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The FPGA-Based Realization of the Electromagnetic Effect Defined FitzHugh-Nagumo Neuron Model

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ABSTRACT The electrical transmission, which occurs on the surface of the neuron membranes, is based on the flow of charges such as calcium, potassium and sodium. This potential change means a current flow and if there is a variable current flow, a flux change comes into question. Accordingly, recent studies have suggested that these electrophysiological neuronal activities can induce a time-varying electromagnetic field distribution. The electric field is usually defined as an external stimulation variable of the biological neuron models in literature. However, the electric field is included in the biological neuron models as a new state variable in another perspective and it is described the polarization modulation of media. Here, this study focused on that the electric field is a state variable in the biological neuron model. The numerical simulations of the FitzHugh-Nagumo neuron, which is improved by including the electromagnetic effect, are re-executed in this study. Then, the hardware realization of this system is built on the FPGA device. Therefore, it is shown that it is also possible to perform the hardware realizations of the neuronal systems, which have a new state variable for the electric field definition.

KEYWORDS
Electromagnetic field
Biological neuron model
Hardware realization
Field Programmable Gate Array (FPGA)
FitzHugh-Nagumo

INTRODUCTION

The basic unit of the nervous system is neuron cells and it also constitutes the main unit of the communication system, which is based on electrical transmission, in the living beings. The electrical transmission, which occurs on the surface of the neuron membranes, is based on the flow of charges such as calcium, potassium and sodium. This potential change means a current flow and if there is a variable current flow, a flux change comes into question [Ma and Tang 2015; Lv *et al.* 2016; Lv and Ma 2016; Wu *et al.* 2017; Xu *et al.* 2017; Ma *et al.* 2017; Ge *et al.* 2018]. Accordingly, recent studies have suggested that these electrophysiological neuronal activities can induce a time-varying electromagnetic field distribution.

In [Lv *et al.* 2016], the expression magnetic flux is associated with a memristor element. The membrane potential definition is combined with the memristor definition. Thus, it has been suggested that magnetic flux can be used to explain the effect of electromagnetic induction. Based on the result in [Lv *et al.* 2016], different studies have also been put forward. For example in [Wu *et al.* 2016], the electromagnetic radiation has been considered as an external stimuli of the FitzHugh-Nagumo model and it have been observed the electrical activates of the neuron by relating with the sudden heart disorder under the heavily electromagnetic radiation. An improved cardiac model has been exposed to an external electromagnetic radiation in [Ma *et al.* 2017] and it has been founded that the electromagnetic radiation causes the quiescent state of the membrane potentials.

When the electric field distribution induced by the fluctuations in the action potential becomes apparent, this effect has been included in the definitions of the biological neuron models. For example, in [Bao *et al.* 2018], Hindmarsh–Rose neuron model has been modified by utilizing the memristor device characteristic. It has been thought to observe neuronal dynamics under the electromagnetic induction and these studies have been confirmed by the circuit breadboard based experimental results. In [Bao *et al.* 2019], an electromagnetic induction current has been generated by the threshold memristor. This current has been applied to Hindmarsh-Rose neuron model instead of the external current definition. This neuron model has been presented as a memristive defined system and this system has been implemented with discrete device on hardware breadboards for validating electronic neuron.

A locally active memristive defined neuron model has been proposed by using the FitzHugh-Nagumo neuron model in [Lin *et al.*

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2020]. The firing patterns and multistability of this neuronal system have been investigated and these systems have been realized by emulating the memristor definition with the analog electronic elements. In [Bao *et al.* 2021], a memristive neuron model with the adapting synapse has been imitated by a flux controlled memristor and a memristive mono-neuron model has been implemented by a fitting activation function circuit.

The electric field has been defined as an external stimulation variable of the biological neuron models in the outlined systems in above. However, the electric field has been included in the biological neuron models as a new state variable in [Ma *et al.* 2019] and it has been described the polarization modulation of media that is resulted from the external electric field or the intrinsic change of ions on the membrane surface in mentioned study. Inspiring by [Ma *et al.* 2019], the numerical simulations of the FitzHugh-Nagumo neuron, which is improved by including the electromagnetic effect, are re-executed in this study. Then, the hardware realization of this system has been built on the FPGA device for the first time. Therefore, it is shown that it is also possible to perform the hardware realizations of the neuronal systems, which have a new state variable for the electric field definition, similar to the memristive defined ones.

