

Low Power CMOS Adaptive Electronic Central Pattern Generator Design

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Abstract—In this paper, low power VLSI implementation of adaptive analog controller for autonomous robot is presented using standard CMOS process with 2V supply voltage. Electronic neuron and synapse circuit are developed based on Hindmarsh-Rose neuron model and first order synapse model. In order to achieve low power consumption, CMOS subthreshold circuit techniques are used. The power consumption is 4.8 mW and die size is 2mm by 2mm. Simulation results demonstrate that the proposed design is viable for adaptive analog controller for autonomous robots.

I. INTRODUCTION

Robots can be used in a broad spectrum of applications from industrial to field applications. Most contemporary robots, however, operate only in well controlled environments. There is a strong demand for consumer, industrial, and scientific applications to have autonomous robots that perform their jobs in unpredictable environments. Existing robots are commonly controlled by algorithm based systems such as finite state machines[5]. However, algorithm-based robots controlled by digital processors show deterministic operation due to inability to anticipate all contingencies. When one considers operation in natural environments, it is desirable to adopt the strategies of real animals [1]. To overcome this problem, several researchers have focused on emulation of biological nervous systems[1].

The innate behavior of animals is controlled by central pattern generators (CPGs) resident in central ganglia or the spinal cord[4]. It is our contention that if CPG-based controllers are imitated, many problems due to deterministic control program can be solved and it is feasible to develop an adaptive autonomous robot that operates with adaptability and flexibility in natural environment[6]. CPGs can be constructed from electronic neurons based on non-linear dynamical models of biological neurons[7]. However, these circuits are built from discrete components and are not realistic solution due to their size and power. The CPG is described in section II, and section III discusses Electronic CPG circuit design. The simulation results are demonstrated in section IV.

II. CPG AND ITS SUB-BLOCKS

Central pattern generators are normally turned and modulated by descending motor commands and coordinated among themselves by coordinating neurons that provide a governed

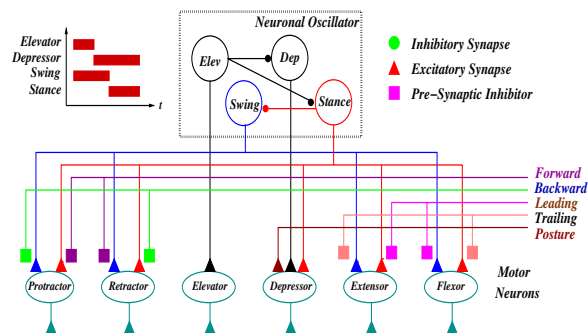


Fig. 1. The block diagram of Central Pattern Generator

oscillator with information about the activity status of a governing oscillator to maintain gait. During locomotion the motor programs generated by central pattern generators are modulated by sensory feedback. Depending on the locus of action of the sensory feedback within the CPG it can either modulate the amplitude of the output or reset its timing to adapt to environmental contingencies. We have been developing robots based on this central pattern generator model. Our lobster-based platform is intended for remote sensing applications in the littoral zone. This robot features a physical plant based on the lobster body, artificial muscle fabricated from shape memory alloys, neuromorphic sensors and a controller based on known lobster circuitry[6].

As shown in Figure 1, electronic CPG consists of 6 motor neurons, 4 inter-neurons, 6 inhibitory synapses, 12 excitatory synapses, and 8 pre-synaptic inhibitory synapses. Neurons are represented by large circle and inhibitory and excitatory synapses are represented by small circle and triangle, respectively. The presynaptic inhibitory synapses, which is represented by square, is a synapse that gates off an excitatory synapse. Electronic CPG is divided into four sub-blocks as follows.

- 1) 4-State Neuronal oscillator - The neuronal oscillator is the clock of the CPG and is composed of neurons that are endogenous bursters. The oscillator is turned on by motor commands that function as inward current sources. The four phase motor program emerges from the inhibitory connectivity between the endogenous

bursters. During operation, the circuit continuously generates *elev*, *dep*, *swing*, and *stance* signal. These output signals determine the movements of lobster's leg in conjunction with *forward*, *backward*, *leading*, *trailing*, and *posture* signal from the command and coordinate controller. *elev* and *dep* are mutually exclusive, and *swing* and *stance* are also mutually exclusive.

- 2) Protractor and Retractor - The outputs of these blocks move lobster robot back and forth. Stance and swing operations are required to generate propulsive force during forward or backward walking. The inputs of these blocks are *swing* and *stance* from neuronal oscillator and the inappropriate connections are gated off by *forward* and *backward* signal from the command neurons.
- 3) Elevator and Depressor - Elevator and depressor signals control leg to move upward during the early swing and downward during the late swing and stance. Input signal of elevator block is *elev* which comes from 4-state neuronal oscillator, and depressor's inputs are *posture* which is external input to control height, pitch and roll and *dep* from 4-state neuronal oscillator.
- 4) Extensor and Flexor - It moves the distal joint of the leg during in lateral walking. Flexor and extensor signals are controlled by *stance* and *swing* and gated by the motor commands for *trailing*, and *leading*.

