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Financial time series prediction using a dendritic neuron model

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ABSTRACT

As a complicated dynamic system, financial time series calls for an appropriate forecasting model. In this study, we propose a neuron model based on dendritic mechanisms and a phase space reconstruction (PSR) to analyze the Shanghai Stock Exchange Composite Index, Deutscher Aktienindex, N225, and DJI Average. The PSR allows us to reconstruct the financial time series, so we can prove that attractors exist for the systems constructed. Thus, the attractors obtained can be observed intuitively in a three-dimensional search space, thereby allowing us to analyze the characteristics of dynamic systems. In addition, using the reconstructed phase space, we confirmed the chaotic properties and the reciprocal to determine the limit of prediction through the maximum Lyapunov exponent. We also made short-term predictions based on the nonlinear approximating dendritic neuron model, where the experimental results showed that the proposed methodology which hybridizes PSR and the dendritic model performed better than traditional multi-layered perceptron, the Elman neural network, the single multiplicative neuron model and the neuro-fuzzy inference system in terms of prediction accuracy and training time. Hopefully, this hybrid technology is capable to advance the research for financial time series and provide an effective solution to risk management.

1. Introduction

Financial market time series comprise chaotic dynamic systems with high volatility and irregular movements, and thus previous researchers have treated financial data as highly unpredictable [1]. Various factors influence time series, which can be categorized in two main ways: macro-variables affect the stock market in the long term, such as economic policy tactics or the gross national product; and micro-variables affect the market in the short term, including random events, the irrational behavior of investors, and market rumors. Macro- and micro-variables contribute to decisions based on evolving variables in dynamic systems. However, the factor with the greatest effect on the system is not known. Indeed, the only major factors we can extract from the system are the price and the time interval. The price is a one-dimensional time series, which can be denoted as $x(t_1), x(t_2), \ldots, x(t_n)$, and the time interval can be represented by $t_i = x_0 + \Delta t$. The one-dimensional time series of the financial market is generally nonlinear with an abundance of noisy information.

Some traditional statistical time series models have been proposed in previous studies, such as the moving average model [2], auto-regressive model [3], and autoregressive moving average model [4]. However, the predictions obtained using these traditional models are usually imprecise, and it is difficult to utilize these models to approximate nonlinear and irregular financial time series.

In recent years, nature-inspired methods and modern machine learning methods have been proposed for financial times series prediction [5–20], where artificial neural networks (ANNs) have received much interest. The first conceptual model of an ANN was proposed in 1943 by a neuroscientist, McCulloch, and a logician, Pitts [21]. In their thesis, they employed a logical calculus with imminent nervous activity, where a single cell receives input signals in a network, before processing them and generating an output. Later, Rosenblatt [22] proposed the perceptron model based on a two-layer learning computer network, which uses simple addition and subtraction to solve pattern recognition problems. Using the McCulloch–Pitts neuron and based on the discoveries of Hebb, Rosenblatt created the first perceptron that could learn in the Hebbian sense, and based on the weighting of inputs, the perceptron was instrumental in the later development of neural networks. However, the perceptron still could not solve XOR and NXOR

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functions until the back-propagation algorithm was proposed by Werbos [23].

ANN has been developed for financial time series prediction in many methods, such as different structures [10,11,14,24–27], hybrid learning methods [15,28,29], ensemble techniques [30], fuzzy theories [31,32], and time delay methods [33,34]. Some of the main methods are described as follows. A stock trading model where the core component included two phases with multi-layered perceptrons (MLPs) was proposed in [35]. A time delay recurrent neural network was employed to predict stock trends using a false alarm rate as low as zero while missing most of the profit opportunities [36]. A neural oscillatory-based recurrent network was proposed for finance prediction to provide both long-term and short-term stock price forecasting [37]. In [6], a four layer bat-neural network multi-agent system architecture was proposed to address the distributed nature of the stock prediction problem. A neuro-wavelet model [38] was proposed for application to any high-frequency financial series by specifying a particular series during the construction of the model. A neuro-fuzzy model [39] achieved outstanding forecasting performance with four well-known benchmark data sets. By combining ANN with other meta-heuristics, such as the genetic algorithm (GA) [40], the feature instances selected by the GA could also enhance the predictive performance of ANNs and reduce the learning time. Moreover, Kim and Shin [41] employed adaptive time delay neural networks with a GA to detect the temporal patterns in stock market prediction tasks.

Various ANNs have been proposed, but it is difficult to identify the best compared with others over all financial time series instances [42]. Thus, each ANN has its distinct characteristics and limitations, which influence the prediction performance when applied in financial scenarios. For example, despite the widespread applicability of MLP, the back-propagation-based MLP can only learn an input-output mapping for static or spatial patterns that are independent of time [41]. The time-delayed ANN may be the simplest choice for representing a wide range of mappings between past and present values [33,34], but the fixed time delays in these ANNs remain constant throughout training after initialization, thereby risking a mismatch between the choice of time delay values and the temporal locations of important information in the input patterns [26,41]. The Elman recurrent ANN [43,44] has advantages compared with the MLP because the memory features obtained using a feedback mechanism can be used to extract time dependencies from the data. However, the traditional recurrent ANN algorithms based on the gradient descent approach are well known for their slow convergence and high computational costs [45,46], so it is difficult to utilize them in actual applications. Moreover, all of these ANNs are implemented using a complex architecture with multiple neurons, whereas few studies have utilized a single neuron for forecasting.

Based on the latest research into the properties of neurons [47–50], we proposed a realistic computation model of a single neuron with synaptic nonlinearities in a dendritic tree (NBDM) in our previous study [51]. By modeling the synaptic nonlinearity with a sigmoid function, this single neuron is capable of computing linearly non-separable functions and approximating any complex continuous function. The nonlinear interactions in a dendrite tree are expressed using Boolean logic, i.e., AND (conjunction), OR (disjunction), and NOT (negation), instead of calculating complex functions. In the present study, we investigate the effectiveness of NBDM for predicting future stock prices. In data forecasting scenarios, a hybrid methodology generally achieves better accuracy than a single forecasting method [52]. Real-world financial time series perform chaotically and unpredictably according to long-term observations, and thus it is difficult to obtain reliable future forecasts. By contrast, they exhibit periodicity when reconstructed as a phase point in a phase space. Thus, making predictions in the phase space

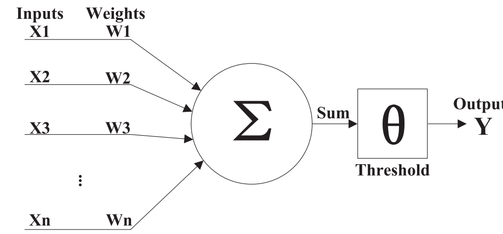

Fig. 1. McCulloch-Pitts model.

is easier than using a one-dimensional time series. In this study, we propose the combination of NBDM with phase space reconstruction (PSR) [53] to predict financial time series and we verified our proposed method based on four instances, i.e., the Shanghai Stock Exchange (SSE) Composite Index, Deutscher Aktienindex (DAX), Nikkei 225 (N225), and Dow Jones Industrial (DJI) Average. The PSR theory advocates that the components of a chaotic time series are not isolated, and thus there is a correlation among them [54]. Therefore, an apparently one-dimensional time series actually contains high-dimensional information, which makes financial data nonlinear, irregular, and difficult to predict. However, by utilizing the effects of PSR, the acceptable dimensions and time delay of the attractors in the SSE DAX N226 and DJI can be obtained, thereby allowing the time series data to be manipulated without losing the dynamic behavior and structural topology. Short-term predictions can then be made based on the NBDM. Our experimental results demonstrated that the proposed methodology performed better than traditional multi-layered perceptron, the Elman neural network, the single multiplicative neuron model (SMN) and the neuro-fuzzy inference system (ANFIS) in terms of the prediction accuracy and training time.

2. Methodology

There are two main methodologies that contribute to our study most. One is the neuron model, and another is chaos. This chapter is to introduce the basic knowledge and principles of them.

2.1. Studies of neuron models

2.1.1. McCulloch-Pitts model of a neuron

The first model of an artificial neuron was introduced by McCulloch and Pitts [21] in 1943 (Fig. 1). The McCulloch–Pitts neural model is also known as the linear threshold gate. The McCulloch–Pitts model of a neuron is simple but it has great computing potential. It also has a precise mathematical definition; however, this model is so simplistic that it only generates a binary output with fixed threshold values.

2.1.2. Koch–Poggio–Torre model

Koch, Poggio, and Torre investigated the mechanism of dendritic construction based on understanding the functions of cells [55]. The interaction between the excitatory synaptic input and the steady-state shunting inhibitory input was elucidated using cable theory. It was shown that there is a logic operation in dendrites, where δ-like cells comprise the morphological substratum employed for directional selectivity in the retina. In addition, Koch et al., developed a model of a retinal ganglion neuron with directional selectivity for moving visual inputs, thereby enabling linkage to logic operations.

Fig. 2 shows a general example of a δ-like cell with excitatory inputs (•) and inhibitory inputs of the shunting type (■). The highly branched pattern is also depicted in terms of logic operations from [55]. The inhibitory inputs can clearly be restrained if