In this context, firstly after the introducing of the improved the FitzHugh-Nagumo neuron model by including the electromagnetic effect, the repeated numerical simulation results are given in Section 2. The FPGA-based hardware implementation stages of the relevant model and its obtained experimental results are presented in Section 3. The outputs of this study are discussed in the last section.

THE INVESTIGATING OF THE ELECTROMAGNETIC EFFECT DEFINED FITZHUGH-NAGUMO NEURON MODEL

The electrical transmission, which occurs on the surface of the neuron membranes, is based on the flow of charges such as calcium, potassium and sodium. This potential change means a current flow and if there is a variable current flow, a flux change comes into question [Ma and Tang 2015; Lv *et al.* 2016; Lv and Ma 2016; Wu *et al.* 2017; Xu *et al.* 2017; Ma *et al.* 2017; Ge *et al.* 2018]. Accordingly, recent studies have suggested that these electrophysiological neuronal activities can induce a time-varying electromagnetic field distribution. In order to describe this electromagnetic field distribution, the membrane surface has been considered as a charged plate and the charge density τ of its surface has been written as the ratio of the electrical charge 'q' to the surface area 'S' of the plate, namely.

When the dielectric constant is 'ϵ', the induced electromagnetic field has been given as '$E = (q/2S\epsilon)$' or '$E = (q/2\epsilon)$' for a sphere shape neuron with the 'r' radius. The voltage difference between the charged plates can be defined by depending on the electromagnetic field as in '$V = rE \cong E\sqrt{S}$'. In neurons, the lipid layers of the neuron membrane are considered as conductive material and the space between these layers as an insulating material, so a capacitor definition 'C' is usually added to the biological neuron models [Hodgkin and Huxley 1952; Morris and Lecar 1981]. Similarly, the induced electromagnetic field 'E' has been considered as a new state variable in [Ma *et al.* 2019] by taking into consideration the inductance 'L' of the media 'p'. This assumption is formulated in general terms as in Eq.1.

$$
\begin{aligned}
C\frac{dV}{dt} &= f(V,i,p)\\
L\frac{di}{dt} &= g(V,i) + rE\\
\frac{dE}{dt} &= \frac{1}{2S\epsilon}\frac{dq}{dt} = \frac{1}{2S\epsilon}i = ki
\end{aligned}
\tag{1}
$$

In Eq.1, 'f' and 'g' functions are the nonlinear expressions and they represent the membrane potential and the transmembrane current. These features have been adapted to the FitzHugh–Nagumo neuron model and the electromagnetic effect defined FitzHugh-Nagumo neuron model has been improved as in Eq.2 [Ma *et al.* 2019].

$$
\begin{aligned}
\tau\frac{dx}{dt} &= x - \frac{x^3}{3} - y + I_{ext}\\
\frac{dy}{dt} &= ax + by + d + rE\\
\frac{dE}{dt} &= ky
\end{aligned}
\tag{2}
$$

where, while the 'x' state variable describes activation of the membrane potential, the 'y' state variable represents the inactivation of the neuron. The 'a', 'b', 'd' and 'τ' are the model parameters. The external current stimulates are given by the 'I_{ext}' parameter. In biological neuron models that do not include the electromagnetic field effect, the external currents applied to the neurons are generally defined as the DC currents [Izhikevich 2003; Fitzhugh 1965; Hindmarsh and Rose 1984]. However, a flux change, namely a time-depended current, requires for seeing the effect of the electromagnetic field. Thus, the external current in the electromagnetic effect defined FitzHugh-Nagumo neuron model can be formed as a sinusoidal source. In fact, the amplitude and the frequency of this current affect the dynamical behaviors of the neuron model. The effect of the frequency on the dynamical behaviors of the electromagnetic effect defined FitzHugh-Nagumo neuron model have been observed via a bifurcation diagram in Figure 1 by fixing the amplitude to 0.1 in here.

The numerical simulation results re-executed for four different frequency values of the sinusoidal source are given in Figure 2, respectively. In these numerical simulations, the values of 'a', 'b', 'd' and 'τ' parameters have been chosen as follows: $a = 3, b = -3, d = 5, k = 15, r = 0.0001$ and $\tau = 0.1$.

THE FPGA-BASED REALIZATION PROCESS

Some specialties are desired in the electronic equipment that is used in the hardware realization studies of the bio-inspired systems. Some of these most preferred ones are low power and low device consumption, allowing different designs to be tested without the need for additional processes, and rapid prototyping. While there are studies in which biological neuron models are supported by the discrete device based hardware for providing advantages in terms of material supply and practical implementation in the literature [Sánchez-Sinencio and Linares-Barranco 1989; Linares-Barranco *et al.* 1991], the studies using programmable and reconfigurable analog/digital devices have also attracted attention in recent years [Korkmaz *et al.* 2016; Korkmaz and Kilic 2014; Karataş *et al.* 2022]. The programmable and re-configurable analog/digital devices combine many features mentioned above.

