Analog Circuit Model of Lamprey Unit Pattern Generator

Elizabeth J. Brauer[1], Ranu Jung[2], Denise Wilson[1], and James J. Abbas[2]

[1]Department of Electrical Engineering
453 Anderson Hall
University of Kentucky
Lexington, KY 40506-0046
brauer@engr.uky.edu, wilson@engr.uky.edu

[2]Center for Biomedical Engineering
Wenner-Gren Laboratory
University of Kentucky
Lexington, KY 40506-0070
jung@pop.uky.edu, abbas@pop.uky.edu

Abstract

Neural circuitry within the spinal cord of the lamprey, a primitive vertebrate, can generate self-sustained oscillations for locomotion (swimming). This pattern generator can be modeled as a chain of oscillatory unit pattern generator segments. In this paper, the design and implementation of an analog electronic circuit which mimics the behavior of such a unit pattern generator of the lamprey is presented. The circuitry mimics a neural network containing 6 neurons with simplified biophysical properties. The analog circuit is capable of generating stable oscillatory output at different frequencies with the appropriate phase relationships among the different neural outputs. This work is the first in a series of circuits designed to have possible applications in neuroscience research and in the development of artificial locomotor systems.

1. Introduction

It is now well established that motor patterns underlying various rhythmic motor activities in biological systems can be obtained from pre-determined fixed pattern generators that exhibit self-sustaining oscillations independent of external periodic forcing [1, 2]. Such central pattern generators (CPG) for locomotor activity in vertebrates have been localized to the spinal cord [2]. To better understand the role of central pattern generators in locomotor control, several experimental and computational investigations have been conducted on a primitive vertebrate, the lamprey [3-6]. Our goal is to develop analog electronic circuitry that mimics the autonomous oscillatory behavior of the swim CPG used by the lamprey. Such analog circuitry mimicking a simple vertebrate CPG has several applications. For example, it may be used as a tool by neuroscientists in their investigations of the neural basis for locomotor control in the lamprey; it may be used as the basis for a central pattern generator in an autonomous swimming robot; or it may be used as a component of the control systems for providing cyclic control of leg movement in paraplegic subjects [7].

In this paper, we describe an analog circuit inspired by the biological lamprey CPG. The circuit implements a mathematical neural network model that has previously been used in computational studies [5] of the lamprey CPG. We first give a brief description of the physiological central pattern generator for swimming in the lamprey. Then we describe the mathematical model for the CPG used in the computational studies. Next, we give the detailed implementation of the differential equation used to model a single neuron in the mathematical model, using analog circuitry. The circuitry is divided into subcircuits representing different aspects of the mathematical model. Last, we characterize the behavior of the subcircuits individually and characterize the overall oscillatory behavior of the artificial central pattern generator, and compare these behaviors to the published results from the numerical analysis of the mathematical model.

2. Lamprey

2.1. Physiological background for the Lamprey swim CPG

The lamprey is a jawless vertebrate. The advantage of using the lamprey as an animal model for understanding locomotor control is that it can be used both for studying behavioral aspects in intact animals and for probing the underlying neurophysiology in *in-vitro* preparations. Furthermore, the nervous system of the lamprey is simpler with fewer cells than that of higher vertebrates while the brain has structures similar to those of higher vertebrates.

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The lamprey spinal cord has a distributed spinal CPG for locomotion along its 100 spinal segments [8]. The CPG for swimming can be viewed as a chain of interconnected segmental unit pattern generators (uPG) where each uPG consists of: excitatory (E) interneurons with ipsilateral (same side) projections [9], lateral (L) inhibitory interneurons with ipsilateral projections, and crossed (C) inhibitory interneurons with contralateral (opposite side) projections [3]. Motoneurons receive input from the E and the C interneurons and are not considered to be part of the CPG [8]. The motoneuron output is delivered via the ventral roots and the motor nerves to cause muscle activation During swimming, muscle activity in the left and right sides of each body segment is anti-phasic. These neural classes form the architecture for the NN models we analyze in this paper.

