EXPERIMENTAL STUDY OF ELECTRICAL MORRIS-LECAR NEURON

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Introduction

A key problem to study brain behavior is to understand how the neurons represent and bind sensory informations converging to the brain from different channels. Neurons exhibit and transmit electrical activity that researchers try to model by different ways. While the most famous model has been developed by Hodgkin and Huxley (HH) [1], some of its derived models, as FitzHugh Nagumo (FHN) [2, 3] or Morris Lecar (ML) [4, 5, 6] ones, despite their simplicity, give interesting results as different behaviors appear according to tunable parameters. In the present work, we propose a complete electronic implementation of ML model of type I, candidate to become an experimental unit tool to study collective association of robust coupled neurons. Experiments on this electrical neuron can enlighten the robustness of the obtained behaviors as it includes intrinsic and extrinsic noise. We present firstly the equation set of ML model, then the circuit design. Finally, we compare our experimental results with the various theoretical predictions of this model.

The Morris-Lecar Model

The Morris-Lecar Equations

The Morris-Lecar model [4] of biological neuron was developed to reproduce the variety of oscillatory behaviors with respect to the calcium Ca^{++} and potassium K^{+} conductances in the giant barnacle muscle fiber. The Morris-Lecar model is a two-dimensional system of nonlinear differential equations:

$$C_m\frac{dV}{dt} = I_{app} - g_{Ca}M_\infty(V)(V-V_{Ca}) - g_K W(V-V_K) - g_L(V-V_L), \quad (1)$$

$$\frac{dW}{dt} = \frac{W_\infty(V)-W}{T_W(V)}, \quad (2)$$

where

$$M_\infty(V) = \frac{1}{2}+\frac{1}{2}\tanh\left(\frac{V-V_1}{V_2}\right), \quad (3)$$

$$W_\infty(V) = \frac{1}{2}+\frac{1}{2}\tanh\left(\frac{V-V_3}{V_4}\right), \quad (4)$$

$$T_W(V) = \frac{T_0}{\cosh\left(\frac{V-V_3}{2V_4}\right)}. \quad (5)$$

Equivalent Circuit

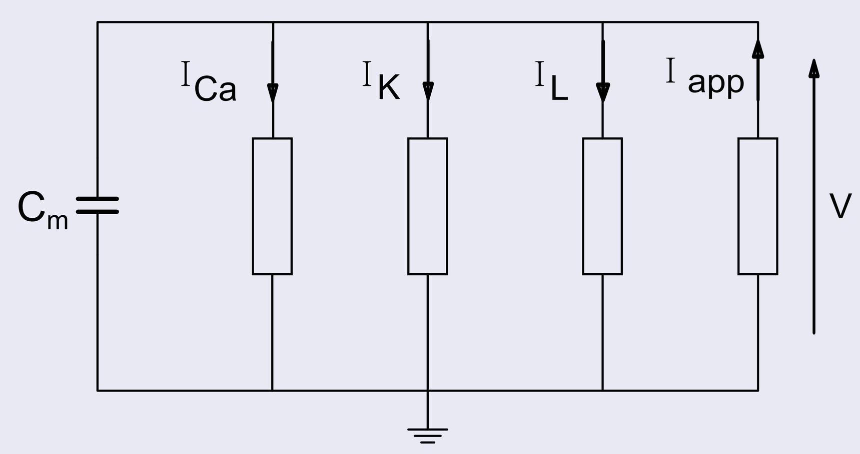

Figure 1 : Equivalent circuit for the M-L model

$$C_m\frac{dV}{dt} = I_{app} - I_{Ca} - I_K - I_L$$

$$I_{Ca} = g_{Ca}M_\infty(V)\cdot(V-V_{Ca})$$
$$I_K = g_K W(V-V_K)$$
$$I_L = g_L(V-V_L)$$

V membrane voltage, C_m membrane capacitance and I_{app} current applied to the neuron. I_{Ca}, I_K and I_L are the calcium, potassium and leak currents respectively in $\mu A/cm^2$, while W represents the recovery variable.