In this study, the Field Programmable Gate Array (FPGA) device is used for the hardware implementation of the electromagnetic effect defined FitzHugh-Nagumo neuron model. In addition

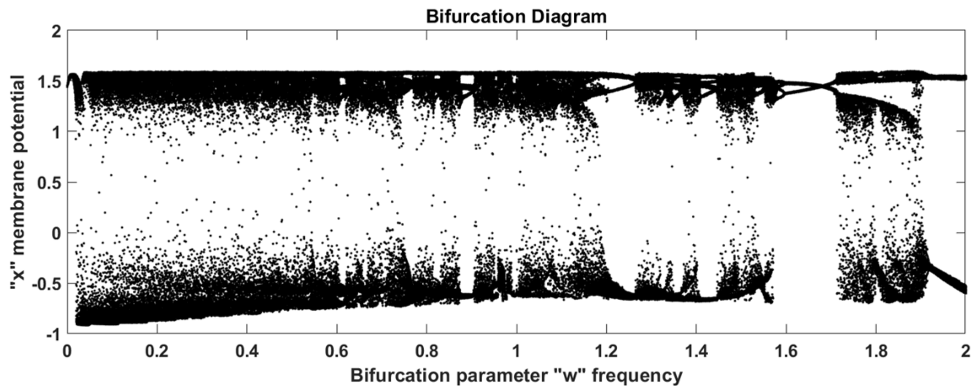

Figure 1 Bifurcation diagram of the membrane potential that is plotted by applying different frequencies in external stimulus within 200 time sample.

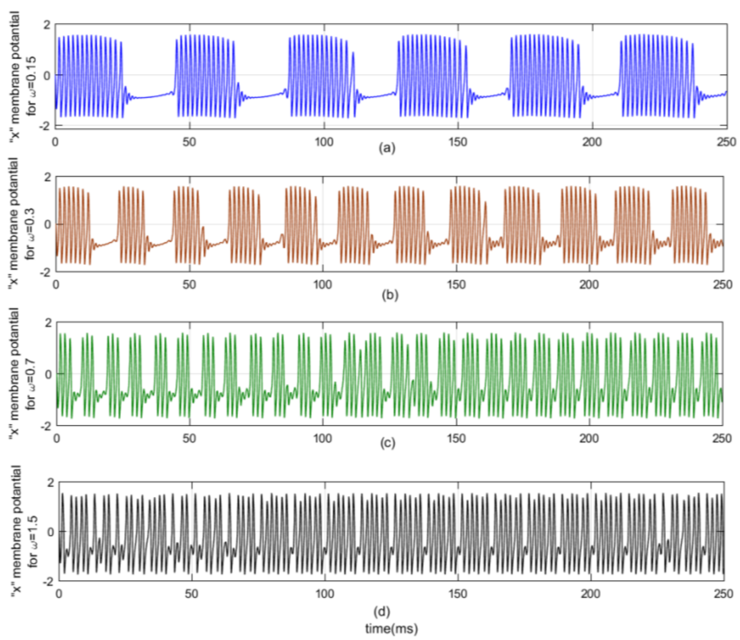

Figure 2 Numerical simulation results of the electromagnetic effect defined FitzHugh-Nagumo neuron model for different frequencies [a) 0.15, b) 0.3, c) 0.7 and d) 1.5] of the external stimulus.

to features mentioned above, the FPGA device is a digital electronic equipment operating with a parallel working procedure and having the programmability and reconfigurability features. The FPGA is preferred for the prototype realization of many models. Since the FPGA device is digital electronic equipment; the electromagnetic effect defined FitzHugh-Nagumo neuron model, which is defined by the ordinary differential equations, must be converted to a discrete-time expression for the FPGA-based implementation. Here, the Euler discretization method is used for this conversion process and the step size is set as $\Delta h = 0.01$. After applying the discretization method to the model in Eq.2, the obtained final definition is given in Eq.3.

$$
\begin{aligned}
x_{i+1} &= [\frac{x_i - \frac{x_i^3}{3} - y + I_{ext}}{\tau}] * \Delta h + x_i \\
y_{i+1} &= [ax_i + by_i + d + rE_i] * \Delta h + y_i \\
E_{i+1} &= [ky_i] * \Delta h + x_i
\end{aligned}
\tag{3}
$$

