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A digital neurmorphic circuit for a simplified model of astrocyte dynamics

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HIGHLIGHTS

- A digital neuromorphic circuit to implement the astrocyte dynamics in hardware was proposed.
- The digital astrocyte can produce similar responses to the biophysical model.
- The digital astrocyte has several applications in reconfigurable neuromorphic devices.

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ABSTRACT

Recent neurophysiologic findings have shown that astrocytes (the most abundant type of glial cells) are active partners in neural information processing and regulate the synaptic transmission dynamically. Motivated by these findings, in the present research, a digital neuromorphic circuit to implement the astrocyte dynamics is developed. To model the dynamics of the intracellular Ca^{2+} waves produced by astrocytes, we utilize a simplified model which considers the main physiological pathways of neuron–astrocyte interactions. Next, a digital circuit for the astrocyte dynamic is proposed which is simulated using ModelSim and finally, it is implemented in hardware on the ZedBoard. The results of hardware synthesis, FPGA implementations are in agreement with MATLAB and ModelSim simulations and confirm that the proposed digital astrocyte is suitable for applications in reconfigurable neuromorphic devices which implement biologically brain circuits.

1. Introduction

Astrocytes, the predominant type of glial cell in the central nervous system (CNS), have long been believed to provide only structural and metabolic supports [12,18]. However, recent researches have demonstrated that astrocytes intervene actively in information processing and control of synaptic transmission [2,4,13]. Bidirectional communications between astrocytes and neuronal cells are necessary for the normal functioning of the nervous system during signal processing [9]. Although astrocytes cannot generate action potentials, they respond to neuronal activities with an elevation of their intracellular calcium levels. In this way, not only astrocytes can *sense* neuronal transmission but also their calcium elevation leads to the *release* of gliotransmitters including glutamate or ATP and other neuroactive substances that are capable, by a feedback mechanism, of modulating synaptic strengths between nearby neurons which can modulate and control the synaptic strength of neighboring neurons [15,17]. In this way, the astrocyte "listens and responds" to the synapse and regulates normal operation of synapses via astrocytic mechanisms [5].

On the other hand, recent advances in neuromorphic engineering have focused mainly on neural mechanisms such as neural spiking and spike timing dependent plasticity (STDP) [10,20]. An increasing interest in neuron–astrocyte signaling has paralleled our development of neuromorphic circuits incorporating astrocytes [11]. Hence, it is essential to develop digital and analog circuits which consider neuron–astrocyte interactions. This will help us to go in the direction of developing and emulating simple brain like computing systems. Therefore, in the present research, we have implemented a functional approach to develop a digital neuromorphic circuit and to explore the feasibility of using FPGAs (field-programmable gate arrays) for implementing neuron–astrocyte interactions. Although neuromorphic VLSI (very

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Table 1
The parameter values of the closed loop system taken from [16].

Parameter	Value	Parameter	Value	Parameter	Value
k_1	1	k_2	2	k_3	2
k_4	1	k_5	0.05	k_6	1.5

large scale integrated circuit) implementation is an important tool for investigating and implementing neural algorithms, its developing is more time consuming and cannot be reconfigured easily [24]. However, FPGA hardware is an ideal technology to have a rapid prototyping platform for neural models with similar flexibility to general purpose microprocessors [22]. Its stability, reliability, and flexibility are interesting features to use FPGAs for designing neuromorphic systems [14]. Nevertheless, a characterization of how astrocyte actively shapes the dynamics of neuronal function, from the hardware point of view, remains largely unstudied. This standpoint helps to enhance the information processing capabilities of the neuromorphic circuits. Therefore, in the current research, and as a first step, a digital circuit of astrocyte dynamical model is presented. Indeed, our specific goal in this paper is to create a digital neuromorphic circuit that demonstrates some first-order intercellular behaviors, illustrating the astrocyte dynamics. In this way, we use the astrocyte mathematical model proposed by Montaseri et al. [16] which in turn is a simplified version of the biophysical model of the astrocyte calcium dynamics developed by [21]. Next, a digital circuit is proposed and then simulated in ModelSim and finally it is synthesized and implemented in hardware using ZedBaord development board. The results of the FPGA implementation are in agreement with those of ModelSim and MATLAB simulations and verify that a digital astrocyte could be used in reconfigurable neuromorphic applications.