Electronic Circuit

Global Circuit

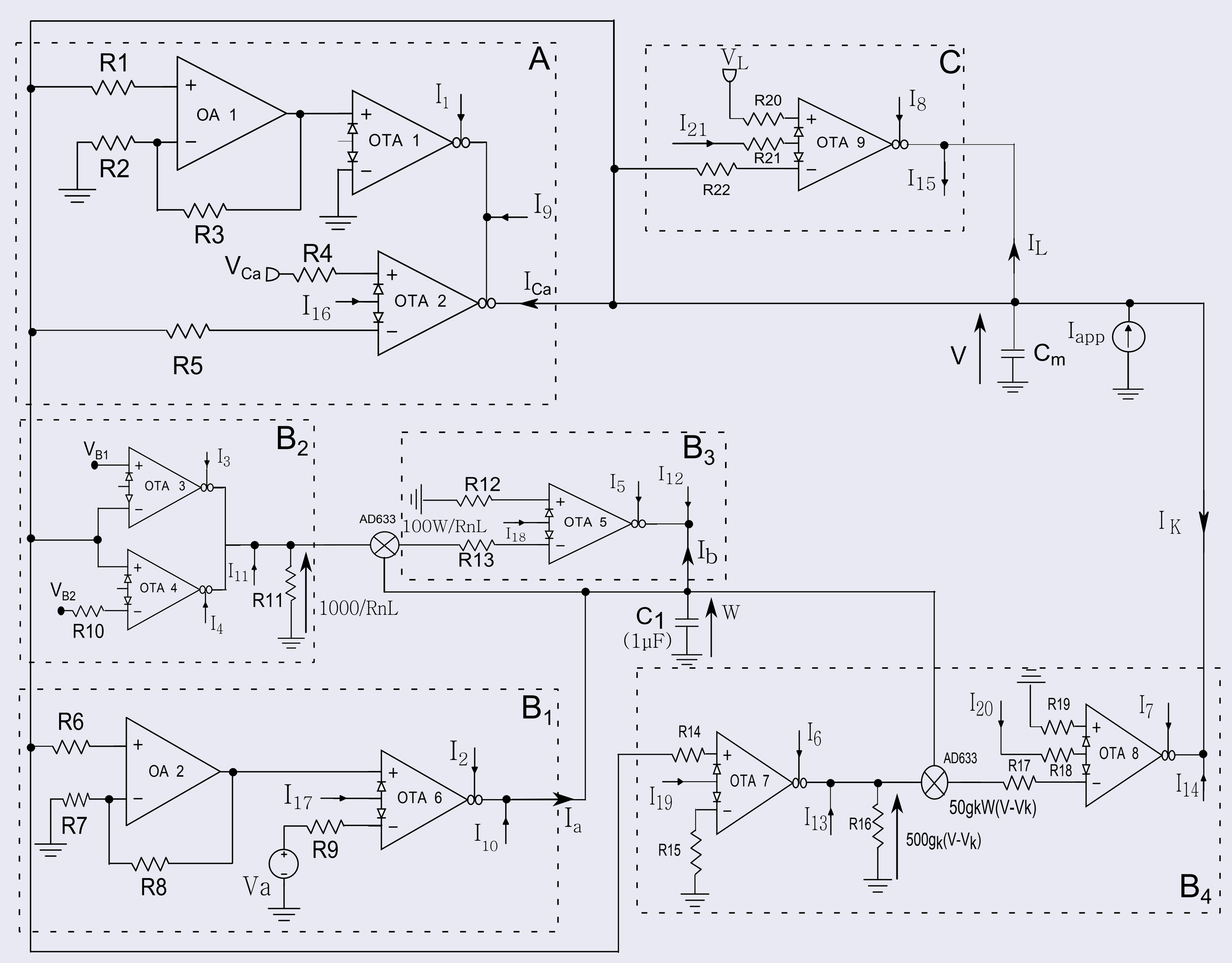

Figure 2 : Global circuit where I_1 to I_8 are bias currents, I_9 to I_{15} are offset currents and I_{16} to I_{21} are diode currents.

Different Currents

The calcium current I_{Ca} : To build the current I_{Ca} (see block A, Fig. 2), we use two Operational Transconductance Amplifiers (OTA) LM13700 [7], whose gain can be controlled via either bias current or diode current. To obtain the slope of the sigmoid function $M_\infty(V)$ according to eq (3), we amplify a OTA 1 entry tension with an operational amplifier (OA) UA741. With the OTA 2, we multiply both signals $g_{Ca}M_\infty(V)$ and $(V-V_{Ca})$.

The potassium current I_K : To solve the problem of the differential equation (2), we build a circuit with a capacitance C_1 and a nonlinear resistance Rnl such as $C_1\frac{dW}{dt} = I_a - I_b = I_a - \frac{W}{Rnl}$.

- **Current** I_a**:** it is given by block B_1 in Fig. 2, which is composed by an OTA, an OA and current sources.
- **Catenary curve** $1000/Rnl$**:** it is obtained by adding output currents of two OTAs, with inverted inputs, as shown in block B_2.
- **Current** I_b**:** it is produced with an analog multiplier (AD633) and a voltage-current converter (see block B_3).
- **Current** I_k**:** to complete the production of I_k current, we use an OTA for the voltage $500g_K(V-V_K)$ and a multiplier by W. Finally another OTA is used as a voltage-current converter and negative multiplier by (-50) as shown in block B_4 (see Fig. 2).