The "System Generator for $DSP - XILINX^{TM}$" program tool is used for the FPGA-based implementation of the electromagnetic effect defined FitzHugh-Nagumo neuron model in Eq.3. This program provides an automatic conversion between the $MATLAB - SIMULINK^{TM}$ and the $XILINX^{TM}$ codes. After the conversion process, the system built on $MATLAB - SIMULINK^{TM}$ can be embedded into the FPGA device produced by $XILINX^{TM}$, directly [Xilinx July, 2022]. Figure 3 shows a diagram that is designed with the System Generator for DSP tool for the electromagnetic effect defined FitzHugh-Nagumo neuron model.

A multiplexer is added to this design for the selection of the frequency values as $\omega(rad/s) = [0.15, 0.3, 0.7, 1.5]$. Thus, instead of adjusting the frequency to four different values separately, the all frequency values are embedded to the FPGA in the same design. Thus, the implementation results could be easily observed by changing the switch positions on the FPGA development board.

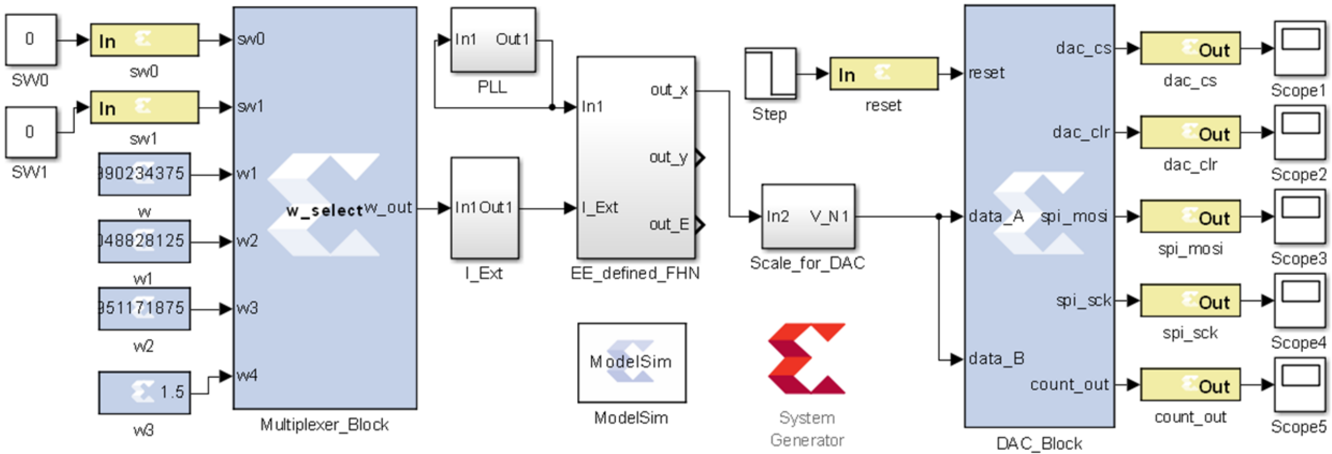

Figure 3 System Generator for DSP tool based design schema for the electromagnetic effect defined FitzHugh-Nagumo neuron model.

The electromagnetic effect defined FitzHugh-Nagumo neuron model has been built by using the predefined blocks in the System Generator for $DSP - XILINX^{TM}$ tool and it has been given by a subsystem illustrations named by "EE_defined_FHN" in Figure 3. The fixed-point arithmetic $Q = (32, 18)$ has been used in the design. After the automatic conversion process, the VHDL codes have embedded to the SPARTAN-3AN development board of $XILINX^{TM}$ company. A digital-to-analog converter (LTC2624) is available on this development board. The measurement results performed for the $\omega(rad/s) = [0.15, 0.3, 0.7, 1.5]$ frequency values have recorded by using the mentioned digital-analog converter. The FPGA-based realization results of the electromagnetic effect defined FitzHugh-Nagumo neuron model are given in Figure 4 for these frequencies. Therefore, it has been proved that it is also possible to perform the hardware realizations of the neuronal systems, which have a new state variable for the electric field definition.

This realization results are very similar to the obtained results for the numerical simulation in Figure 2. According to this similarity, the FPGA-based hardware implementation of the electromagnetic effect defined FitzHugh-Nagumo neuron model has been completed successfully. Some synthesis results of the FPGA-based realized model are presented in Table 1.

