

# A Low Power 65nm CMOS Electronic Neuron and Synapse Design for A Biomimetic Micro-Robot

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**Abstract**—This paper presents an electronic neuron and synapse design, that can mimic the natural behavior of animal neuron and synapse and generate swimming patterns for a biomimetic micro-robot. The electronic neurons are based on the Hindmarsh-Rose neuron model, and the electronic synapse is constructed based on a first order chemical model. The proposed design is based on 65nm Predictive Technology Model (PTM) at a 0.8V supply, with which the power consumption and chip area will be reduced compared with the latest design which was implemented using a 0.25 $\mu$ m CMOS process powered at 2V supply. Simulation results demonstrate that the proposed 65nm CMOS design performs all of the expected functions at the extremely low supply of 0.8V.

## I. INTRODUCTION

Biomimetic robots have broad applications including environmental investigations and resource exploration in remote regions such as ocean bottoms. Such environments generally exhibit great irregularities. For example, ocean water flow fluctuations and bottom obstructions present a series of difficulties when designing typical robots. Therefore, the controller of the robotic movement should be able provide adaptability for varying environmental conditions in realistic situations. Furthermore, low voltage design is required for the robots operating in remote locations to increase the battery lifetime. The micro-robot design faces great challenges due to the requirements of robustness, low power, and miniaturization of the circuit.

Recent advances in synthetic biology suggested a new direction in design [1], which is to imitate neuron-based behavioral capabilities of simple animal models, such as the sea lamprey using sensors and actuators formed from engineered cells. Studies have shown that the Central Pattern Generator (CPG) is an innate animal behavior control unit resident in central ganglia or the spinal cord [2]. It modulates the animals' behavior using a governed oscillation signal formed in different ways to coordinate different activity patterns [3]. Experiments have been carried out to mimic this control pattern utilizing digital microprocessors and ultra low power A/D and D/A converters [4]. However, the discrete time operation and deterministic programming inherently exhibit the shortcomings of slow reaction to the continuous time environment and they increase hardware complexity due

to A/D and D/A converters as well as controllers. On the other hand, analog based CPGs provide the desired ability of continuous time operation and adaptive control. This paper describes the design of a CMOS low power implementation of the CPG based on the research on novel autonomous bio-hybrid robot called "Cyberplasm" shown in Figure 1.

The aim of the Cyberplasm project is to create a novel, autonomous bio-hybrid micro-robot. It utilizes sensors and muscles engineered from living cells while simple CPGs create rhythmic swimming patterns. A block diagram map for the electric nervous system is shown in Figure 1. Connections with circles are inhibitory synapses and triangles are excitatory. Chemical sensors direct direction while the photoreceptor activates the overall map. Connections between Lseg and Rseg create out of phase oscillations when excited. Intersegment connections between Seg1 and Seg2 propagate oscillations from front to the rear creating propagating waves of muscle contractions for forward swimming.

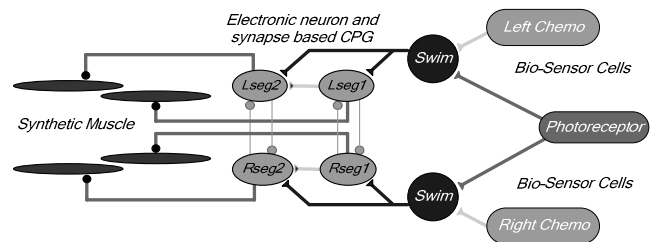


Figure 1 block diagram of control system linking the various components of Cyberplasm.

The state of the art is to implement CPGs using a 2V power supply [5]. However, 2V is still too high for long-term operation in the era of nano- scale technology. Therefore, it is critical to design a system that performs the same function in nanoscale CMOS and a lower power supply voltage. This paper accomplished the electronic neuron and synapse using 65nm CMOS PTM [6] at 0.8V power supply with less hardware count. Simulation results verified the proposed circuit implementation perform the expected function at power supply of 0.8V.