2.2. Mathematical model of the unit Pattern Generator

The CPG for swimming in the lamprey can be modeled as a chain of uPGs where each uPG is a neural network (NN) [4, 5, 6, 8]. The NN models have the main spinal neural classes (E, L, and C), tonic input, and excitatory and inhibitory interconnections based on anatomical and functional information obtained from physiological investigations. In connectionist NN models, each neural class is represented by a single neuron with simplified membrane properties which are chosen such that oscillatory output can be obtained from each neuron with the correct phase relationships among different neurons [3, 5, 6]. The NN model analyzed by Jung et. al. [5] was used as the basis of the design of our analog circuitry. The model is a left-right symmetric network with 6 neurons. The six neurons each have a tonic synaptic input and are interconnected by inhibitory and excitatory synapses, as shown in Fig. 1. There are 12 interneuronal synapses per uPG.

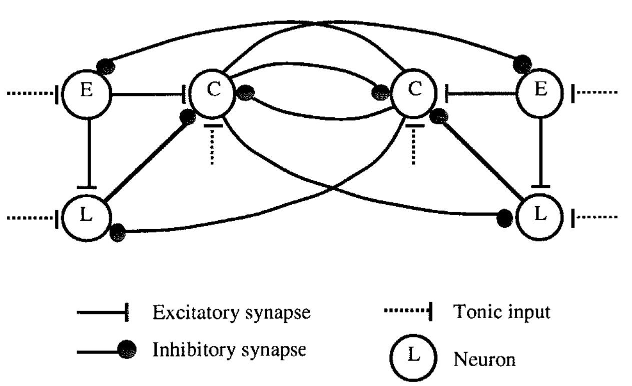


Figure 1. Lamprey uPG model with 6 neurons, 12 interneuronal synapses, and 6 tonic inputs. The uPG is left-right symmetric.

The behavior of each neuron is governed by the following differential equation describing the flow of current across the neuron membrane [5]:

$$C_M^i \frac{dv_i}{dt} = G_R^i\left(V_R^i - v_i\right) + G_T^i\left(V_T^i - v_i\right) + \sum_j G_{ji} h\left(v_j\right)\left(V_{syn}^j - v_i\right) \quad (1)$$

where v_i is the membrane voltage of neuron i, and C^i_M is its membrane capacitance, G^i_R is the maximum conductance across the membrane for currents flowing at rest, and V_R is the resting potential for neuron i. G^i_T is the maximum conductance for tonic synaptic input into the neuron i and V^i_T is the reversal potential for the tonic current input. G_{ji} is the maximal synaptic conductance for phasic synaptic input from neuron j to neuron i, and V^j_{syn} is the synaptic reversal potential for the synaptic current from neuron j to i. The neuron's output represents the firing frequency and is assumed to be related to its membrane voltage by a nonlinear function $h(v)$. Thus, the term on the left hand side corresponds to the total capacitive current through the neuron membrane at any given instant. The first term on the right-hand-side corresponds to the leak current across the membrane at rest. The second term on the right-hand-side corresponds to the current due to the tonic synaptic input, while the third term corresponds to the current across the membrane due to the synaptic connections between neurons.

Table I shows the default dimensionless values used in the analysis of the above model. With default parameter values, the network exhibits a stable oscillatory state with appropriate phase relationships amongst the oscillations of the 6 neurons [5].

The reversal potentials for the different currents dictate the range for the voltage excursion from -1 to +1. The value of V_{syn} is +1 for excitatory synapses and -1 for inhibitory synapses. The function $h(v)$, shown in Fig. 2, was approximated as a piecewise seventh order polynomial [5]

i	E	L	C
C_M^i	1.0	1.0	1.0
G_R^i	3.5	3.5	3.5
G_T^i	0.875	0.35	3.5
V_R^i	0	0	0
V_T^i	1	1	1
G_{Ei}	–	35	35
G_{Li}	–	–	35
G_{Ci}	35	35	35

Table I. Default parameter values used in numerical studies.

$$h(v) = -20v^7 + 70v^6 - 84v^5 + 35v^4 \text{ for } 0 \le v \le 1$$
$$= 0 \text{ for } v < 0 \qquad (2)$$
$$= 1 \text{ for } v > 1$$