In addition to the leg CPGs, exteroceptive sensory inputs modulate the motor commands.

III. ELECTRONIC CPG DESIGN

In this section, electronic CPG is described and its simulation results are presented.

A. Electronic Neuron Circuit

To design electronic neuron circuit, Hindmarsh-Rose neuron (HR) model is used [8], [7]. The mathematical expression of HR model is given by

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

$$\frac{dy}{dt} = c - dx^2 - y \quad (2)$$

$$\frac{dz}{dt} = r(s(x - x_1) - z) \quad (3)$$

where, x : membrane potential of neuron, y : recovery current of neuron, z : adaptation current of neuron, I : applied current, and x_1 : the leftmost equilibrium point of the neuron model without adaptation.

Coefficients of the Equation (1),(2) and (3) are:

$a = 1$, $b = 3$, $I = 3.024$, $c = 1.01$, $d = 5.0128$, $r = 0.0021$, $s = 3.966$, and $x_1 = 1.605$.

The schematic of HR model is shown in Figure 2 and HSPICE simulation results of this circuit are shown in Figure 3. As shown in Figure 3, the output burst signal of electronic neuron is modulated by the input DC level. To implement electronic neuron circuit, operational amplifier, analog multiplier, and MOS resistor circuits were designed and validated by HSPICE simulation[9].

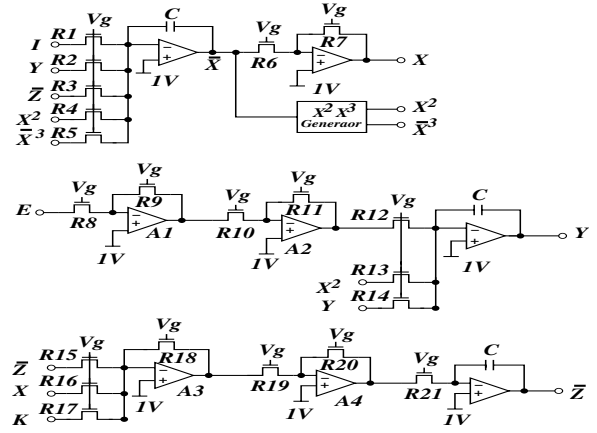


Fig. 2. The Schematic of HR Model

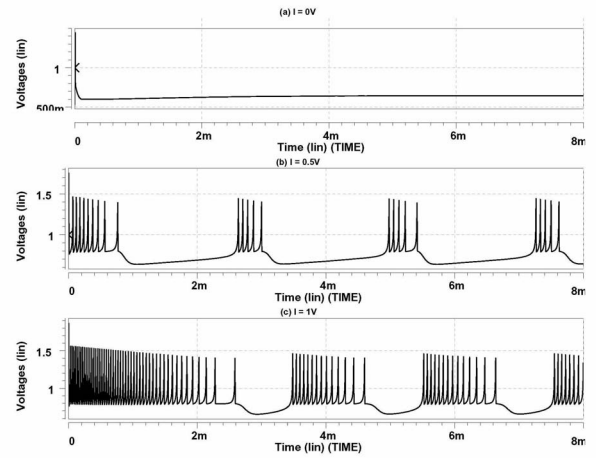


Fig. 3. HSPICE Simulation Result of Electronic Neuron

B. Electronic Synapse Circuit

A biological chemical synapse is modeled as [7],

$$I = gS(t)(V_{rev} - V_{post}) \quad (4)$$

$$\frac{dS(t)}{dt} = \frac{S_{\infty} - S(t)}{\tau_S(1 - S_{\infty})} \quad (5)$$

$$S_{\infty} = \tanh\left(\frac{V_{pre} - V_{thres}}{V_{slope}}\right) \quad (6)$$

for $V_{pre} > V_{thres}$, otherwise, $S_{\infty} = 0$

g : maximal synaptic conductance

$S(t)$: instantaneous synaptic activation

S_{∞} : steady-state synaptic activation

V_{rev} : synaptic reversal potential

V_{pre} and V_{post} : presynaptic and postsynaptic voltages

V_{thres} : synaptic threshold for transmitter release

V_{slope} : synaptic slope voltage

τ_S : synaptic time constant

Based on this equation, electronic synapse circuit is designed and the schematic of this circuit is shown in Figure 4[10].