The paper is organized as follows: Section II starts with the introduction of Hindmarsh-Rose neuron model and its

analog implementation. Section III covers the topology and circuit design of the synapse followed by simulation results in Section IV, and section V presents conclusion of this paper.

## II. NEURON CIRCUITS

### A. Neuron Model

The equations of the Hindmarsh-Rose (HR) model describe the behavior of the biological neuron's action potential [7]. This model is preferable to others because of its lower order of equations and accurate output frequency versus input current relationship. The three dimensional HR neuron equations are as follows:

$$dx/dt = y - ax^3 + bx^2 - z + I \quad (1)$$

$$dy/dt = c - dx^2 - y \quad (2)$$

$$dz/dt = r(s(x - x_1) - z) \quad (3)$$

Where,  $x$  is membrane potential,  $y$  is recovery current,  $z$  is adaptation current,  $I$  is applied current, and  $x_1$  is the leftmost equilibrium point of the neuron model without adaptation. The initial conditions for state variables ( $x_0, y_0, z_0$ ) are (0, 0, 0). While the coefficients of HR neuron equations are:  $I=3.024, a=1, b=3, c=1.01, d=5.0128, r=0.0021, s=3.966$  and  $x_1=1.605$ .

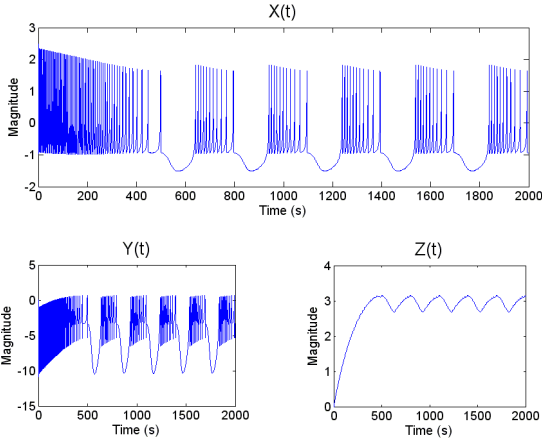


Figure 2. MATLAB simulation result of HR model:  $x(t)$ ,  $y(t)$  and  $z(t)$ .

Figure 2 shows a MATLAB simulation of HR's three variable  $x$ ,  $y$  and  $z$ . After about 500 seconds startup time, both  $x$  and  $y$  begin a tonic oscillation, which is a set of spikes

followed by a rest period. The  $x$  variable is the desired output which mimics the animal's neural bio-oscillation.

### B. Scalling of HR equation

As shown in the vertical axis of variable  $x, y, z$  in Figure 2, the magnitudes are all beyond the supply rail in the proposed implementation. Therefore, magnitude scaling is required. Meanwhile, time scaling is also demanded when the implementation is on chip [5]. However, the time scaling meets a compromise since an aggressive time scaling may lose HR neuron's biologic meaning. Scaled parameters are defined as:  $x_{new} = x/x_{ms}, y_{new} = y/y_{ms}, z_{new} = z/z_{ms}$ , and  $t_{new} = T_s \times t$ . Applying the scaled parameters to equation (1), (2), and (3), new equations are obtained as follows:

$$\frac{dx}{dt} = \frac{1}{T_s} \left( \frac{y_{ms}}{x_{ms}} y - x_{ms}^2 a x^3 + x_{ms} b x^2 + \frac{1}{x_{ms}} I - \frac{z_{ms}}{x_{ms}} z \right) \quad (4)$$

$$\frac{dy}{dt} = \frac{1}{T_s} \left( \frac{1}{y_{ms}} c - \frac{x_{ms}^2}{y_{ms}} d x^2 - y \right) \quad (5)$$

$$\frac{dz}{dt} = \frac{1}{T_s} \left( r \left( s \left( \frac{x_{ms}}{z_{ms}} x - \frac{x_1}{z_{ms}} \right) - z \right) \right) \quad (6)$$

To maintain the signal magnitude within the 0.8 volt rail limit and keep the tonic oscillation both frequency biologically reasonable and circuit achievable, the following scaling factors are chosen:  $x_{ms} = 28, y_{ms} = 60, z_{ms} = 15$ , and  $T_s = 2.2e-3$ .

