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Digital implementation of Hodgkin-Huxley neuron model for neurological diseases studies

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Abstract: Neurological disorders affect millions of people which influence their cognitive and/or motor capabilities. The realization of a prosthesis must consider the biological activity of the cells and the connection between machine and biological cells. Biomimetic neural network is one solution in front of neurological diseases. The neuron replacement should be processed by reproducing the timing and the shape of the spike. Several mathematical equations which model neural activities exist. The most biologically plausible one is the Hodgkin-Huxley (HH) model. The connection between electrical devices and living cells require a tunable real-time system. The FPGA (Field Programmable Gate Array) is a nice component including flexibility, speed and stability. Here we propose an implementation of HH neurons in FPGA serving as a presage for a modulating network opening a large scale of possibilities like damage cells replacement and the study of the effect of the cells disease on the neural network.

Keywords: Silicon neuron, Hodgkin-Huxley, FPGA, neurological diseases

1 INTRODUCTION

Millions of people worldwide are affected by neurological disorders which could cause variety of symptoms including paralysis and dementia. Such a number is likely to increase in the next years and current assistive technology is still limited. Since last decades Brain-Machine Interfaces (BMIs) and generally neuroprosthesis [1-4] have been object of extensive research and may represent a valid treatment for such disabilities. The development of these devices has and will hopefully have a profound social impact on the quality of life. The realization of such prostheses implies that we know how to interact with neuronal cell assemblies, taking into account the intrinsic spontaneous activity of neuronal networks and understanding how to drive them into a desired state or to produce a specific behavior. The long-term goal of replacing damaged brain areas with artificial devices also requires the development of neuronal network models. They will fit with the recorded electrophysiological patterns and will produce in their turn the correct stimulation patterns for the brain so as to recover the desired function. The hardware set-up that will be used to interface the biological component is a Spiking Neural Network (SNN) system [5-8]. SNN implements biologically realistic neural network models, spanning from the electrophysiological properties of one single neuron up to network plasticity rules. Biomimetic neural network is one solution in front of neurological diseases. The neuron

replacement should be processed by reproducing the timing and the shape of the spike.

In the human brain, types of neurons are radically different. Complexities of neuronal cells are abstracted by a wide variety of methodology to help the understanding of the different aspects of neural networks' development, function, or learning. The neuronal model is a mathematical description of the electrophysiological properties of neuronal cells, or neurons. It tries to accurately describe and predict their biological processes.

In order to provide a SNN, the first step is the choice of the neuromimetic mathematical model. Indeed, the mathematical model, based on differential equation, can reproduce a behavior more or less close to biological cell. In order to choose our model, we are looking two criteria: the variety of firing rate dynamics that can be reproduced and the shape of action potential for modelling neurological disease. Regarding those criteria, we can compare all models like threshold-models: the Leaky Integrate and Fire (LIF) [9] or the Izhikevich model (IZH) [10] or like complete model: the Hodgkin-Huxley model (HH) [11]. The HH model can reproduce all kind of neurons with a good accuracy in terms of shape of spike or complex firing activities compared to threshold models. The drawback is its computation cost but our objective is to simplify this model for a few resource implementation in to digital board.

Various software solutions are currently available for simulating neuron models. Less conventional than software-based systems, hardware based solutions are also provided

which generally combine digital and analog forms of computation. Analog implementations are fast and efficient however they are inflexible, sensitive to variations and require a long development time. As in many other fields of microelectronics, a mixed implementation offers both the advantages and disadvantages of both solutions: analog circuits have a higher integration density, and digital platforms have better programmability. Recently, as a midpoint in the design space, FPGAs have been used to build spiking neuronal networks. Digital FPGA implementations offer a significant speedup over software designs, as well as size, weight, and power efficiency. Compared to analog VLSI, digital FPGA designs are stable and flexible in design alterations. Previous works have already implemented neuronal networks on FPGA [12-14]. However, those designs have been realized for computation purposes without taking into account biological real time. Few FPGA implementation are used for hybrid experiments [15-17] but they used threshold neuron model. The implementation in FPGA of HH model are rare [18], [19]. These works are used for neural network simulation (accelerated-time) and they are not optimized in terms of surface and number of neurons. In this paper, we present the implementation in FPGA platform of HH neurons dedicated to the simulation of neurological diseases.

2 HODGKIN-HUXLEY FORMALISM

2.1 Equations

The first biologically relevant mathematical neuron model was proposed in 1952 by Hodgkin and Huxley (HH). Their four-dimensional set of equations describes the ionic conductance's dynamics of the giant axon, which are the starting point for detailed neuron models which account for numerous ion channels, different types of synapses, and the specific spatial geometry of an individual cell. Such class of models, conductance based models, successfully describe and reproduce the neuronal activity. Moreover the parameters of the HH model have biophysics meaning. Thus, in case of study of neurological diseases, we can modify the original model to easily include the cell degeneration.