2. Biological background and astrocyte model

The most abundant type of glial cells are star-shaped astrocytes. They control the content of extracellular fluid and electrolyte homeostasis, regulate neurotransmitter release and control synapse formation [8]. Astrocytes are also involved in the detection of the synaptic release of neurotransmitters and respond to neuronal activities with an elevation in their intracellular calcium levels [8,17]. Calcium elevation leads to the release of various gliotransmitters including adenosine triphosphate (ATP) or glutamate [6,7]. Glutamate, by activating *N*-methyl-D-aspartate (NMDA) is able to produce postsynaptic slow inward currents (SICs) in nearby neuronal receptors [19]. These findings, all together, indicate that astrocytes provide reciprocal signaling to neighboring neurons and that the concept of the "tripartite synapse" recapitulates this feature [23].

To model the dynamics of the intracellular Ca^{2+} waves produced by astrocytes, several models have been proposed. In this research, a recently simplified dynamic model of the astrocyte is used [16]. This simplified model is based on the biophysical astrocyte model proposed by [21]. The Postnov's model is a generalized functional model for a small neuron–astrocyte ensemble. It considers the main pathways of neuron–astrocyte interactions. Montaseri et al. [16] show that despite some simplifications, the main and essential properties of the biophysical astrocyte model are preserved in the structure of their simplified' model. The model is explained with the following set of differential equations:

$$\dot{q} = (1 + \tanh[k_1(Z - k_2)])(1 - q) - k_3 q \tag{1}$$

$$\dot{p} = -k_4 p + k_5 + k_6 q \tag{2}$$

where q is the astrocyte internal state, k_i, $i = 1,2,\ldots 6$ are constants listed in Table 1 and are taken from [16]. These values are based on the Postnov' s astrocyte functional model (2009). Z and p are the input and output of the model, respectively. The interaction between astrocyte and neuron is denoted with the parameter Z (astrocyte input) that shows the synaptic activity of the neuron. The neural activity triggers the production of the second messenger, inositol (1,4,5)-trisphosphate (IP_3), modeled by the internal variable q which finally leads to the increase of intracellular Ca^{2+} concentration. As a result of augmentation of calcium concentration in the cytoplasm, the astrocyte mediator p is released and thereby can regulate nearby neurons.

Table 2
The parameter values of the individual lines for the 7-line segment approximation.

Region of Z	a	b
$Z > 4.632$	0	1
$Z > 3.694$ and $Z \leq 4.632$	0.0587	1.0341
$Z > 3.015$ and $Z \leq 3.694$	0.2457	1.0172
$Z > 0.985$ and $Z \leq 3.015$	0.7565	−1.5356
$Z > 0.306$ and $Z \leq 0.985$	0.2457	−1.3509
$Z > -0.632$ and $Z \leq 0.306$	0.0587	−1.1442
$Z < -0.632$	0	−1

3. Hardware implementation

In this section, a novel digital circuit for the simplified astrocyte model is presented. One of the main challenges in digital implementation of the astrocyte dynamic model is the presence of the nonlinear *q-nullcline* in the form of tanh(.) function. In this paper, we use the linear approximation method and try to approximate the *q-nullcline* with several line segments which decreases the implementation cost significantly (compared to the original tanh function). The *p-* and *q-nullclines* of the dynamical system of the stimulator is obtained by calculating:

$$\dot{q} = 0 \rightarrow (1 + \tanh[k_1(Z - k_2)])(1 - q) - k_3 q = 0 \tag{3}$$

$$\dot{p} = 0 \rightarrow -k_4 p + k_5 + k_6 q = 0 \tag{4}$$

Since the *p-nullcline* is linear, it can be easily discretized and implemented. However, the *q-nullcline* should be approximated with several line segments so that it preserves the dynamical characteristics of the original system. Fig. 1(a) shows the line approximation of the *q-nullcline*. An exhaustive search algorithm is utilized to find the best parameter values of the line segments which results in a minimum