### C. Circuit Implementation

Taking integration on both sides of equation (4), (5), and (6), an equivalent circuit is constructed with operational amplifier based integrators, as shown in Figure 3. The integrators' time constants are determined by time scaling factor  $T_s$  and input signals' corresponding coefficients.  $L, M$ , and  $K$  are bias voltages representing the constant terms in (4), (5) and (6) respectively.  $L$  can be changed from 0.54V to 0.65V to vary this electronic neuron's bursting type. A finely designed two stage operational amplifier working in sub-threshold region is also presented in Figure 3. The N-type differential pair is preferred for the input stage since it provides higher trans-conductance than P-type counterpart due to its about three times higher mobility.

It is noticed that additional circuit is required to produce

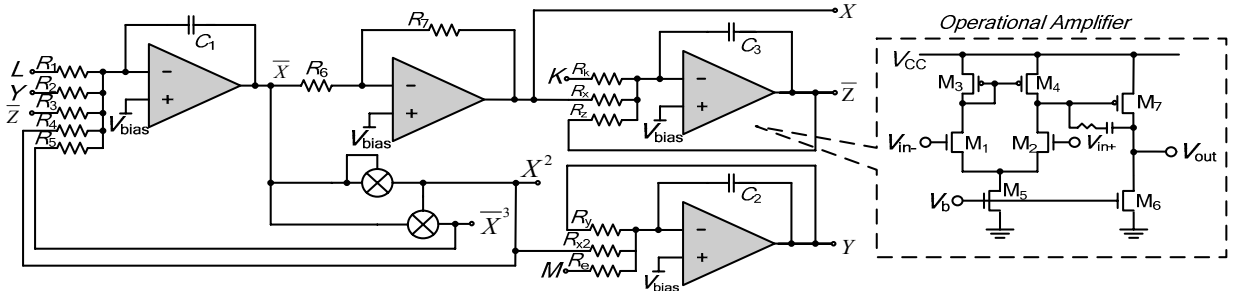


Figure 3. Electronic neuron circuit based on HR neuron model.

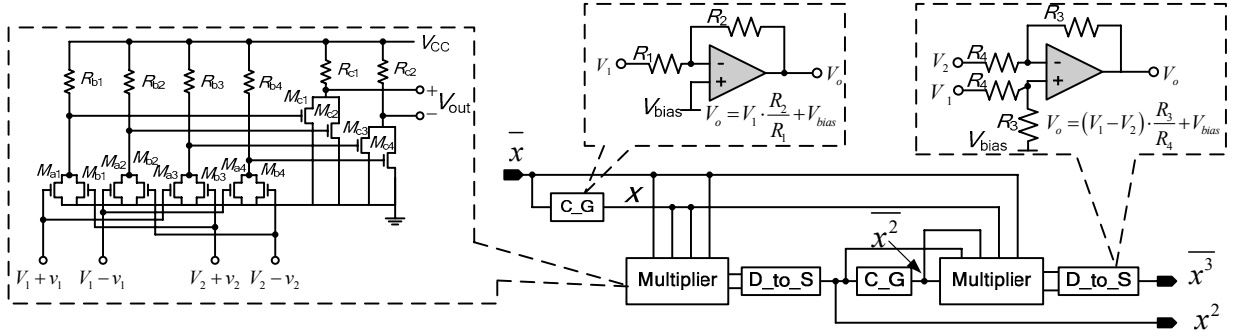


Figure 4. Square and cubic generator circuit.