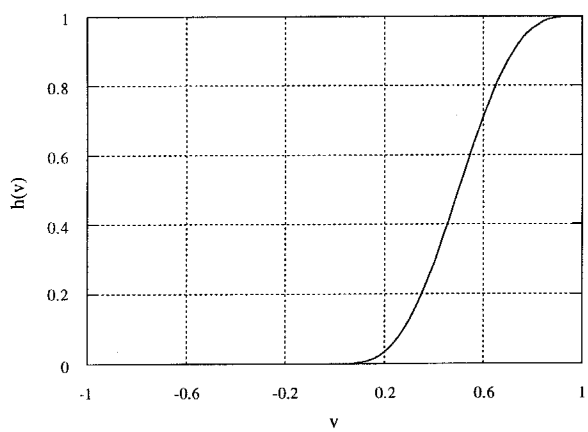


Figure 2. The function *h*(*v*) from (2).

3. uPG Analog Circuit

In this section, we present the analog circuit of our artificial lamprey uPG. We divide the circuit into neuron, tonic input, and synapse subcircuits. The synapses are modeled by the third term on the right-hand side of (1). There are three types of synapses: inhibitory, excitatory, and tonic. The inhibitory synapse removes current from the neuron i based on the voltage of neuron j while the excitatory synapse adds current to the neuron i based on the voltage of neuron j. These synapses must generate the term $G_{ji}(V_{ref} - v_i)$ and multiply that value times $h(v_j)$. The tonic synapse adds current to the neuron i.

3.1. Inhibitory Synapse

The desired inhibitory synapse current is

$$i_{syn,inh} = G_{ji}(V_{ref} - v_i) \cdot h(v_j) \qquad (3)$$

Our design begins with the four-quadrant, wide-range Gilbert multiplier [10]. This design requires only one quadrant of operation for two positive operands so we removed the circuitry for negative operands. We then add an op amp to generate the term $G_{ji}(V_R - v)$ for one of the multiplier inputs. See Fig. 3 for the inhibitory synapse schematic.

Signal V_{CS} controls the current in M_1. The op amp plus transistors M_1-M_5 generate the $G_{ji}(V_{ref} - v_i)$ current. Transistors M_6-M_7 perform the multiplication by $h(v_j)$ and transistors M_8 and M_9 mirror the output current back to neuron i. The signal V_{mid} is the reference for $h(v_j)$ and sets the midpoint of the sigmoid function. The signal V_R is the reference voltage for the op amp output.

3.2. Excitatory Synapse

The desired excitatory synapse current is

$$i_{syn,exc} = -G_{ji}(V_{ref} - v_i) \cdot h(v_j) \qquad (4)$$

The excitatory synapse is identical to the inhibitory synapse with the addition of a PMOS current mirror (M_{10} - M_{11}) at the output to invert the current signal. Thus, the excitatory synapse adds current to the neuron i. The advantage of this approach is the similarity of operation to the inhibitory synapse. See Fig. 4 for the excitatory synapse schematic.

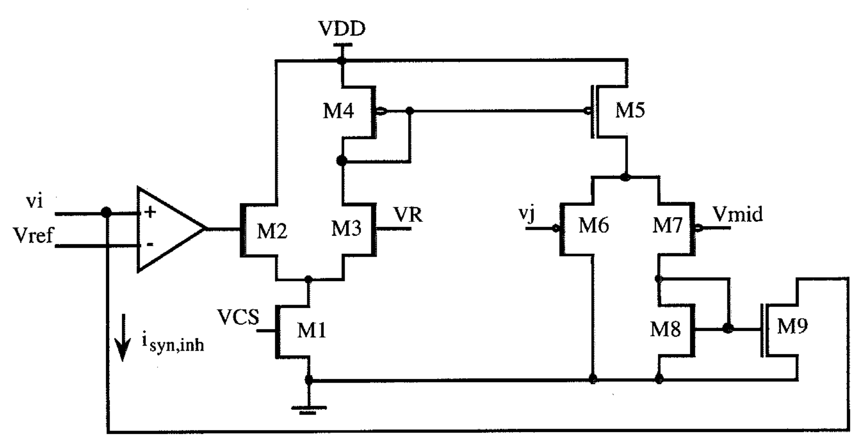


Figure 3. Inhibitory synapse. The current $i_{syn,inh}$ is removed from neuron *i*.

