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Complex dynamical behavior of neural networks in circuit implementation

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ABSTRACT

Neural networks have abundant dynamic behaviors in nonlinear fields. In this paper, several circuit units are combined to realize some neuron-network models. The results of circuit simulation described by Multisim software demonstrates complex dynamical behaviors. It is shown that the phenomenon such as hyperchaos, limit cycles, homoclinic orbits of the designed circuits are closely similar to the results of numerical experiments.

1. Introduction

Artificial neural networks rise in artificial intelligence since the 1980s. It abstracts human brain neuron-network from the perspective of information processing to establish some simple models and different networks according to different compositions. Neural network is a computing model, composed by a large number of interconnected nodes (or neurons). The network itself is usually approximation to some kind of algorithm or function in nature, it may be the expression of a logical strategy. Neural network is a highly nonlinear dynamical system. Although the structure and function of each neuron is not complicated, the dynamic behavior of neural network is very complex, so using neural networks can express a variety of phenomena in the physical world. In the past ten years, the study of artificial neural networks continued to deepen and merged with wavelet analysis, rough sets, chaos and fractal theory. It has made great progress in pattern recognition, intelligent robot, automatic control, prediction estimate, biology, medicine, economy and other fields and has successfully solved the practical problems which are difficult for many modern computers, showing good intelligence [1–10].

Generally speaking, the design for neural networks heavily depends on their dynamical behaviors. In the literatures, it has been known that neural networks have complex dynamical behavior, such as chaos and bifurcations [11–41]. Therefore, chaotic neural network is considered to be one of intelligent information processing systems that can achieve real-world computing, and current research on chaotic neural network is still in initial stage, the study is limited to understanding chaotic characteristics of single neuron and behavior analysis of simple chaotic neural network. In addition, chaotic dynamics can be used to overcome the drawback of being trapped in local minima in nonconvex optimization problem. Li et al. [11] demonstrated hyperchaos in a classical Hopfield-type neural network with four neurons for some weight matrices. In [12], Lu et al. investigated the complex dynamical behavior of delayed neural networks with two neurons. Typically, the bifurcation corresponds to the critical value of some system parameters, the system state will be mutated when the parameters pass through the critical value. We can get the conditions that bifurcation occurs after balance instability through analyzing the stability of the system equilibrium point. Complicated bifurcation behavior, such as homoclinic, heteroclinic orbits, and limit cycles, can be interpreted as stored memories. For the bifurcation behaviors of neural networks, Li et al. [13] investigated Hopf bifurcation and chaos, and using center manifold reduction and the normal form method, He et al. [14] discussed Bogdanov–Takens bifurcation, and it is shown that the model can exhibit saddle-node, pitchfork, homoclinic, heteroclinic and double limit cycle bifurcation, Song et al. [15] obtained the global perspective of system dynamics through analyzing the intersection points of the pitchfork and Hopf bifurcation curves in an inertial two-neural coupling system with multiple delays.

Software implementation is suitable for the algorithm and simulation, hardware runs faster and is able to achieve real-time processing requirements comparing with software implementation. As is known to us all, realization of artificial neural network

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in the engineering applications needs to make circuit boards, therefore, design of the circuit is the basis of neural networks' application in Engineering. Due to the chase of high order information processing, the circuitry implementation of neural-network model is very important. For example, Duan and Liao [16] gave an electronic implementation of chaotic Liao's delayed neuron model. Moreover, S. Gomor and A. Ahmadi [17] proposed a set of models for biological spiking neurons, which are efficiently implementable on digital platforms and can reproduce different biological behaviors with a high precision. In this paper, we propose a circuit that achieves the activation function and time delay, then we further detect the correctness of the circuit model, the circuit simulation is described and the implementation is supported by Multisim simulation results. Considering the universality of the circuit model, we discuss the hardware implementation of different kinds of neuron models proposed in [11,12,14,15], respectively. Therefore we confirm the circuit designed is correct and can be employed to realize other different neural network models, such as delayed neural network, inertia neural network and inertia coupling neural network. For these models, this paper, firstly, introduces the mathematical models of neural network and determines the initial values of parameters. Subsequently, several circuit units including activation function unit and time delay unit are combined to realize these neuron-network models. Of course, circuit implementation for these models is organized according to the complexity of the neural network model. Firstly, a relatively simple neural network, called Hopfield-type neural network (HNN) is implemented. Then we concerned a model with time delay, called delayed neural network (DNN) with two neurons. Next, a second-order neural model, named single inertia neural network (SINN) is thought carefully to achieve. On the basis of the implementation for second-order neural network, we further study the realization for inertia coupling neural network (ICNN). Finally, the circuit simulation is described and the implementation is supported by Multisim simulation results. It is shown that the phenomena such as hyperchaos, limit cycles, homoclinic orbits of the designed circuits are closely similar to the results of numerical experiments. Simulation results verify the existence of complex chaos and bifurcation phenomena in neural networks. The proposed circuit may be used as delayed chaos generator, a chaotic neuron circuit unit, even a cell for cellular neural network. It has potential applications to communications and signal processing. In addition, the proposed activation function circuit unit and time delay circuit can be also employed in other circuit designs.