The main advantage of this formalism is that it relies on biophysically realistic parameters and describes individual ionic and synaptic conductances for each neuron in accordance with the dynamics of ionic channels. Electrical activity of a neuron is the consequence of the diffusion of different ionic species through its membrane. The HH formalism provides a set of equations and an equivalent

electrical circuit (Figure 1), which describes the conductance interplay underlying the genesis of action potentials.

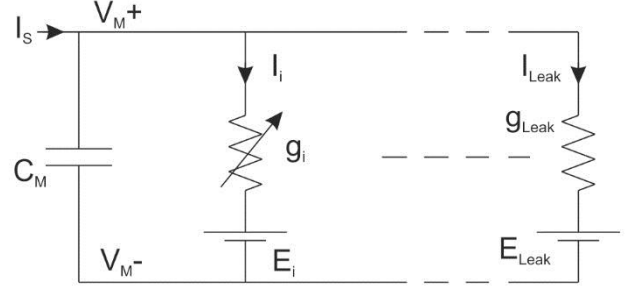


Fig. 1. Equivalent electrical circuit of a neuron.

The current flowing across the membrane is integrated on the membrane capacitance, according to expression (1):

$$C_M \frac{dV_M}{dt} = - \sum_i I_i + I_{Leak} + I_S \quad (1)$$

Where V_M is the membrane potential, C_M is the membrane capacitance, I_i denotes the individual ionic currents of the model, I_{Leak} the leakage current, and I_S is a stimulation or a synaptic current. I_i is the current for a given type of channel, and its associated equation is:

$$I_i = g_i \cdot m^p \cdot h^q \cdot (V_M - E_i) \quad (2)$$

Where g_i is the maximum conductance; m and h are gating variables for activation and inactivation, respectively, representing the fraction of open gates available at any given time and voltage. E_i is the ion-specific reversal potential and p and q are integers.

$$C_M \frac{dV_M}{dt} = - \sum_i I_i + I_{Leak} + I_S \quad (3)$$

According to Hodgkin and Huxley [11], the values of activation and inactivation's parameters are updated by equation (4).

$$\frac{dx}{dt} = \frac{x_\infty(V) - x}{\tau_x(V)} \quad (4)$$

Where $x \in \{m, n, h\}$ and $\tau_x(V)$ and $x(V)$ are obtained by (5) and (6).

$$\tau_x(V) = \frac{1}{\alpha_x(V) + \beta_x(V)} \quad (5)$$

$$x_\infty(V) = \frac{\alpha_x(V)}{\alpha_x(V) + \beta_x(V)} \quad (6)$$

Where α and β are exponential-based equations defined in [11].

2.2 Implementation

The connection between electrical devices and living cells requires a real-time system. In addition, studying neurodegenerative troubles requires a tunable appliance. The FPGA (Field Programmable Gate Array) is the best component including flexibility, speed and stability. Here we propose biomimetic neurons designed by FPGA as a central processing unit and DAC (Digital to Analog Converter) as the spike generator. The system is integrating a configurable main unit managing the computation neuron core, the sampling and the communication with the DAC.

The implementation has been set on the “Genesys 2” board which contains a Kintex 7 FPGA “xc7k325tffg900”. The signal has been output using the DA4 Pmod from Digilent which has an AD5628 Digital to Analog Converter (DAC) of 12 bits. The frequency of the system has been assigned at 200MHz. A length of 32bits (16 decimals) has been used as data for the operations. A pipelined architecture is used (see fig. 2) using the Euler method to solve differential equation and Taylor series for exponentials calculations. A Δt sampling time of $50\mu s$ is used for the Euler method.

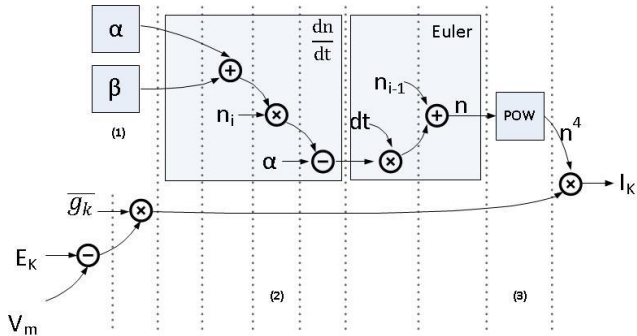


Fig. 2. Pipeline architecture of an ionic current which take 400 cycles (1) Alpha and Beta has to be calculated to continue the operation (2) According to the kintex 7 DSP, input and output of the multiplier need to be pipelined and 9 cycles is used to perform the operation. (3) The power module has a number of cycles depending of operations order.

The result show limited resources taken into the FPGA for the calculation of 25 neurons (table 1).