Considering, circuit complexity (required number of adders, multipliers, comparators) and the required computational accuracy, the 7-line segments approximation of the *q-nullcline* has been used in this research. The approximated *q-nullcline* is as follows:

$$(1 + az + b)(1 - q) - k_3 q = 0 \tag{5}$$

where a and b are parameters of linear approximation as listed in Table 2. Thus, the discrete equation for the astrocyte dynamic model is described by:(6)$q[n+1] = ((1 + (aZ[n] + b)(1 - q[n]) - k_3 q[n])h + q[n]$

$$p[n+1] = (-k_4 p[n] + k_5 + k_6 q[n])h + p[h] \tag{7}$$

where h is step size and is set to 0.01. The scheduling diagram for digital astrocyte is demonstrated in Fig. 1(b) and (c). This figure also shows binding of the multipliers and adders that disclose each operation done with which block and in what time. Fig. 2(b) illustrates the scheduling diagram for q dynamics. In the initial stage, the input is applied to the approximation unit and then based on the input region and Table 2, the appropriate a and b are selected. They will be updated after the each iteration by the new state. Temporary register is a computational register to prevent missing data when

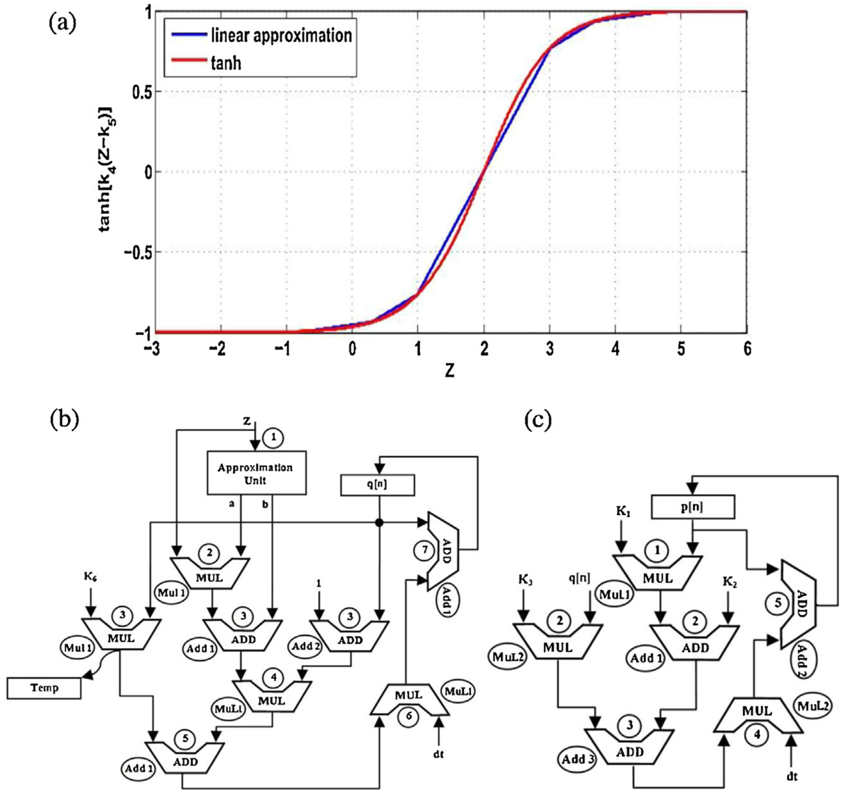

Fig. 1. (a) 7-line segments approximation for the tan h(.) function of the *q-nullcline*. The scheduling diagram of the astrocyte dynamics; (b) the *q*-dynamic; (c) the *p*-dynamic.

going from one step to the next and is used to store the obtained data. With efficient use of the 20-bit registers (4 bits for integer part and 16 bit for fractional part) in our design, the digital astrocyte circuit was simulated and synthesized using Verilog HDL and Xilinx ISE tools resulting 1% utilization and a maximum clock frequency of 139 MHz.