the square and cubic terms of  $x$  variable in Figure 3. Figure 4 reveals the corresponding design.  $\bar{x}$  is the input, and  $x^2$  and  $\bar{x}^3$  are the outputs. A multiplier described in [8] is suitable for the proposed 65nm electronic neuron for its low supply voltage requirement. However, this multiplier takes differential inputs with their complementary ones and generates differential outputs, auxiliary blocks (complementary signal generator: C\_G and differential to single-ended converter: D\_to\_S) are necessary. Since all the transistors in the multiplier need work in saturation region, signal integrity is assured, but the range of input signals and their complementary ones should be constrained. Simulation results show that the input signal must be higher than 0.4V. So a 0.55V virtue ground voltage  $V_{bias}$  and 0.1 V peak amplitude of  $x$  is imposed, thus both  $\bar{x}$  and  $x$  are within the limit of the multiplier. The major constraint of the signal amplitude of this electronic neuron circuit comes from this.

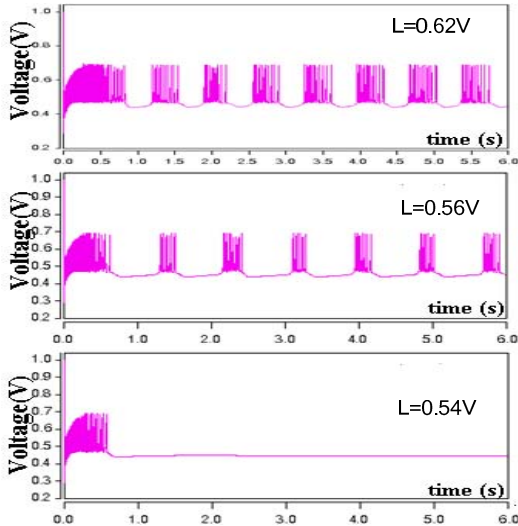


Figure 5. Simulation results of electronic neuron with different input  $L$ .

#### D. Simulation results

The simulation results of the 65nm electronic neuron are included in Figure 5. The horizontal axis represents time in seconds and vertical axis indicates magnitude in volts. The

three waveforms show the different behaviors based on the value of input  $L$ . With  $L$  lower than the threshold (0.543V), the electronic neuron will remain silent. With an increased  $L$ , the burst duration is elongated and silent period is shortened, which is an innate property of HR neuron model. The global behavior of this neuron works almost the same as MATLAB simulation.

### III. SYNAPSE

#### A. Synapse Model

An important function of synapses is to coordinate individual neurons so that bursting is either synchronous (excitatory coupling) or asynchronous (inhibitory coupling). The chemical synapse model [9] is given as:

$$I = gS(t)(V_{rev} - V_{post}) \quad (7)$$

$$\frac{dS(t)}{dt} = \frac{S_{\infty} - S(t)}{\tau_s (1 - S_{\infty})} \quad (8)$$

$$S_{\infty} = \tanh\left(\frac{V_{pre} - V_{thres}}{V_{slope}}\right) \text{ when } V_{pre} > V_{thres} \quad (9)$$

Otherwise,  $S_{\infty} = 0$

Where,  $g$  is the maximal synaptic conductance,  $S(t)$  is instantaneous synaptic activation,  $S_{\infty}$  is the steady-state synaptic activation,  $V_{rev}$  is the synaptic reversal potential,  $V_{pre}$  is presynaptic voltage,  $V_{post}$  is the postsynaptic voltage,  $V_{th}$  is the synaptic threshold for transmitter release,  $V_{slope}$  is the synaptic slope voltage, and  $\tau_s$  is the synaptic time constant.

The current injected into the post synaptic electronic neuron is always hyperpolarizing for inhibitory synapses and depolarizing for excitatory synapses, the same as in biological synapses.

#### B. Circuit Implementation

Figure 6 shows the 65 nm implementation of electronic synapse circuit. The operational amplifier is the same as the one shown in Figure 3. Since the maximum input amplitude to the hyperbolic tangent function is less than 100mV, a simple linearization of the hyperbolic tangent function is a reasonable approximation to simplify the circuit. A multiplier is required to modulate the integrator output either above the virtual

ground in excitatory synapses or below the virtual ground in inhibitory synapses. A transmission gate shown as SW and an analog inverter (-x) in Figure 6 performs the multiplication function.