The leak current I_L : Only one OTA, restricted to its linear zone, is enough to give I_L (see block C, Fig. 2).

Test of the Global Electronic Circuit

Bifurcation Diagram

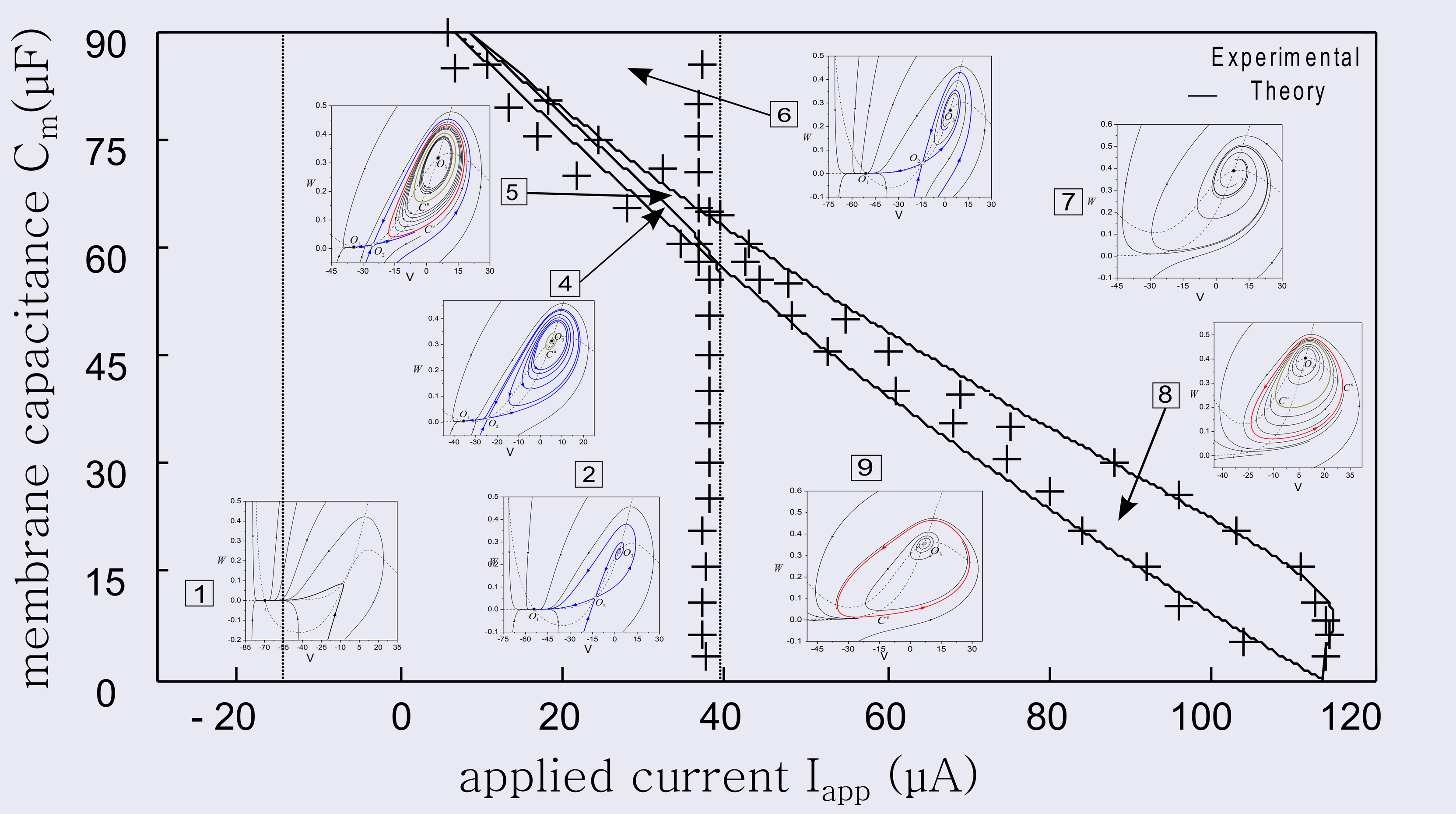

Figure 3 : Bifurcation diagram, I_{app} and C_m are tunable parameters. This figure shows the different areas of bifurcation of codimension 2 (C_m, I_{app}). With this circuit, we have managed to clearly distinguish between the different areas of bifurcation. We do not draw the border that separates the region 4 and 5 because they are very thin.