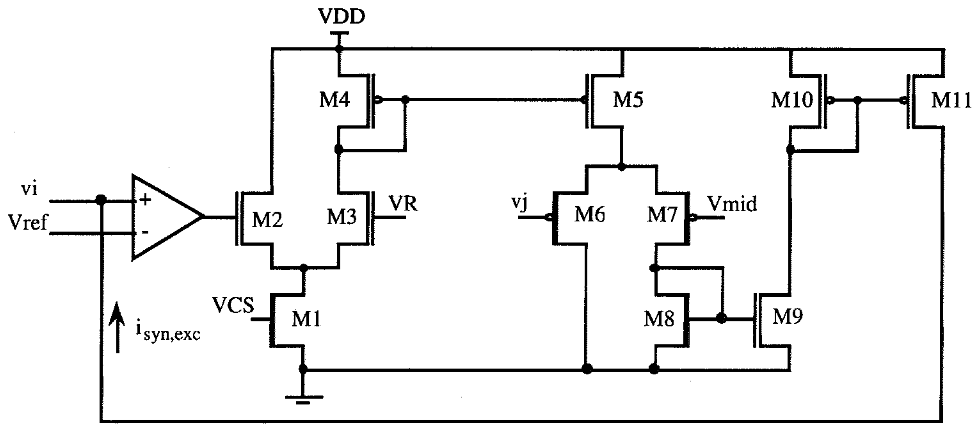


Figure 4. Excitatory synapse schematic. The current $i_{svn.exc}$ is added to neuron i.

3.3. Tonic synaptic input

The tonic synapse implements the second term on the right-hand side of (1). See Fig. 5. It is an excitatory input that injects current into the neuron.

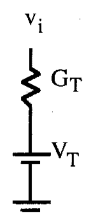


Figure 5. Tonic input for each neuron.

3.4. Neuron circuit model

The neuron circuit implements the term on the left-hand-side and the first term on the right-hand side of (1). See Fig. 6. The schematic represents the behavior of the neuron at rest.

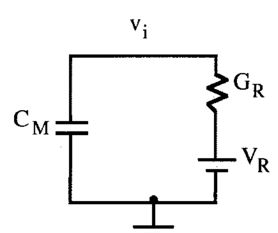


Figure 6. Neuron schematic.

3.5. uPG model

The lamprey uPG is constructed from the inhibitory synapse, excitatory synapse, tonic synapse, and neuron subcircuits described above. The subcircuits are connected as shown in Fig. 1 to implement an autonomous oscillatory circuit that mimics its biological counterpart.

4. Simulation Results

In this section, we examine the behavior of our analog circuit representing the unit Pattern Generator and compare this behavior to the default oscillatory behavior of the mathematical model [5] on which the analog circuit design is based. We first analyze and characterize the synapse subcircuit electrical behavior. We then show the electrical behavior of the complete analog unit pattern generator and demonstrate the oscillatory behavior simulated using the SPICE circuit simulation tool [11].

The default parameter values given in Table I are scaled by a factor of 1e-6. The voltage range is scaled to 1.5 to 3.5 V with a power supply voltage of 5 V. We use a reference voltage, V_{ref}, of 2.5 V. The transistors operate in the saturation region. Transistor parameters are from a 2.0 μm analog process.

4.1. Synapse

We performed two DC sweeps on the synapse subcircuits to characterize the function $h(v)$ and the value of G_{ji}. The first simulation held v_i constant and swept the v_j node from 1 to 4 V. We measured i_{syn} and scaled it by the maximum value to obtain the function $h(v_j)$ shown in Fig. 7(a). The shape of the $h(v_j)$ curve is similar to the curve in Fig. 2.

The second simulation held v_j constant and swept the v_i node from 1 to 4 V. We took the derivative of i_{syn} with respect to v_i to measure G_{ji} as a function of v_i. See the plot in Fig. 7(b). The curve shape and peak conductance value of the excitatory and inhibitory synapses are similar to each other although the curves are shifted about 500 mV which required a shift in V_{ref} for the two synapses. Thus, unlike the e numerical studies which used a constant $G_{ji,}$, in the analog implementation $G_{ji,}$ is a function of v_i.