Table 1 Area usages and synthesis results in the FPGA-based implementation of the electromagnetic effect defined FitzHugh-Nagumo neuron model.

Area Usages Name	Area Usages Rate%
The used amount from 11776 REGISTER	184 (1%)
The used amount from 11776 4-INPUT LUT	1825 (15%)
The used amount from 5888 SLICE	975 (16%)
The used amount from 24 BUFGMUX	2 (8%)
The used amount from 20 MULT18X18SIO	19 (95%)
Maximum Delay (ns)	1083

CONCLUSION

In this study, the FPGA-based hardware realization of the electromagnetic effect defined FitzHugh-Nagumo neuron model has been handled. This biological neuron model stands out in terms of explaining the effect of the electric field on the neuron with a new state variable. In this context, after the investigating of the electromagnetic effect defined FitzHugh-Nagumo neuron model briefly, a bifurcation diagram has been plotted to observe the effect of the external time-depended sources on the dynamical behaviors of this neuron model. Numerical simulation studies have been carried out to observe neuron dynamics for different angular frequency values. Then, in order to demonstrate the adaptability of this biological definition to an electronically platform, the electromagnetic effect defined FitzHugh-Nagumo neuron model has been implemented with the FPGA device.

In the model definition, a time-depended current requires for seeing the effect of the electromagnetic field and a sinusoidal signal has been included in the model definition. In this study, this sinusoidal external signal in continuous time has been constructed on the FPGA device without requiring the usage of a LUT block or an external ADC. The System Generator for DSP tool has been used in this implementation process. The recorded experimental results show that an electromagnetic effect defined FitzHugh-Nagumo neuron model can be implemented with FPGA device, successfully.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Availability of data and material

Not applicable.

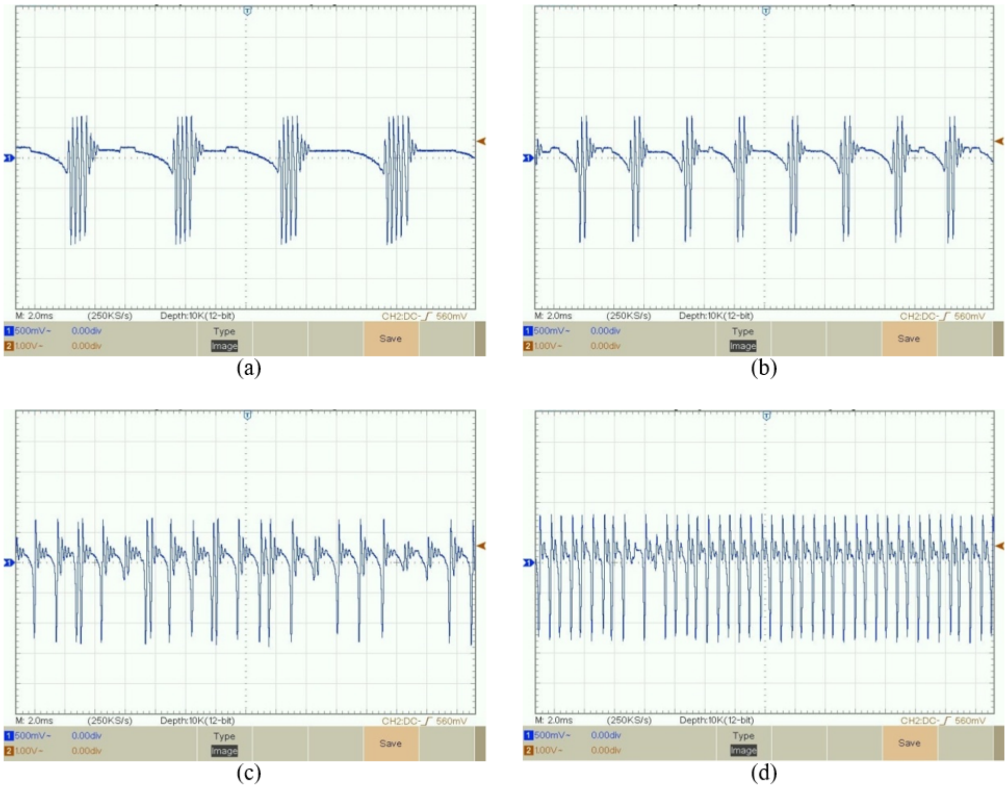

Figure 4 FPGA-based experimental realization results of the electromagnetic effect defined FitzHugh-Nagumo neuron model for different frequencies [a) 0.15, b) 0.3, c) 0.7 and d) 1.5] of the external stimulus.

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