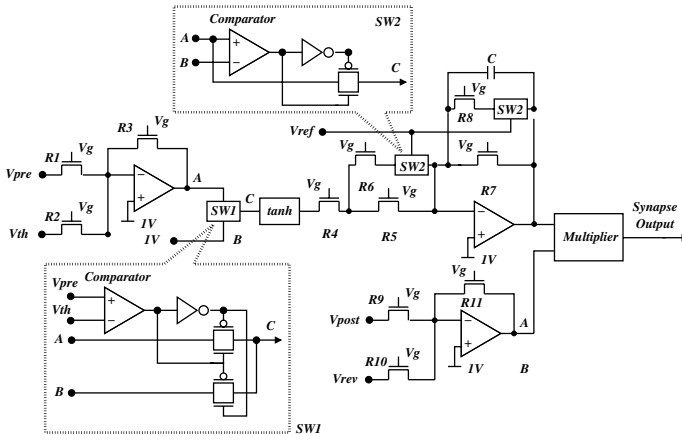


Fig. 4. Synapse Circuit

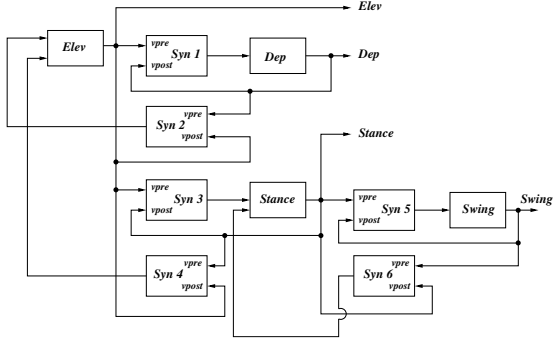


Fig. 5. The Block diagram of 4-state Neuronal Oscillator Circuit

C. 4-State Neuronal Oscillator Circuit

Figure 5 shows the block diagram of 4-state neuronal oscillator circuit. The role of 4-state neuronal oscillator is to generate basic rhythmic timing to control the behaviors of animal [3]. The output timing diagram of 4-state neuronal oscillator circuit is shown in the left-top of Figure 1. There are overlapped time slot between *dep* and *swing* signal in order to smoothly perform walking function. To generate basic timing signals of *elev*, *dep*, *stance* and *swing*, the coefficients of electronic synapses and neurons are slightly changed and their values are summarized in Table I and II. HSPICE simulation results are shown in Figure 8. The top four signals in the figure are *elev*, *dep*, *swing* and *stance* in order.

D. Pre-Synaptic Inhibitor

Figure 6 shows a circuit diagram of pre-synaptic inhibitor circuit, which is somewhat different from synapse circuit. While the role of synapse circuit is to provide information which determines the output signal of neuron connected to

Coefficient	Elev	Dep	Stance	Swing
DC Input (I)	1.2V	2V	1.9V	1.6V
R_1 in Figure 2	1.48M Ω	0.22M Ω	2.65M Ω	2.65M Ω

TABLE I

THE COEFF. OF ELECTRONIC ELEV, DEP, STANCE AND SWING NEURONS

Coefficient	Syn_{ed}	Syn_{es}	Syn_{ss}
V_{rev}	1.60V	1.80V	1.60V
V_{thres}	0.85V	0.85V	0.85V
V_{slope}	3.3	3.3	3.3
V_{comp}	0.9V	0.75V	0.75V

TABLE II

THE COEFF. OF ELECTRONIC INHIBITORY SYNAPSE CIRCUITS: $Syn_{ed,es,ss}$ STANDS FOR SYNAPSE BETWEEN ELEV AND DEP, ELEV AND STANCE, AND STANCE AND SWING NEURON, RESPECTIVELY.

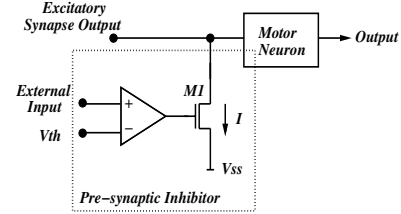


Fig. 6. Pre-synaptic Inhibitor Circuit

the output port of synapse itself, the role of pre-synaptic inhibitor is to prohibit the signal propagation from one neuron to another when the input of pre-synaptic inhibitor is activated to select the motor patterns for walking in different directions. Therefore, pre-synaptic inhibitor circuit is implemented using comparator and switch circuit. For example, in Figure 1, if *forward* signal is activated and it is higher than V_{th} , the output signal of pre-synaptic inhibitor turns on M1 in Figure 6, and the effect of *stance* signal is nullified by pre-synaptic circuit. Finally, output of protractor neuron is synchronized with *swing* signal. On the contrary, if *backward* signal is activated, the output of protractor neuron is synchronized with *stance* signal.

IV. ELECTRONIC CPG AND ITS SIMULATION RESULTS

Figure 7 shows the complete block diagram of CPG circuit. The simulation results of this circuit are shown in Figure 8 and 9. The order of waveforms shown in Figure 8 and 9 are *elev*, *dep*, *swing* and *stance* from 4state neuronal oscillator circuit, *elevator*, *depressor*, *protractor*, *retractor*, *extensor*, and *flexor* from output signals of CPG, and *forward*, *backward*, *trailing*, *leading* and *posture* from input signals. For case I, protractor/retractor is synchronized with *stance/swing* by *backward* signal, and extensor/flexor is synchronized with *stance/swing* by *trailing* signal. In this case, *forward* and *leading* signals are off. The pulse width of depressor is sum of *dep*, *posture* and *stance*. On the contrary, protractor/retractor is synchronized with *swing/stance* by *forward* signal, and extensor/flexor is synchronized with *swing/stance* by *leading* signal. (*backward* and *trailing* signals are off.)

V. CONCLUSION

An electronic CPG circuit using 2V power supply is implemented using 0.25 μ m CMOS technology. The electronic CPG is able to mimic the nervous system behavior of biological CPG. Each building block is designed for low power and