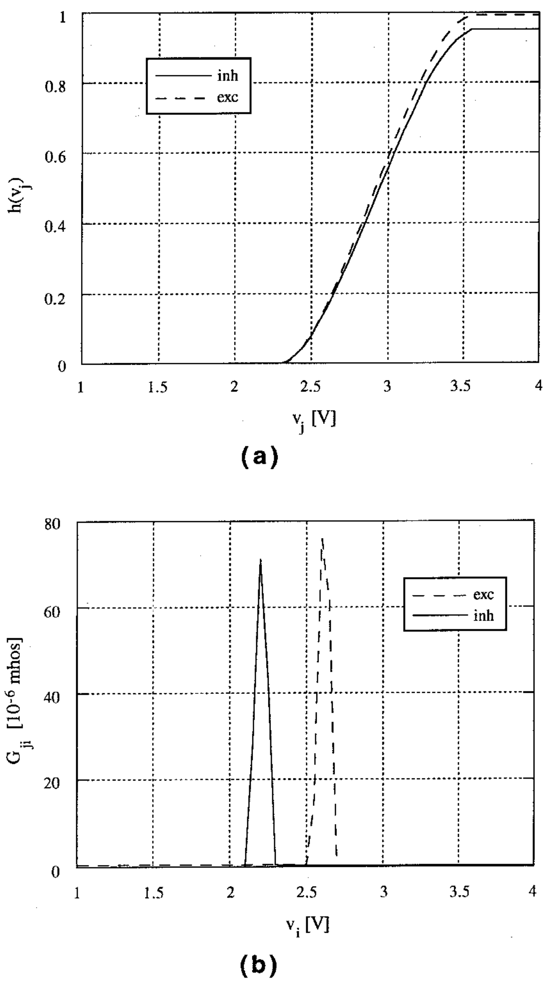


Figure 7. Synapse behavior. (a) $h(v_j)$: i_{syn} with v_i constant (b) G_{ji}: di_{syn}/dv_i with v_j constant.

4.2. uPG

We performed a transient simulation on the complete uPG segment consisting of 6 neurons with tonic inputs and 12 synapses shown in Fig. 1. The simulated behaviors are symmetric oscillations at a frequency of about 0.77 Hz. The two halves of the segment exhibited identical behavior with a phase shift of 180°. Simulation results are shown in Fig. 8. The voltage waveforms of the C, E, and L neurons on the left half are shown in Fig. 8(a). The C neuron peak leads the E and L neuron peaks. Fig. 8(b-d) show the C, E, and L neurons on the left and right sides to illustrate the symmetric behavior. In particular, the C neuron voltage swing was between 2.26 and 2.68 V, compared to the default oscillatory behavior of the mathematical model of - 0.59 to + 0.58. In the mathematical model, the node voltage was a dimensionless quantity with an average value of 0. In our circuit, the E neuron voltage swings from 2.2 to 2.48 V compared to - 0.70 to + 0.80 in the numerical study while the L neuron voltage swings from 2.20 to 2.58 V versus - 0.70 to + 0.92 in the numerical study. Generally, the swing in the electronic circuit was somewhat reduced compared to the numerical study due to the nonlinearity in the transconductance. The oscillation frequency is 0.77 Hz compared to 0.5 Hz in the numerical model. The frequency can be adjusted by changing the membrane capacitance.