Exemple of Stable Cycle

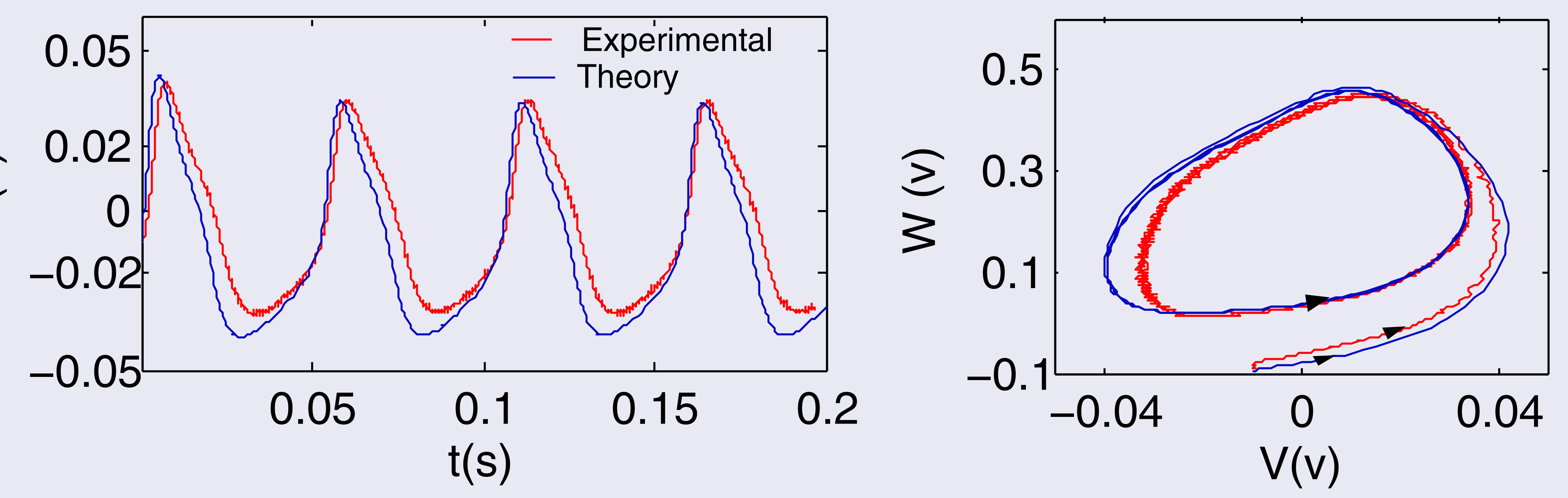

Figure 4 : Region 9 of Fig. 3, $C_m = 20\mu F$; $I_{app} = 68\mu A$; $V_{in} = -10mV$; $W_{in} = -96mV$. Left: action potential versus time, Right: phase plane. We compare these experimental results with numerical simulations of the complete model ML (using a 4^{th} order Runge-Kutta scheme). We found a nice agreement in Region 9 between experiments and theory as well as for the other regions shown in Fig. 3.

Conclusions and Future Works

It is worthwhile to remark that in our implementation of ML electronic neuron, $T_W(V)$ is indeed fonction of V according to Eq. (5). This improves the circuit given in [5]. Moreover, with OTA technology, switching to microelectronics is easy. The large-scale simulation of the neuron behaviors takes too much calculation time, but with electronic neurons, the real time results can be obtained. The next stage will be to couple a sufficient number of such neurons and to study their real dynamics to find a way to introduce them into the information transmission science.

References

[1] A.L. Hodgkin and A.F. Huxley. A quantitative description of membrane current and its application to conduction and excitation in nerve. *The Journal of physiology*, 117(4):500, 1952.

[2] R. Fitzhugh. Impulses and physiological states in theoretical models of nerve membrane. *Biophysical journal*, 1(6):445–466, 1961.

[3] VB Kazantsev, AS Tchakoutio Nguetcho, S. Jacquir, S. Binczak, and J.M. Bilbault. Active spike transmission in the neuron model with a winding threshold manifold. *Neurocomputing*, 2012.

[4] C. Morris and H. Lecar. Voltage oscillations in the barnacle giant muscle fiber. *Biophysical journal*, 35(1):193–213, 1981.

[5] A. Wagemakers, M.A.F. Sanjuán, J.E.M. Casado, and K. Aihara. Building electronic bursters with the Morris–Lecar neuron model. *International Journal of Bifurcation and Chaos*, 16(12):3617–3630, 2006.

[6] K. Tsumoto, H. Kitajima, T. Yoshinaga, K. Aihara, and H. Kawakami. Bifurcations in Morris–Lecar neuron model. *Neurocomputing*, 69(4):293–316, 2006.

[7] Ray Marston. Understanding and using OTA OP-AMP ICs. *Nults & Volts Magazine*, pages 70–74, May 2003.