage of photovoltaic (PV) systems.

Although the FWNN has been successfully applied in many complex problems, it has two shortcomings. First, due to its feedforward network structure, it represents a static mapping, which leads to a poor performance in dealing with dynamic systems. Thus, to obtain a reasonably good control performance, the use of a large number of neurons is required, but finding the optimal number of neurons is challenging. Moreover, the use of a large number of neurons will increase the dimension and parameters of the network, and so in real-time applications the time needed to update the network parameters will increase. Second, since the training of the FWNN is usually performed based on the back propagation (BP) or gradient descent (GD) training algorithm with a fixed learning rate, it is difficult to find the optimal learning rates in the GD algorithm. In this case, if the learning rates are chosen to be small, then the convergence of the network is slow and will take a long time to converge. On the other hand, a large value for the learning rate leads to a non-stable learning procedure and a diverging of the network. The first problem can be solved by applying a recurrent wavelet neural network (RWNN) in the consequent part of the FWNN structure which is able to store the previous data of the network [4,40]. The modified model by capturing the past dynamic behavior of the system, will enhance the computational strength and the generalization ability of FWNN and hence is more appropriate in dealing with the control of non-linear complex systems and identification problems. To solve the second problem, an adaptive learning rate (ALR) based on the Lyapunov stability theory has been applied by researchers in previous studies [17,41]. Applying the ALR in the gradient descent training algorithm demonstrates a fast and optimal convergence in the network parameters.

The aim of this research study is to develop a single-hidden-layer fuzzy recurrent wavelet neural network (SLFRWNN) for the function approximation and identification of dynamic systems. The proposed model is based on a TSK fuzzy model, in which the consequent part of each fuzzy rule is developed by a single neuron with the ability to store the past data of the network. All of the parameters in the antecedent and consequent parts of the fuzzy rules are initialized using an efficient genetic algorithm while the consequent parameters are selected to be updated during real-time operation. To guarantee the convergence and to speed up the process of training, the optimal learning rates of the consequent parts are determined in an on-line mode based on the Lyapunov stability theory. The proposed SLFRWNN not only decreases the number of parameters to be updated but it also exhibits a fast reaction to the input changes due to it having a single neuron consequent part structure. The efficiency of the developed model is investigated by three different types of wavelet families in approximating a benchmark piecewise function.

According to the results obtained from the three different types of wavelet families, the wavelet function with a higher performance is chosen as a wavelet function to be used in the identification problems studied in this paper. Then, two nonlinear dynamic plants are considered to demonstrate the feasibility of the SLFRWNN in the system identification. The results indicate that SLFRWNN achieves higher accuracy and needs a lower number of parameters than the other models. The rest of this paper is organized as follows. Section 2 describes the architecture of the proposed single-hidden-layer fuzzy recurrent wavelet neural network. The initialization of the proposed SLFRWNN by the GA approach is presented in Section 3 while the learning procedure for the SLFRWNN is given in Section 4. The optimal learning rates using Lyapunov stability theory are introduced in Section 5. Design validation and simulation results are provided in Section 6. Finally, the conclusions and future work are presented in Section 7.

2. Single-hidden-layer fuzzy recurrent wavelet neural network

The TSK fuzzy model has some merits such as greater sensitivity to dynamic input changes, less processing time, and more accuracy and robustness over the Mamdani fuzzy inference system. However, when the consequent part of a traditional TSK fuzzy model is substituted with a WNN including a large number of neurons, the reaction speed of the TSK fuzzy model to the input changes can decrease. Thus, in this paper, we have proposed using a single-hidden-layer recurrent wavelet neural network structure as a consequent part for the TSK fuzzy model, referred to as the SLFRWNN. The proposed consequent part is constructed using a single neuron with the ability to store the past data of the network. The output membership function of a TSK fuzzy model and the proposed structure are shown in Fig. 1. This structure not only retains the simplicity of the consequent part of the TSK fuzzy model, but it also increases the computational power and convergence