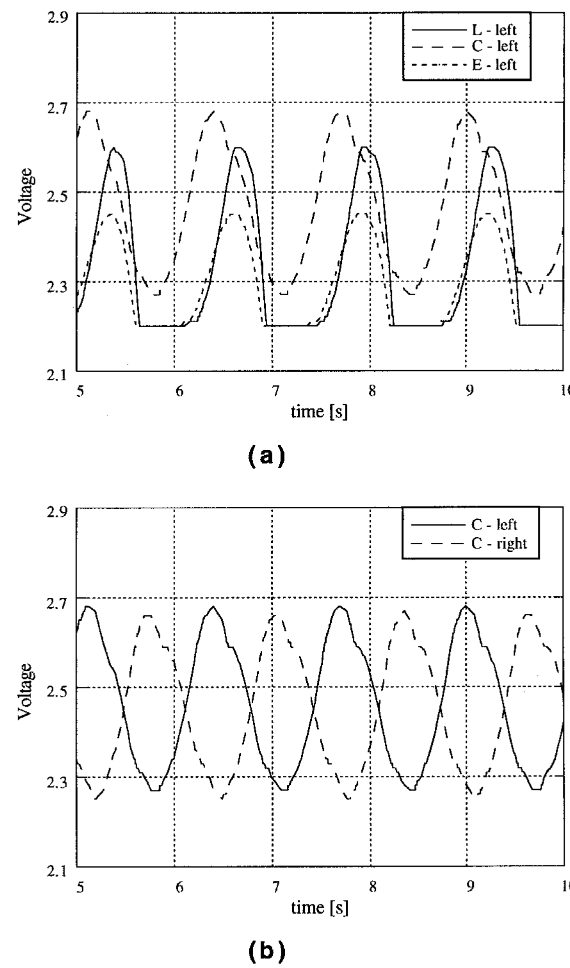
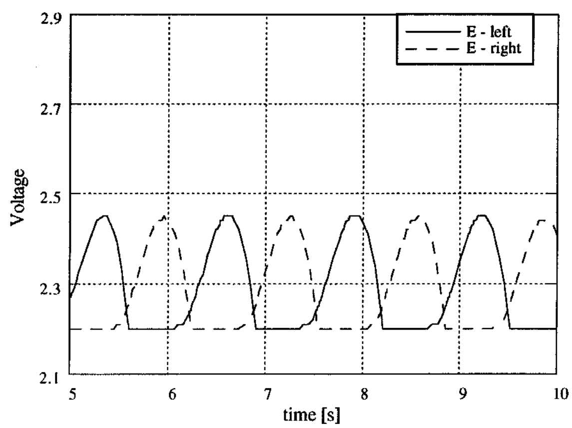
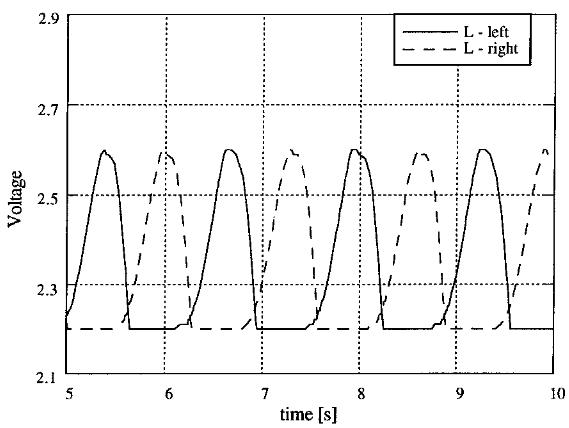


Figure 8. Simulation results of analog circuit segment showing oscillatory behavior with frequency of 0.77 Hz. (a) neuron voltages of left half segment (b) C neuron voltages, left and right side (c) E neuron voltages, left and right side (d) L neuron voltages, left and right side



(c)



(d)

Figure 8. (con't)

5. Discussion

In this work, we have designed and simulated an analog electronic circuit mimicking the unit pattern generator for locomotion in a simple vertebrate, the lamprey. The design was based on a mathematical model used to mimic the biological neural circuitry. Similar to the default oscillatory behavior of the mathematical model, our analog circuit exhibits stable symmetric oscillations. The phase relationships amongst the neuron voltage waveforms are maintained, although the relative shapes of the oscillations differ from those exhibited by the mathematical model neurons. Unlike the mathematical model, the conductance values in our circuit vary with the neuron voltage. There is neurophysiological evidence for voltage dependent conductances. In the future, we could investigate the role of this voltage dependence on the CPG output using our analog circuit. To obtain the desired oscillatory behavior, the membrane capacitance could not be reduced significantly below 1 μF. Additionally, the voltages were shifted to positive values for operation with a positive power supply. These circuit implementations employ standard CMOS technology with transistors operating above threshold. We may be able to utilize a design based on subthreshold transistor to reduce the capacitance such that integrated circuit implementation of the membrane capacitance would be feasible. Subthreshold implementation would also reduce the power usage of the circuitry.

6. References

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