Neuroinformatics

1539-2791/04/417–436/$25.00

Original Article

An FPGA-Based Approach to High-Speed Simulation of Conductance-Based Neuron Models

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Abstract

The constant requirement for greater performance in neural model simulation has created the need for high-speed simulation platforms. We present a generalized, scalable field programmable gate array (FPGA)-based architecture for fast computation of neural models and focus on the steps involved in implementing a single-compartment and a two-compartment neuron model. Based on timing tests, it is shown that FPGAs can outperform traditional desktop computers in simulating these fairly simple models and would most likely provide even larger performance gains over computers in simulating more complex models. The potential of this method for improving neural modeling and dynamic clamping is discussed. In particular, it is believed that this approach could greatly speed up simulations of both highly complex single neuron models and networks of neurons. Additionally, our design is particularly well suited to automated parameter searches for tuning model behavior and to real-time simulation.

Index Entries: Neuron models; simulation; multicompartmental models; FPGA; multiplexing.

Introduction

Given that neurons are complex dynamical systems, realistic simulation has been an extremely important tool in creating and evaluating hypotheses on neural mechanisms and modes of action. Neural models have traditionally been implemented on computers with the help of a dedicated neural modeling software (Hines and Carnevale, 1997; Bower and Beeman, 1998; Cannon et al., 2003). However, the constant requirement for greater performance in neural model simulation has created the need for ever faster computational solutions. Custom hardware implementations of a model would achieve the

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fastest possible realization, but are hindered by very long (several months) design cycles and the need for a computer architecture expert. The approach described here provides a fast alternative to general-purpose computers. On the basis of the capabilities of field programmable gate arrays (FPGAs), we have developed a generalized, scalable neuron simulation architecture that dramatically reduces simulation times and at the same time maintains much of the flexibility of general-purpose computer simulators.

An FPGA is a programmable device consisting of an array of configurable logic elements, typically interspersed with fixed-logic resources (e.g., multipliers and memory modules). Wiring lines run horizontally and vertically in between these logic blocks, selectively connecting them to one another or to input/output blocks. Figure 1 shows the basic architectural features of an FPGA. Reconfigurable FPGAs offer the opportunity to design, program, and reconfigure the logic circuit elements and interconnect as many times as needed. Because the hardware architecture can be tailored to a particular application, a processor is not required to control the logic. Thus, a fully parallel approach can be undertaken to design the system. This gives FPGAs the potential to run a task much faster than a general CPU would run it.

In the area of neural computation, FPGAs have been used to build fast implementations of artificial neural networks (ANNs) (Girau, 2000). In particular, they have helped simulate large pulse-coupled neural networks (PCNNs) with pattern recognition capabilities (Waldemark et al., 2000; Schaefer et al., 2002). A biologically motivated model of an auditory neuron has also been implemented on an FPGA for integration in a cochlear implant (Meyer-Base and Scheich, 1997). All of these neural models, although biologically inspired, rely on simplistic versions of the constituting neurons. Additionally, these designs are limited in scalability in that larger models require more hardware (i.e., more or larger FPGAs).

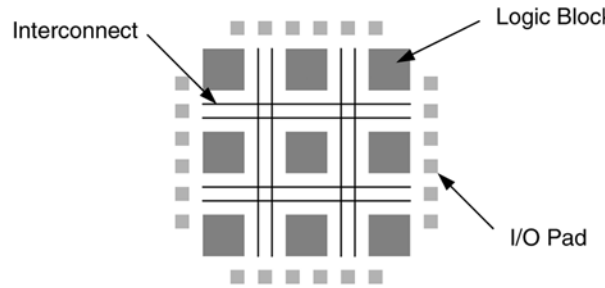

Fig. 1. Simplified FPGA architecture.

In this paper, we develop a novel interleaving strategy for designing and programming biologically realistic neuron models on an FPGA that permits much higher utilization of the computational power of the FPGA and much greater scalability to large models. It is demonstrated that, using this strategy, FPGAs can outperform computers in simulating relatively simple neural models with results that suggest that even larger performance gains over computers would be possible in simulating more complex models. Notably, the recent development of FPGA design tools based on MathWorks Simulink graphical modeling environment makes programming FPGAs much more accessible to modelers not familiar with FPGA technology. The potential of this method for improving neural modeling and dynamic clamping (Sharp et al., 1993) is discussed. In particular, it is believed that FPGAs could dramatically reduce the time needed to perform automated parameter searches, greatly speed up the simulation of large multicompartmental models of single neurons as well as multineuron networks, and allow more complex models to be used in dynamic clamp applications.

Example Neuron Models

Two neuron models were implemented in FPGA hardware. The first model is based on the original Hodgkin–Huxley (HH) equations for the squid's giant axon (Hodgin and Huxley, 1952). The HH model was chosen because, although relatively simple, it typifies conduc-