The remainder of this paper is organized as follows. In the next section, some mathematical models including HNN, DNN with two neurons, SINN with delay and ICNN with multiple delays are introduced. In Section 3, the circuit implementation of the activation function unit, time delay unit and neural-network models introduced are given and discussed respectively. Finally, Section 4 concludes this paper.

2. Mathematic models of some typical neural networks

2.1. Hopfield-type neural network

The HNN abstracted from man-brain dynamics is a very important neural model in neurocomputing. HNN in which has been observed chaotic dynamics [18,19,20] can be described by

$$C_i\frac{dx_i}{dt}=-\frac{x_i}{R_i}+\sum_{j=1}^{n}w_{ij}f_i(x_i)+I_i, i=1,2,\cdots,n. \quad (1)$$

Where f_i is a differentiable function and denotes a measure of response or activation to its incoming potentials; $W=(w_{ij})$ is an $n\times n$ matrix, called weight matrix describing the synaptic connection weight of the unit j on the unit i; I_i correspond to the external bias or input from outside the network to the unit i; the parameter R^{-1} is the rate with which the unit self-regulates or resets its potential when isolated from other units and inputs.

Considering that hyperchaos does not occur in autonomous continuous time systems when the system dimensions $n\le 3$ [21], so in this section, set $n=4$, then the 4D HNN can be simplified to the following equations:

$$\dot{x}_i=-c_ix_i+\sum_{j=1}^{4}w_{ij}f_i(x_i), i=1,2,3,4 \quad (2)$$

where $W=(w_{ij})$ is a 4×4 matrix, and [11] has shown that the 4D HNN can exhibit hyperchaotic phenomena for some carefully chosen weight matrices.

2.2. Delayed neural network with two neurons

Delay as an objective phenomenon, presents in various engineering, biological and economic systems and often results in poor dynamic network behavior, such as vibration, bifurcation or instability. Therefore research on DNNs' dynamic behavior is of

Table 1
Parameter annotation.

Parameters	Meaning
I_S	Saturation current
V_{BE}	Base-emitter voltage
V_T	The thermal voltage
k	Boltzmann constant
q	The electron charge
T	The temperature

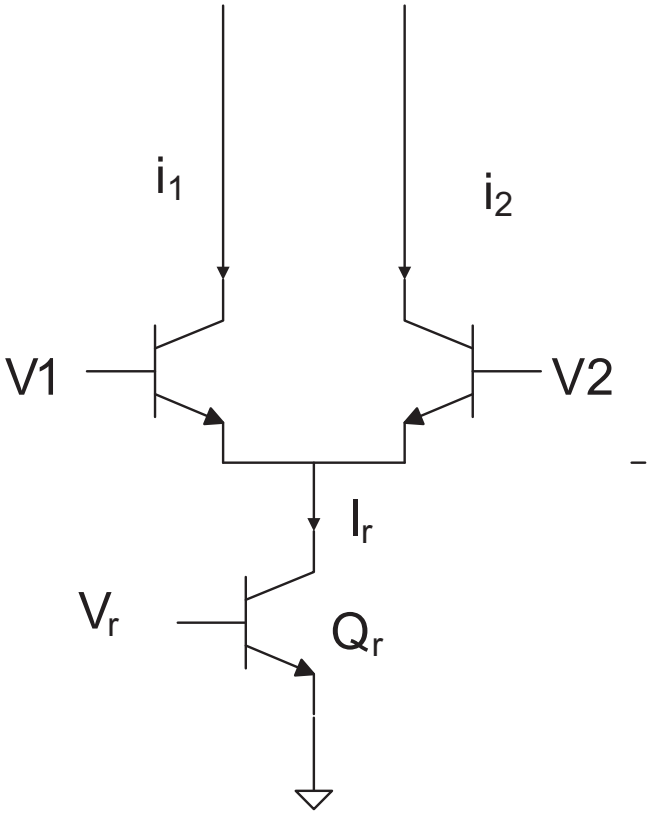

Fig. 1. The circuit analysis diagram in [24].