4. Results of simulations and hardware implementation

In this section, the results of simulations and hardware implementation of the astrocyte dynamic model are presented. We discuss how the digital astrocyte maintains the essential properties of the astrocyte dynamic model and responds to different inputs having various amplitudes and frequencies. To do that, the astrocyte input (Z) are set to $Z = A\sin(\omega t)$ and the values of the other parameters are listed in Table 1. We used the sinusoidal signal as the input of the digital astrocyte to mimic the amount of the neurotransmitter released by the neuron. In Fig. 2(a), the first panel shows the input sinusoidal input with $A = 1$ and $\omega = 0.2$ rad/s. The second panel depicts the p and q dynamics of the astrocyte model simulated in MATLAB. The third panel demonstrates the results of the ModelSim simulations of the proposed digital circuit. The behavior of the astrocyte circuit was verified by Verilog simulation. A sinusoidal signal is applied to the circuit and the p and q potentials (V_p and V_q) are monitored and compared to the expected dynamics of Eqs. (1) and (2). Comparing, the middle and bottom panels, it is apparent that the designed digital circuit for the astrocyte model performs quite well. The root mean square error (RMSE) between MATLAB simulation of the model and designed digital circuit is listed in Table 3.

We proceed and plot the phase plane for both biophysical model and digital circuit. Fig. 2(b) shows the phase portrait of astrocyte dynamics in $(p - q)$ space (first panel) and the proposed digital circuit in $(V_p - V_q)$ space (second panel). As it is observed, the phase portraits ultimately converge to the approximately the same *limit cycle*. So, it is expected that the digital circuit behaves similar to the biophysical astrocyte model. We will continue by further simulations to reveal the efficiency of the proposed digital astrocyte in mimicking the behavior of the biophysical astrocyte. In this way, to evaluate the performance of the digital circuit in hardware, it has been implemented on the ZedBoard development kit. The primary objective is to examine the feasibility of FPGA implementation of the model and to show that hardware can reproduce the model responses. The system is developed under the Xilinx ISE 14 Foundation Design Software Environment using Verilog HDL. Fig. 2(c)–(e) displays oscilloscope photographs of the digital implementation of the astrocyte dynamics. Fig. 3(c) is the sinusoidal input signal applied to the digital circuit. Fig. 2(d) shows the V_p and V_q output of the FPGA board shown in yellow and blue colors, respectively and finally Fig. 2(e) depicts the obtained phase plane in hardware. It should be mentioned that we use 4-bit digital to analog converter build in the ZedBoard. Comparing different parts of Fig. 2, it is obvious that the hardware behavior matched the simulated model. Also, considering the important criteria from the hardware point of view such as scaling up the designed circuit, reducing the digital implementation cost and keeping low power operation while obtaining results similar to the biophysical model of astrocyte, 7-line approximation method produces acceptable

Table 3
The RMSE between software simulation and hardware implementation.

RMSE	Between p and V_p	Between q and V_q
Fig. 2	0.0186	0.0167
Fig. 3	0.0645	0.0458

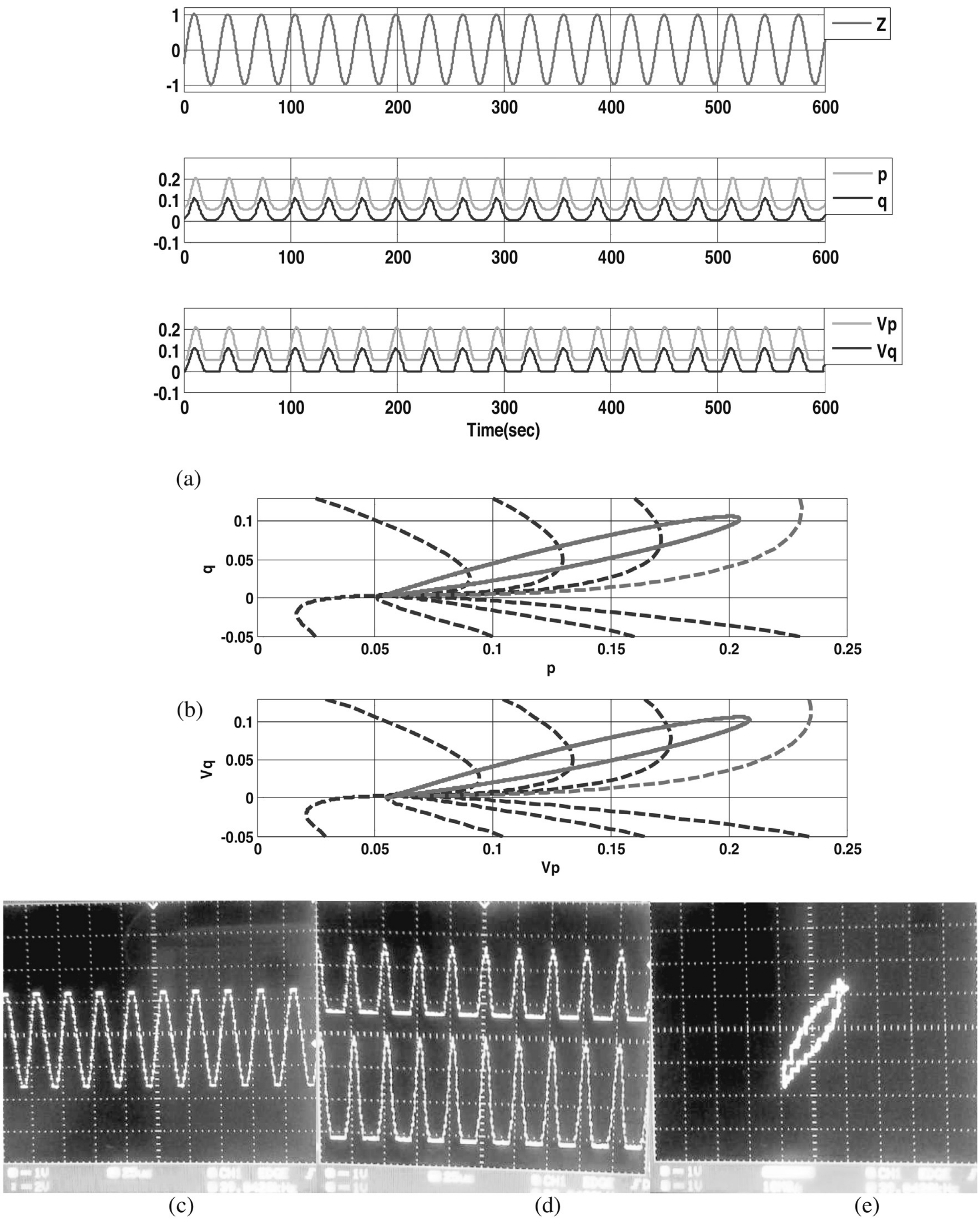

Fig. 2. (a) First panel is the input signal $\omega = 0.2$ rad/s and $A = 1$. Second panel shows the results of the MATLAB simulations for p and q state variables and the third panel displays the results of the ModelSim simulations for V_p and V_q. (b) The phase plane of the astrocyte dynamics in $p - q$ space (first panel) and the digital astrocyte states in $V_p - V_q$ space (second panel). The first and the second panels correspond to the second and third panels of (a), respectively. The dashed curves are the system trajectories and the limit cycle is the solid red circle. (c)–(e) The results of hardware implementation of the designed digital circuit for the astrocyte on the ZedBoard development kit. (c) The input signal (Z). (d) The V_p and V_q output are shown in yellow and blue, respectively. (e) The obtained phase plane by using 4 bit D/A converter. The time and volt divisions of the oscilloscope are set on 25 μs and 1 V, respectively.

In the last set of simulations, we change both amplitude and frequency of the input signal to functionally model the variation in the amount of and the rate of the released neurotransmitter, receptively. The results are shown in Fig. 3. In this figure, for the time intervals 0–200s and 400–600s, the amplitude and the frequency of the input signal is set to $A = 1$, $\omega = 0.2$ rad/s and for the time interval 200–400, they are set on $A = 1.7$, $\omega = 0.4$ rad/s. The RMSE value between the MATLAB and the designed digital circuit is listed in Table 3. For these simulations, the phase plane is also depicted in Fig. 3(b) which illustrates a double limit cycle. Fig. 3(c) displays oscilloscope photographs of the digital implementation of the astrocyte dynamics. Considering Figs. 2 and 3, it is observed that the proposed digital astrocyte has a good performance and accuracy with different input amplitudes and frequencies.