Figure 7 is a neuronal oscillator that can verify the operation of the electronic synapse. The two synapses and neurons are identical. Depending on the type of synapse employed, the output of two electronic neurons may synchronize with excitatory or become out of phase with inhibitory synapses.

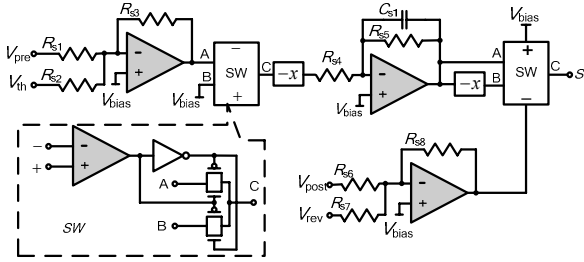


Figure 6. Electronic synapse circuit.

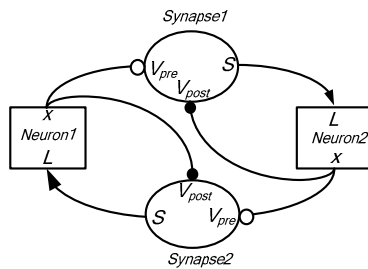


Figure 7. Neuron oscillator diagram.

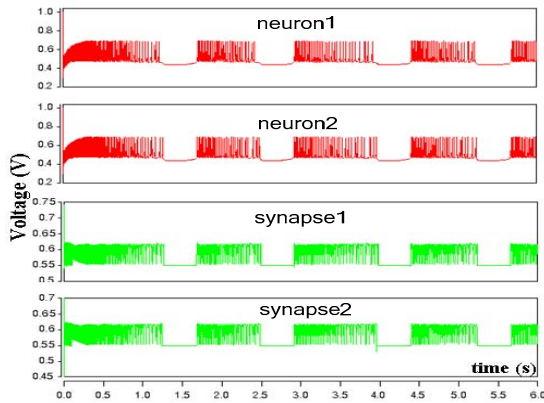


Figure 8.a. Simulation results for excitatory coupling.

### C. Simulation results

Figure 8 shows the neural oscillator simulation results. Figure 8.a is the excitatory coupling with neuron1 and neuron2 synchronized. Figure 8.b presents inhibitory coupling with neuron 1 and neuron2 out of phase.

Analog integrated circuits of electronic neuron and synapse operating at 0.8V power supply are designed and verified using 65 nm CMOS technology. Due to the constraint of supply rail and on-chip passive components, as well as the operation region of sub-circuits, new scaling factors were adopted. Simulation results show that the electronic implementation closely follows the outlined neuron and synapse models, and the simulation results demonstrate that the designed circuits are viable solution for the proposed Cyberplasm robots central nervous system. This approach will be a good reference for the future low power CPG design.

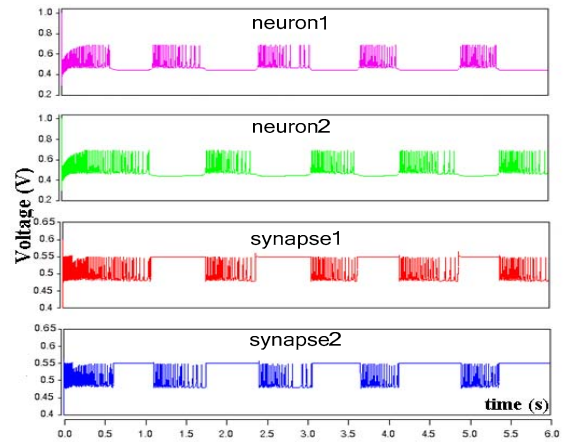


Figure 8.b Simulation results for inhibitory coupling.

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### IV CONCLUSION