Table 1. Device resources using xc7k325tffg900 kintex 7 FPGA for 25 HH neurons

	Used	Utilization (%)
LUT	15481	7.6
LUTRAM	72	0.11
FF	13040	3.2
DSP	132	15.71

4 RESULTS

4.1 Comparaison Matlab FPGA

The results show similar dynamics for ionic currents comparing the simulation on Matlab and the output of the DAC (fig. 3).

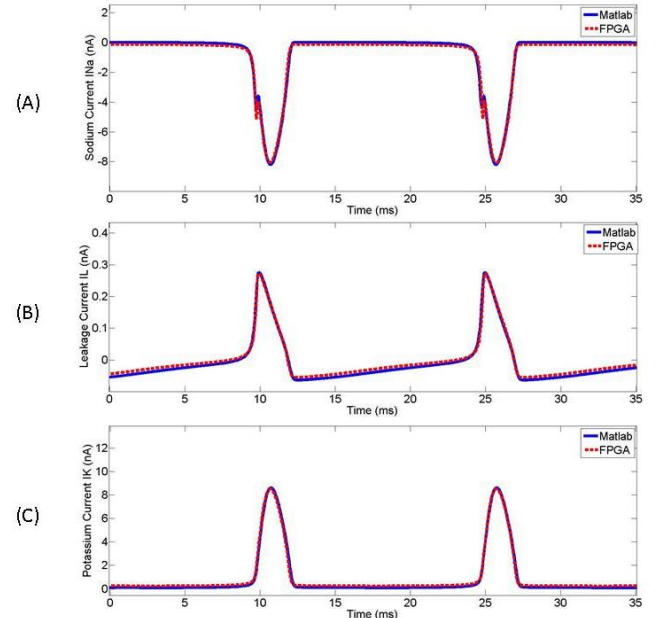


Fig. 3. Comparison of the results from the FPGA and from Matlab (A) Sodium current (B) Potassium current (C) Leakage current

Also, we notice that membrane potential from Matlab and from FPGA are similar in terms of amplitude and frequency (fig 4).

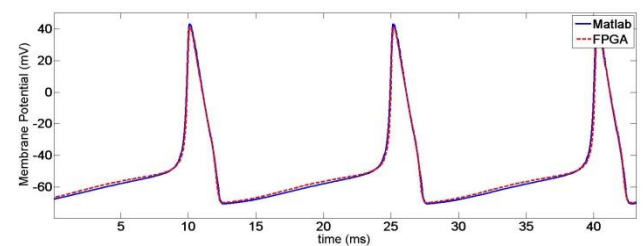


Fig. 4. Comparison of the action potential behavior from the FPGA and from Matlab

These results shows that our implementation in FPGA is valid and that our computation methods (number of bits, Euler method) are valid.

4.3 Neurological disease applications

This HH implementation is used to model neurological disease. From recordings of biological action potential data, our goal is to model the differences between healthy and disease neurons.

Thanks to collaboration with neuroscientists [20], we are working on Tuberous Sclerosis disease. When neuroscientists model Tuberous Sclerosis in ‘in vitro’ neuron culture, they observe bigger neuron soma than the control cells. This behavior can be reproduced by HH model by tuning the parameters [21].

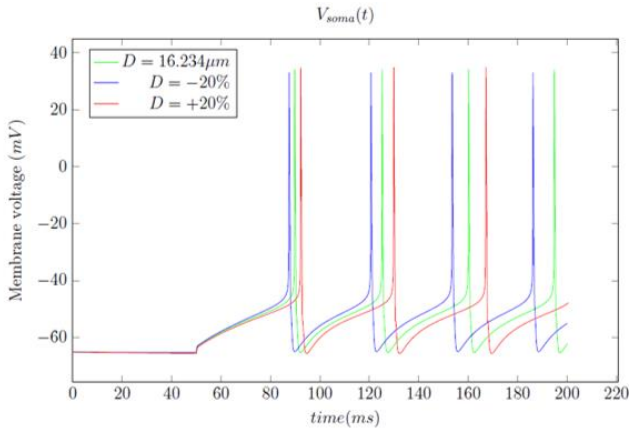


Fig. 5. Action potential behaviors following the diameter of neuron soma.

Fig. 5 describes that following the size of the neuron soma, amplitude and frequency of action potential change. When the soma size increases, amplitude is higher and frequency is lower.

5 CONCLUSION

We presented, in this paper, an implementation of single compartment HH model in FPGA. This system works in real-time and can perform bio-hybrid experiments. We validate our implementation by comparison with software. In the next future, we will implement compartmental HH model, synapses and long-term plasticity to this neural network.

The final goal of the studies is to model neurological disease and implement a ‘disease’ neuron by HH parameters and then study the influence and the behavior of these neurons integrated into a neural network.

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