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FPGA implementation of motifs-based neuronal network and synchronization analysis

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HIGHLIGHTS

- 13 kinds of motifs are implemented in FPGA and be clarified into different categories with synchronization analysis.
- The pipeline structure is adopted to implement motif-based small-world networks of different scales and categories.
- The synchronization properties of motif-based small-world networks are analyzed from three aspects: network size, rewiring probability and coupling strength.

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ABSTRACT

Motifs in complex networks play a crucial role in determining the brain functions. In this paper, 13 kinds of motifs are implemented with Field Programmable Gate Array (FPGA) to investigate the relationships between the networks properties and motifs properties. We use discretization method and pipelined architecture to construct various motifs with Hindmarsh–Rose (HR) neuron as the node model. We also build a small-world network based on these motifs and conduct the synchronization analysis of motifs as well as the constructed network. We find that the synchronization properties of motif determine that of motif-based small-world network, which demonstrates effectiveness of our proposed hardware simulation platform. By imitation of some vital nuclei in the brain to generate normal discharges, our proposed FPGA-based artificial neuronal networks have the potential to replace the injured nuclei to complete the brain function in the treatment of Parkinson's disease and epilepsy.

1. Introduction

Brain as the most complex neuronal network includes various functional modules. All the modules carry out their duties in their own functional areas [1–4]. They combine together to form an effective management mechanism to accomplish human behaviors and cognitive activities in everyday life [5–8]. Motif was first proposed to uncover this functional mechanism as a common organizational form of complex network [9]. The introduction of motifs has improved our understanding about the mechanism of functional integration and specialization of the large-scale complex network. Motifs exist widely and regularly in complex network and support various computational processes [10–15]. They not only constitute the elementary building blocks of networks, but also reflect rich properties of them. People scanned for all possible n-nodes subgraphs in many biological neural networks and counted out 13 kinds of the most common motifs with high occurrence frequency listed in Fig. 1(a). Gollo et al. discussed the 13 kinds of motifs in brain cortical network where different motifs are distributed in a

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variety of functional areas [16]. They profoundly revealed that motif distribution in cortical network plays an important role in determining the overall properties [17,18]. Therefore, the study of the relationship between structure/dynamics on complex networks has gradually stretched for the study of the structure/dynamics relationship in network motifs [19–24]. The fingerprints of these small motifs have already become a standard procedure to understand the structure of complex networks that determines the network dynamics [25–29]. Therefore, the grasp of cortical motifs can enhance our understanding of the brain dynamics and large-scale cortical network. In this paper, we focus on the synchronization of motifs and motif-based small-word neuronal network [30,31], which is considered as the key feature that modulates cortical interactions. Researchers have explored much more about synchronization in synchronization transitions on small-world neuronal networks. Wang et al. not only discussed the effects of information transmission delay and rewiring probability in Refs. [32,33] but also studied the synchronization transitions on scale-free neuronal networks in Ref. [34]. In 2011, synchronous bursts on scale-free neuronal networks with attractive and repulsive coupling are explored in Ref. [35]. Despite synchronization properties in neuronal networks have been extensively studied, they have never been attempted in hardware platform. Here, different from the traditional computer simulation, we establish a hardware platform for the motif implementation and then build a small-world network based on motifs in our proposed hardware platform.

As a semi-conductor digital Application Specific Integrated Circuit (ASIC) chip, Field Programmable Gate Array (FPGA) has evoked a great deal of interest for researchers. In recent years, people have made effort to apply it to biology and neuroscience [36–38] due to its favorable performance. Compared with the software simulation, FPGA shows more advantages over PC-solution especially in the large-scale simulation of neuronal network. First, parallel processing of FPGA significantly improves computational efficiency, which effectively solves the time-consuming problem in a general-purpose system. Second, because of its re-configurable nature, FPGA implementation allows for developing a module repertoire which includes a variety of neuron models for different purposes. It has been proved that FPGA can generate all kinds of firing patterns of single neurons with diverse models. In addition, its small volume and high level integration make it possible to regulate neural activities in prosthetic applications where FPGA is used as biological central pattern generator (bCPG) implanted into brain. Since bCPG is based on a group of three inhibitory neurons which generates normal rhythm regulating the cardio-respiratory system to induce respiratory sinus arrhythmia contributing to normal heartbeat, the implementation of motifs and motif-based network with FPGA, imitating the respiratory bCPG in the brainstem, has great potential to replace the cardiac rhythm management device to accomplish the normal rhythm movement of human body. Given the normal rhythm generated by such bCPG, we can realize the control of pathological rhythm in response to the physiological feedback to address the heart disease.

In this paper, Hindmarsh–Rose (HR) neuron model [39] is used to describe the node of motifs. It is a type of three-order neuron model which was deduced by Hindmarsh and Rose in 1984 based on FitzHugh–Nagumo (FHN) model. As the most appropriate neuronal model to account for the properties of cortical neurons, HR neuronal model has drawn much attention of researchers in exploring the rich dynamics of neural network such as phase synchronization, chaos control and so on Refs. [40–43]. Here, 13 kinds of basic motifs are constructed based on HR neuronal model and then implemented in our target hardware platform. Modular design in DSPBuilder armed with predefined blocks which represent the mathematical operations makes the system modeling much simple and explicit. In this platform, we can observe the bursting status of every node of motif under different coupling strength. With FPGA implementation, we examine the synchronization properties emerged on a number of motifs. We find that some motifs with specific structures facilitate synchronization while others are hindered. This result is consistent with software simulation result. We further build a small-world network based on motifs with the current FPGA platform and make a synchronization analysis for our constructed network, generalizing the wide use of motif in construction of functional network. Fig. 1(b) shows the configuration of our motif-based small-world network. This idea pushes us to make functional network equivalent to motif which will greatly facilitate our research.

The rest of this paper is organized as follows: The detailed implementation method and design flow of motifs and a motif-based small-world network in FPGA are presented in Section 2. Section 3 exhibits the simulation results of partial motifs and constructed small-world network. Synchronization analysis for motifs of different structures and small-world network is also discussed in this section. We conclude our paper with some prospect for future work in Section 4.

2. Model and method

It is an effective way to divide a large complex network into several subnetworks to explore its structures and functions [44,45]. It just likes the human cerebral cortex where each region is portrayed by its own set of motifs which are related to vision, movement and language. We focus on small-world network and attempt to compose it with multiple motifs to make analysis. Hence, our discussion will be spread out across a hierarchy of scales from single neuron to motif then to a motif-based small-world network.

2.1. HR neuronal model

In this paper, we use HR neuronal model to simulate the dynamics of individual node in motifs and network. The mathematical expression of HR model is given as: