Minimal Bursting Neuron for Hardware Implementation

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Abstract

In this paper a circuit model of a bursting neuron is presented, composed of a minimum number of circuit elements. The circuit is related to theoretical models of biological neurons and exhibits similar qualitative properties as observed in some real neuron cells. Results from an experimental prototype are presented.

1. Introduction

In this paper a bio-inspired circuit model of a bursting neuron is presented. Although its very simple appearance, it has a straight relationship with known phenomenological models found in the literature. Biological neuron models are usually based on the Hodgkin-Huxley circuit model of the axon membrane, which is described as a capacitance in parallel with conductances given by the permeabilities of the ionic channels [1]. The primary Hodgkin-Huxley model explains the tonic spiking in the squid giant axon. In animal's brain and nervous system a diversity of signal waveforms is observed. Some examples are shown in Figure 1. See also [2]. To describe such behavior improved Hodgkin-Huxley models have been proposed – see, e.g., [3], [4] and [5]. In the modified models calcium channels and potassium channels sensitive to calcium ions or ATP are added. These modifications aim at describing complex phenomena such as bursting and chaotic electrical activity observed in some pacemaker neurons and in insulin-producing pancreatic β-cells, for example. The study of these models is as a rule made qualitatively or by means of obtaining numerical solutions, with the difficulties put by the nonlinearities of the Hodgkin-Huxley-type equations. An alternative to the mathematically complex Hodgkin-Huxley model is its simplification given by the so-called FitzHugh-Nagumo neuron model, which refers to the space-clamped transmission line circuit proposed by Nagumo et al. [6]. The Nagumo circuit is easily built with a tunnel diode and linear circuit elements and is described by the FitzHugh equations, also called Bonhoeffer-van der Pol, or BVP, equations [7]. The FitzHugh-Nagumo model has been widely studied and is very useful in the modeling of excitable membranes.

Considered adequate for the emulation of small biological systems, an integrated circuit version of the FitzHugh-Nagumo neuron was recently fabricated [8]. The neuron model in the present work can be considered as an improvement of the original Nagumo circuit, aiming at reproducing the complex behavior observed in systems such as those described in [3]-[5]. The circuit was studied experimentally using electronic implementation with discrete circuit elements.
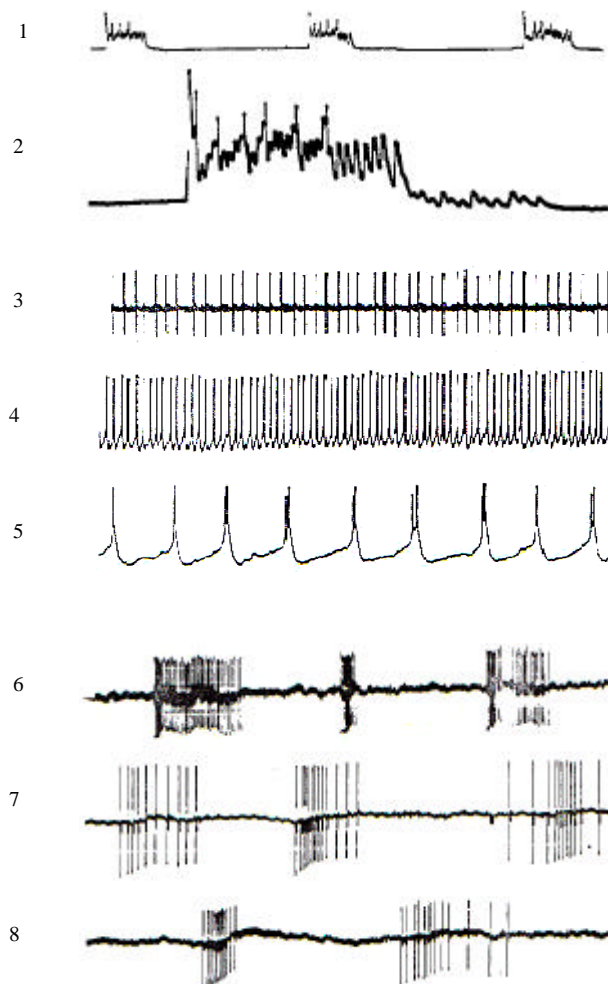

Figure 1: Voltage recordings from: lobster cardiac ganglion (1, 2) [9]; rat medial septal neurons (3-5) [10]; cat thalamocortical neuron (6-8) [11].

2. The circuit

2.1. Endogenous oscillator

The basic minimal circuit, as proposed here, is shown in Figure 2. The output is V(t). Several combinations of R_N, C, L_1 and L_2 values are allowed. Usually $R_N < 0$ and $L_2 > L_1$. Practical choices and experimental results will be shown in Section 3. The circuit in Figure 2 stands for an endogenous neuron, that is, an autonomous system such as a pacemaker signal generator, for example. Once C, L_1 and L_2 are fixed, R_N can be used as a bifurcation parameter. On varying R_N virtually all types of neurons outputs are obtained: silent states, tonic oscillations, bursting etc. The conceptual link between the circuit and biological models is indicated in Figure 2. C plays the role of membrane capacitance. The R_N-D_2 parallel combination models the sodium branch, which represents the collective effect of sodium channels: this is an extreme simplification of the Hodgkin-Huxley model for the sodium pathway in a real membrane [1], nevertheless preserving its qualitative features related to impulses generation. The inductor L_1 in series with D_1 constitutes a new circuit representation of the potassium branch, as compared with the FitzHugh-Nagumo model. It was found experimentally that the diode D_1 is necessary for bursting to occur. The inductor L_2 alone stands for the calcium-controlled potassium channels, which are present in theoretical models of bursting neurons.
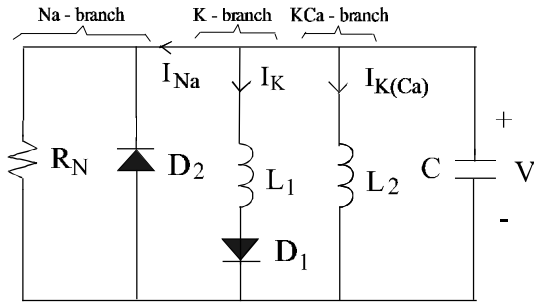

Figure 2: Circuit diagram of the neuron model.

2.2. Adding input ports

In a simplified approach the circuit in Figure 2 represents the entire neuron, and its coupling with other neurons can be made via resistors or RC circuits. It can also be used to model *parts* of a biological neuron, viewed as a complex processing system composed of passive and active dendrites, the soma and the axon. Input signals to a real neuron are inserted via electrotonic dendritic coupling or synaptic connections with other neurons. The excitatory synapses are placed mostly in the dendrites while the inhibitory ones are mostly in the soma [12]. The rapid spiking or bursting signals arriving at a neuron are usually submitted to local and spatial integration, then compounding a resultant electrical fluctuation of lower frequency spectrum. In this paper such low frequency signals are considered as the input signals and, accordingly, only DC test input signals are used in the experiments. In this way, the circuit in Figure 2 can be taken as representing the neuron soma or, more properly, the soma region near the axon hillock.
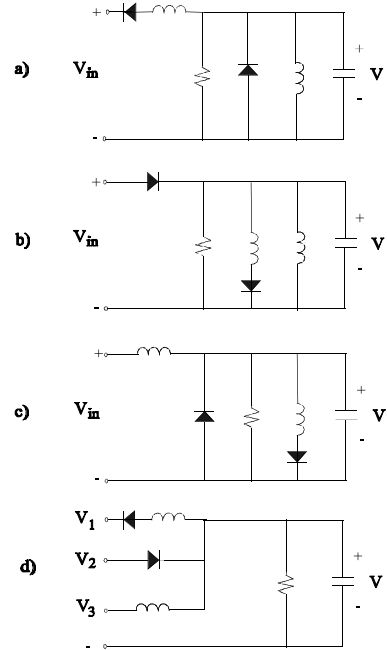

Figure 3: Proposed input-output topologies: a) K-branch input; b) Na-branch input; c) KCa-branch input; d) all-branches input.

A commonly used representation of input signals is in the form of *current* sources drawing charge to the membrane capacitance. In this work a new input strategy is proposed, where the arriving signals are *voltage* fluctuations applied to the "ionic channels" branches. Fig. 3 a-c show how input signals can be applied to the neuron circuit model. These diagrams will be referred to in the next section, where some experimental results are presented. The effect of signals applied to all the three ports will be described with reference to Fig. 3-d. It is worthwhile to note that, in the same way as the circuit's parameters model the intrinsic properties of the neuron, a constant voltage applied to any one of the input ports can also be taken as playing the role of an internal modulating parameter of the neuron.

3. Experimental results

The circuits in Figs. 2 and 3 a-d of the preceding section were implemented for benchtesting under a variety of parameter settings. Several patterns were

observed, such as quiescent states, sub-threshold oscillations, regular and chaotic sequences of spikes and regular and chaotic bursting waveforms of several appearances. The results presented here are from experiments performed on circuits with the following C values: 4.7nF, 33nF, 47nF and 100nF. The negative resistance R_N (ranging from -100Ω to -5000Ω) was obtained using an operational amplifier arrangement; the inductances L_1 (330μ, 500μH and 1000μH) and L_2 (22mH, 100mH and 1H) were obtained with ferrite coils and gyrators, respectively,

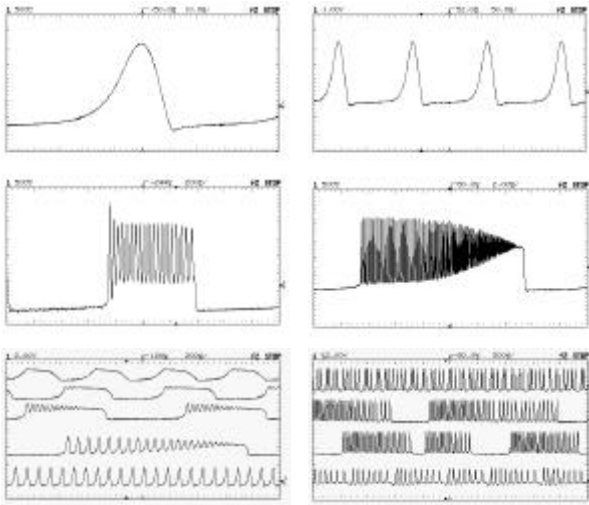## 3.1. No input (autonomous) circuit

Figure 4: Examples of experimental output waveforms from the autonomous circuit of Figure 2. With L_1, L_2 and C fixed, the waveforms changed as R_N was varied.
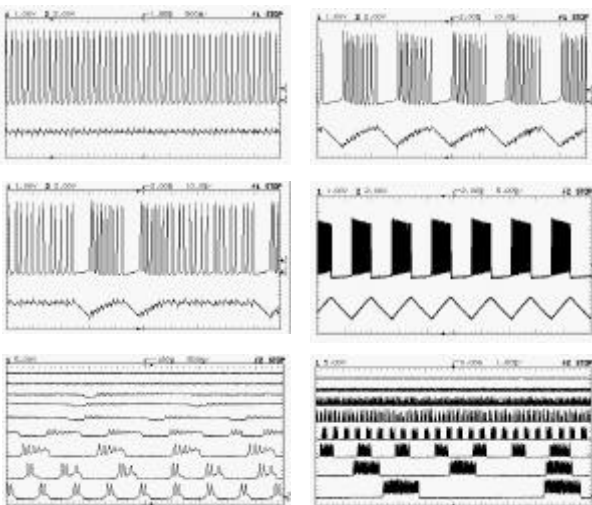
3.2 K-branch input

Figure 5: Experimental V(t) and $I_{K(Ca)}(t)$ waveforms using the circuit of Figure 3-a, observed as the DC input V_{in} was varied.
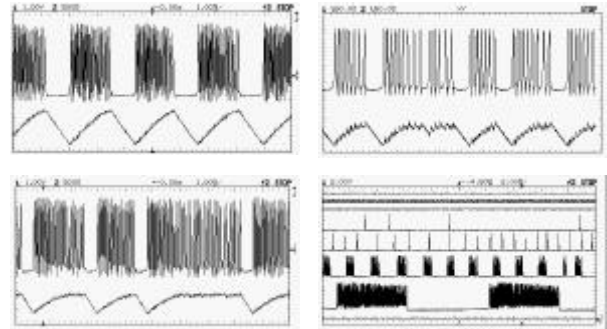
3.3 Na-branch input

Figure 6: Experimental V(t) and $I_{K(Ca)}(t)$ waveforms using the circuit of Figure 3-b, observed as the DC input V_{in} was varied.
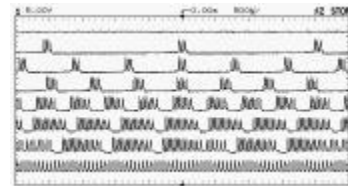
3.4 KCa-branch input

Figure 7: Waveform V(t) using the circuit model of Figure 3-c, observed as the DC input V_{in} was varied.
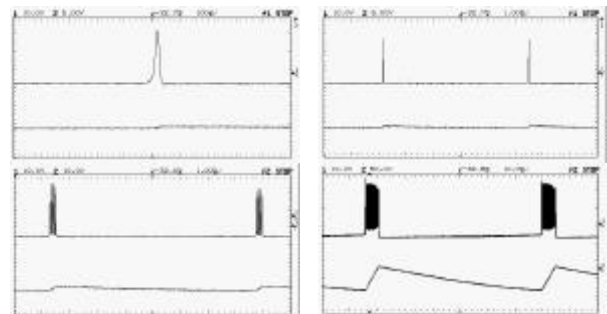

Figure 8: V(t) experimental waveforms from the KCa-branch circuit of Figure 3-c, obtained as V_{in} was varied.
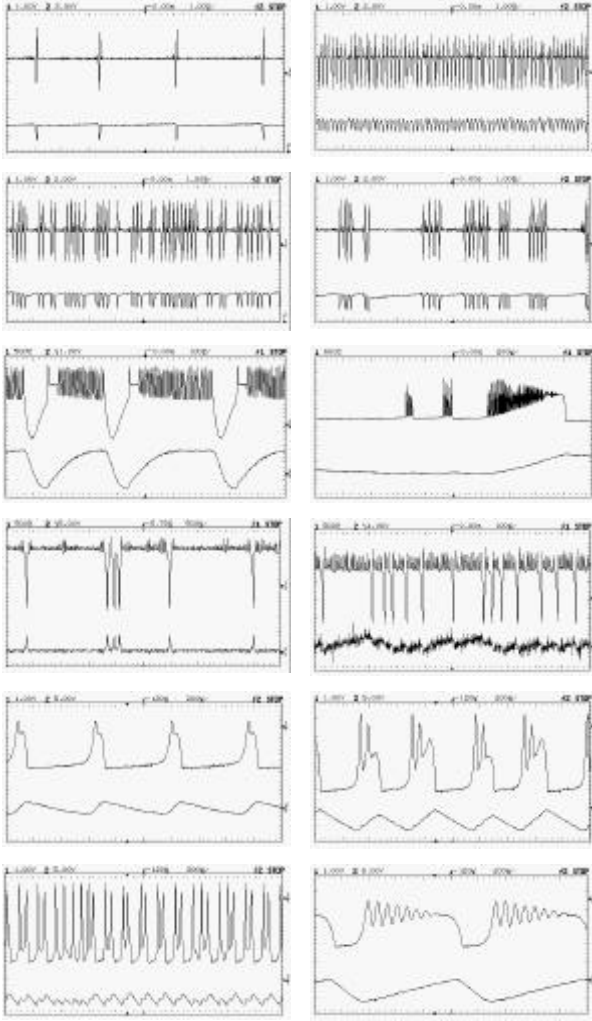
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3.5 All-branches input

Figure 9: V(t) and $I_{K(Ca)}(t)$ for miscellaneous V_1, V_2 and V_3 settings (circuit of Figure 3-d).

4. Mathematical model

Computer studies of the circuit model can be made using simulators as PSPICE, for example. The code is very simple if using ideal reactive elements and ideal negative resistor R_N. For a more mathematically oriented investigation the following state variable approach is to be used. The dynamical equations of the circuit model are:

$$
\begin{aligned}
C\dot{V} &= -I_{Na}(V,V_2) - I_K - I_{K(Ca)} \\
L_1\dot{I}_K &= V - V_{D1}(I_K) - V_1 \\
L_2\dot{I}_{K(Ca)} &= V - V_3
\end{aligned}
\tag{1}
$$

with $I_{Na}(V,V_2)$ and $V_{D1}(I_K)$ the functions

$$
\begin{aligned}
I_{Na} &= \frac{V}{R_N} + I_o\left(e^{(V-V_2)/2V_T} - 1\right) \\
V_{D1} &= 2V_T \ln\left(1 + \frac{I_K}{I_o}\right)
\end{aligned}
\tag{2}
$$

where I_o and V_T are diodes parameters and $R_N<0$. Figures 10 a) and 10 b) show the graphical appearance of (2) and Figure 10 c) shows examples of the N-shaped curves given by the sum of I_{Na} and I_K: these curves are useful to help understanding the bursting oscillatory properties of the equations.
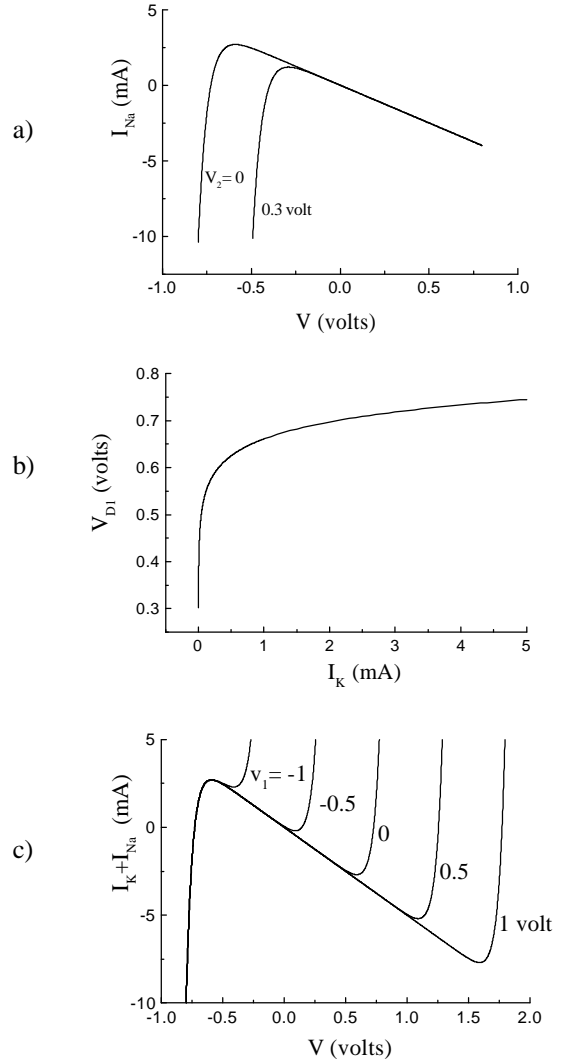

Figure 10: a) Graph of the function $I_{Na}(V,V_2)$ with R_N=-200Ω; b) the diode DC characteristic curve; c) DC characteristics curves of the K + Na branches for R_N=-200Ω and V_2=0, with input voltage V_1 as parameter ($I_o = 3\times10^{-9}$A, V_T= 0.025V).

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Equations (1) can be arranged to have less parameters by defining $\tau = t/\sqrt{(L_1 C)}$ and $b = L_2/L_1$. With $\rho = \sqrt{(L_1/C)}$, $x = V$, $y = \rho I_K$, $z = \rho I_{K(Ca)}$, $e_1 = V_1$, $e_2 = V_2$, $e_3 = V_3$, $f(x,e_2) = \rho I_{Na}(x,e_2)$ and $x_D(y) = V_D(y/\rho)$, Equations (1) are writen as:

$$\dot{x} = -f(x, e_2) - y - z$$
$$\dot{y} = x - x_D(y) - e_1 \qquad (3)$$
$$b\dot{z} = x - e_2$$

Using piecewise linear approximations for the non-linear functions, waveforms V(t) such as in Figure 11 can be obtained by numerical integration of (3).

A deeper numerical and also a qualitative and analytical investigation of the model equations are in process. The mathematical explanation of bursting mechanisms in neurons can be found, for example, in [13].
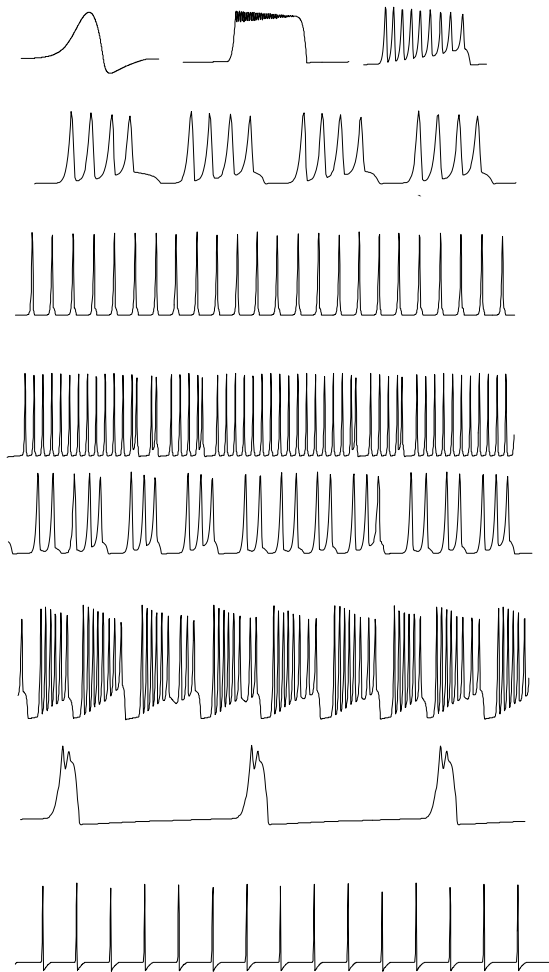

Figure 11 – Some V(t) waveforms obtained by numerical integration of Equations (3).

5. On a VLSI version of the model

The proposed neuron model can be fabricated as an integrated circuit using junction diodes or diode connected MOS-transistors as nonlinear elements, and using operational transconductance amplifiers and gyrators as in [14] or the state variable piecewise linear approach as in [15]. The design and implementation of an integrated circuit prototype of the neuron circuit is object of future work, but some points can be discussed previously. Using the same approach as in [14], with up-to-date technology and working at a lower time scale than the biological time scale, it can be estimated that a single circuit will occupy a total area of 5 to 10 mm^2. As a consequence, less than one hundred circuits can be placed in a die of 400 mm^2. The limiting factor for area reduction are the relatively large capacitance values. Using scale down techniques as indicated in [14], a half thousand units can be achieved. These numbers appear to be adequate for research purposes concerning simulation of small biological systems, as proposed in [8]. For higher densities, the state variable approach proposed in [15] can be used.

6. Comments and future work

The present work is a result of the author's researches on the theoretical and practical representation of an individual neuron as a dynamical system, and the model in Figure 2 is the apex of a lengthy process of depuration. With such a simplest circuit at hand, it can be carefully augmented to improve or modify its performance as wanted. The next step (toward a neural network) is the investigation of the coupling properties of the neuron model. Experiments on diffusive coupling are already in process, and the inclusion of synapses is object of near future work. When a detailed knowledge of all these system's properties is reached, it will be possible to begin designing a network of model neurons to emulate a simple biological ensemble, such as, for example, part of the abdominal ganglion of the marine mollusk *Aplysia*. Another possible application of the circuit model is building networks for producing stimulus-dependent synchronization of the responses, in analogy with those exhibited by some biological systems, as for example for the visual perception and selective attention.

7. Conclusion

A bursting neuron circuit model was presented, which is minimal in the sense that the least number of circuit elements was used to reproduce the properties of real neurons. The paper focused mainly on experimental results, to show the large versatility of such a simple circuit in producing a great variability of output

waveforms similar to the ones found in biological neuron cells. The motivation for this work was that the circuit can be useful for research purposes in the simulation of small biological systems. It is hoped that it can also be useful in the research of neural networks in future applications in fields such as robotics and image processing.

Acknowledgement

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