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Fuzzy wavelet extreme learning machine

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Abstract

Incorporating the time-frequency localization properties of wavelets and the learning abilities of neural network (NN), the approximate reasoning characteristics of fuzzy inference system and the advantages of ELM (one-pass learning and good generalization performance at extremely fast learning speed) can exhibit their characteristics to reveal an effective solution in many applications. Following that, this paper presents a novel structure called fuzzy wavelet extreme learning machine (FW-ELM). The main objectives of FW-ELM are to significantly reduce the network complexity by reducing the number of linear learning parameters, and to decrease the sensitivity to random initialization procedure while the acceptable accuracy and generalization performances are preserved. In the proposed structure, each fuzzy rule corresponds to a sub-wavelet neural network and consists of wavelets with different dilations and translations. In this model, in order to achieve a balance between network complexity and performance accuracy, in the THEN-part of each fuzzy rule, one coefficient is considered for each two inputs. In this work, first, the equivalence of an FW model and an SLFN is proved and then ELM can be directly applied to the model. All free parameters of membership functions and wavelet coefficients are generated randomly, and only the output weights are determined analytically using a one-pass learning method. To evaluate FW-ELM, it is compared with popular fuzzy models like OS-Fuzzy-ELM, Simpl_eTS, ANFIS and several other relevant algorithms such as ELM, BP and SVR on various benchmark datasets. Simulation results demonstrate the remarkable efficiency resulting from the proposed approach. Performance accuracy of FW-ELM is shown to be comparable with OS-Fuzzy-ELM and better than the rest of the well-known methods.

Keywords: Fuzzy wavelet (FW) model; Extreme learning machine (ELM); Wavelet neural network (WNN)

1. Introduction

Soft computing techniques such as artificial neural networks (ANN) [1], Fuzzy Models [2] and wavelet networks [3] have been applied in large variety of areas such as artificial intelligence, pattern recognition, robotics, system identification and so on [4–8]. Among ANNs, feed forward neural network (FFNN) is one of the mostly used learning mechanisms [9,10]. Although FFNNs have learning and generalization abilities, they suffer from network complexity because they may require a large number of neurons [11]. By combining the benefits of neural network (learning

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ability) and fuzzy inference system (FIS), fuzzy neural network (FNN) has been developed [12–15]. FNN employs the learning ability of neural network and the approximate reasoning characteristics of FIS to present a technique to deal with complex problems, which include uncertain or ill-defined factors [11,15].

Multiresolution and time frequency localization properties of wavelets make them powerful approaches to solve difficult problems in the fields of mathematics, physics and engineering [16–19]. By inspiring neural network, fuzzy theory and wavelet transform, fuzzy wavelet neural network (FWNN) has been constructed [20]. FWNNs can improve model accuracy, generalization ability and computational power of neuro-fuzzy systems [21–23]. In FWNNs, the consequent part of each fuzzy rule includes a linear finite set of wavelet functions. A fuzzy wavelet network consists of three types of parameters: wavelet coefficients, parameters of membership functions, and the output layer weights. These parameters should be initialized using an appropriate method, and then they should be updated during training steps of the network [24–29]. In [25], to find unknown parameters of the network, a fast gradient-based-training algorithm, i.e., the Broyden–Fletcher–Gold Farb–Shanno method is used. In [27], an adaptive FWNN was proposed for the control of affine nonlinear systems, in which TSK (Takagi Sugeno Kang) fuzzy model and WNN are combined. The network size, the number of fuzzy rules, the number of wavelets in each sub-WNN and initial weights are determined in a reasonable number of iterations by OLS (Ordinary Least Squares) algorithm, and the algorithm provides good initializations for the learning procedure.

In [28], the algorithm gives the initial parameters by the clustering algorithm and then updates them with a combination of back propagation and recursive least-squares methods. In [29], initially, the antecedent parameters are selected as small random values, the initial consequent layer parameters are determined by least square methods, and training is done using one of the most popular quasi-Newton algorithms known as DFP algorithm.

Generally, in FWNNs, finding efficient methods for parameter initialization and iterative learning step is one of the main issues. Not only these factors are important for determining the speed of training algorithms, but also affect the accuracy of the model.

It is to be noted that all the above-mentioned neural networks are trained by iterative learning methods, and most of them use gradient-based learning algorithms such as back propagation (BP). In spite of good accuracy provided by these algorithms, they suffer from several drawbacks such as finding an appropriate method for adjusting and updating parameters, long computation time, and local optima [30]. To overcome these problems, in [30], Huang–Bin has been presented a method for training a single hidden layer feed forward neural network (SLFN) called extreme learning machine (ELM). In contrast to traditional learning algorithms such as BP, in ELM, parameters of the hidden layer and weights between the hidden layer and the input layer need not be tuned and are assigned randomly for once, and remain fixed throughout learning procedure. The output weights, which link the hidden layer and the output layer, are determined analytically.

According to conventional neural network theories, SLFNs have universal approximation properties when all the parameters of the network are allowed to be adjustable. Ref. [31] in an incremental constructive method proves that input weights and hidden layer biases of SLFNs need not be tuned. Consequently, SLFNs can also work as universal approximators with randomly selected hidden nodes and adjustable output weights.

A number of extensions of ELM have been deployed in various learning fields [32–35]. Huang et al. proposed an online sequential learning machine (OS-ELM) for function approximation and classification of real-world problems [34]. In [35], Huang et al. extended OS-ELM to OS-Fuzzy-ELM, which is based on TSK fuzzy model. Training procedure of OS-Fuzzy-ELM can be done by loading the data chunk by chunk or one by one. In [35], it is shown that efficiency and computation time of OS-Fuzzy-ELM are similar to or better than other well-known learning algorithms such as (ANFIS-Full, ANFIS-Reduced and simplified eTS algorithms (Simpl_eTS) [35]).

Various combination of WNNs and ELM have been proposed in prognostic, health monitoring, forecasting, identification problems, etc. [36–39]. In [36], the authors have proposed summation wavelet-ELM (SW-ELM), which uses summation of an inverse hyperbolic Sine and a Morlet wavelet function as activation function of the hidden layer nodes and Nguyen Widrow method to reduce the impact of a random initialization procedure. In [37], to perform estimation/prediction tasks, features are used to build a model with SW-ELM algorithm. In [38], an automatic system was proposed for target recognition based on wavelet extreme learning machine. In [39], to improve forecasting accuracy, a hybrid wavelet-ELM model was developed. It is noteworthy that in the most extensions of ELM, network complexity and impact of parameter randomness are important issues and should be considered.

To overcome the aforementioned problems, this paper presents a novel structure of fuzzy wavelet model based on theory of multiresolution analysis (MRA) of wavelet transforms, fuzzy concepts and ELM. This method is called fuzzy

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