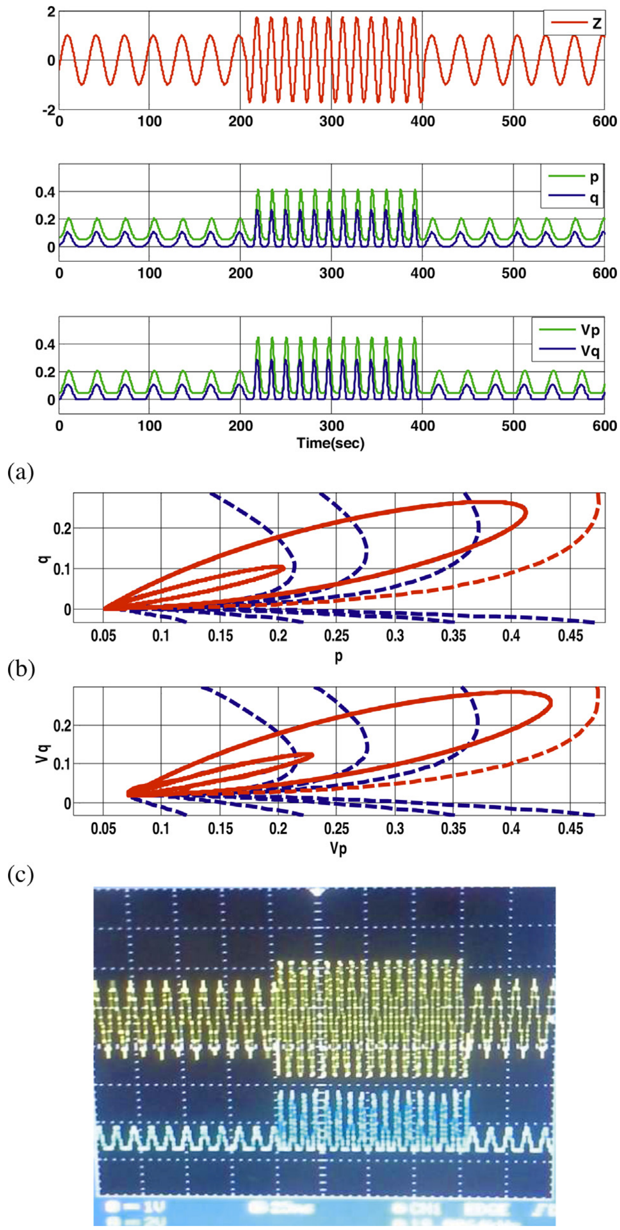

Fig. 3. (a) First panel is the input signal with different amplitudes and frequencies. In this simulation, both the amplitude and frequency of the input signal is increased in the interval 200–400s to 1.7 and 0.4 rad/s, respectively and then it decreased to its original value that is 1 and 0.2 rad/s. The second panel shows the results of the MATLAB simulations for p and q state variables and the third panel displays the results of the ModelSim simulations for V_p and V_q. (b) The phase plane of the astrocyte dynamics in $p-q$ space (first panel) and the digital astrocyte states in V_p-V_q space (second panel). The first and the second panels correspond to the second and third panels of (a), respectively. Due to amplitude and frequency modulation, another limit cycle is emerged in the original astrocyte model which also is appeared in the proposed digital circuit. The dashed curves are the system trajectories and the limit cycle is the solid red circle. (c) The results of hardware implementation of the designed digital circuit for the astrocyte on the ZedBoard development kit. The input signal and V_p output are shown in yellow and blue, respectively. The volt division of the oscilloscope for input signal is set on 1 V and for V_p is set on 2 V. The time division for both channels are set on 25 µs.

5. Conclusion

Over the past two decades, the knowledge about the diverse role of astrocytes in many facets of synaptic transmission has considerably expanded [1,3]. In this way, astrocytes not only thought to be important for metabolic maintenance, but also they are active players in neuronal activity and information processing. In addition, understanding the computational principles used by the brain and how they are physically embodied is crucial for developing novel computing paradigms [20].

The current research presented a new digital circuit mimicking the astrocyte functionality by mapping their state space representations in hardware. We demonstrated that the proposed digital circuit is functionally produces responses that are compatible with those of the astrocyte biophysical model. Moreover, the compartmentalized construction of our neuromorphic circuit and the ability to control astrocyte parameters make it possible to insert additional mechanisms without extensive circuit redesign.

Although the role of glial cells in neural functioning is not completely understood, the proposed circuit provides an experimental tool for researchers to investigate possible influences of astrocyte on neural computation, when they are integrated on the same hardware. Future works aims to extend this model and connect it to the neuron circuit model to form the tripartite synapse. This presents new opportunities for further investigation of the neuron–astrocyte network and provides insights for the relevant applications.

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