Electrically Modeled Reciprocal Inhibitory Oscillator

Christoph Keseberg, Shannon Maio-Cannon, Christopher Mackenzie, Eugene Chabot,
John DiCecco, Jiang Wu, Ph.D., Ying Sun, Ph.D.
Biomedical Engineering Program, Department of Electrical and Computer Engineering
University of Rhode Island, Kingston, RI 02881-0805

Abstract—**A model of the neuronal reciprocal inhibitory oscillator was developed in this study by use of an entirely electronic platform. Neuronal Oscillators were widely studied in previous research due to their important roll as central pattern generators. Our model consisted of two electronic components, the neuron emulator for modeling the electrical activities of a neuron and the artificial synapse for mimicking a synaptic connection between two neurons. The typical bursting patterns of action potentials were demonstrated by connecting two Neuron Emulators with the Artificial Synapse. These electronic devices provided a unique hardware platform for studying reciprocal inhibitory oscillators and other neuronal networks.**

I. Introduction

The reciprocal inhibitory oscillator provides a simple pattern generator that can be found in many nervous systems of invertebrates [1], [2]. This fundamental oscillator generally consists of two neurons or two networks of interdependent neurons with mutually inhibitory synaptic connections. The firing of action potentials in the first neuron inhibits the firing of the second neuron, and vice versa. This action of synaptic inhibition oscillates back and forth between the two neurons, resulting in interleaved bursting patterns. Studies [3] showed that many motor controls in invertebrates, such as the heart of the medicinal leech, the swimming movement of the sea slug, and the stomatogastric tract in the lobster are controlled or dominated by reciprocal inhibitory systems. Mathematical models have been developed to study the behaviors of the reciprocal inhibitory oscillators [4]. Hardware based models for reciprocal inhibitory oscillators have also been studied [5]. However, no study was done in the past to construct an oscillatory model by use of discrete hardware components for the neurons and the synapses. This study was based on our previous work in developing analog neuron emulators [6], [7] and mixed-signal artificial synapses [8]. The long-term objective is to integrate the neuron emulators and the artificial synapses into biological nervous systems. The hardware platform provides a more realistic emulation of the neuronal networks in terms of their electrical properties and noise.

II. Methods

The model of the pattern generator consists of two neuron emulators and one artificial synapse. The neuron emulator is an entirely analog electronic model of a neuron. Several parameters can be adjusted during operation. These parameters are the membrane current, firing frequency, firing threshold, action potential, resting potential, and the passive resistance of the neuron. Figure 1 shows a block diagram of the neuron emulator. The device consists of several sub-circuits. The components of the action potential are generated by an oscillator when a firing threshold is reached. A summation circuit is used to sum up the resting membrane potential, the action potential, and the external stimulus. The neuron emulator has an input port and an output port with impedances (on the order of 1 MΩ) matching those in a typical experimental setting with microelectrodes. Thus, the neuron emulator provides a realistic platform not only for its electrical behavior but also for the levels of voltage, current and impedance.

The artificial synapse is a mixed-signal circuit with analog electronics for input and output and a microprocessor (PIC18F452) for implementing the transfer function of the synapse. It contains an input stage that amplifies a signal to match the input voltage range of the on-chip A/D converter of the PIC processor. The output of the PIC processor is converted to an analog signal by a D/A converter. The signal is used to drive two separate channels, one for excitation and the other for inhibition. The excitatory channel provides a scaled, non-inverting output, whereas the inhibitory channel provides an scaled, inverted output. Figure 2 shows a block diagram for the artificial synapse and how a reciprocal inhibitory oscillator can be modeled by connecting two neuron emulators via two artificial synapses.

At the preliminary project stage, only one artificial synapse was used to interface two neuron emulators. A waveform was generated with the PIC processor that mimicked the baseline variations of a reciprocal inhibitory oscillator. The excitatory output and the inhibitory output were used to drive the two neuron emulators, respectively. The bursting firing patterns of action potentials were resulted from alternating the excitatory and inhibitory outputs.

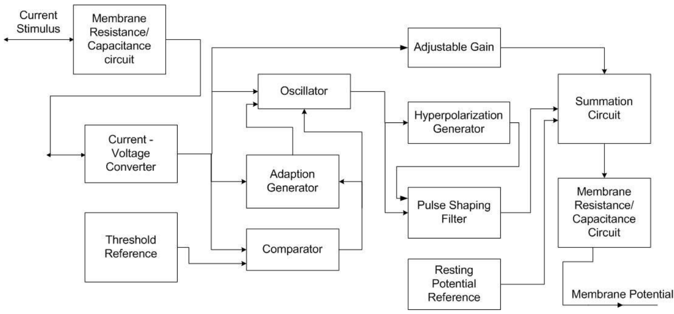

Fig. 1. Block diagram of the neuron emulator.

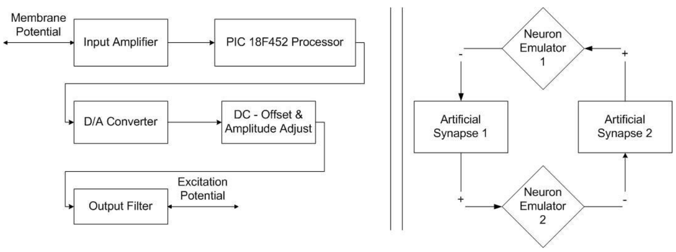

Fig. 2. Block diagrams of the artificial synapse (left) and the reciprocal inhibitory oscillator (right).

III. RESULTS

A typical set of data obtained from two neuron emulators stimulated by one artificial synapse is shown in Figure 3. The neuron emulators were capable of reciprocal oscillation. Firing frequency was higher at the beginning of the stimulation and decreased as the neuron depolarized. The firing ceased when the stimulation drove the membrane potential below the firing threshold. A brief moment of silence was observed during the switch-over phase of the two neuron emulators. This process was repeated in an oscillatory fashion.

The parameters of the neuron emulators were adjusted to represent two different types of neurons. With the artificial synapse turned off, the neuron emulators could be either silent or beating (firing periodical action potentials). In either case the artificial synapse was capable of driving the two neuron emulators into a bursting pattern typically observed in a reciprocal inhibitory oscillation system.

IV. DISCUSSION

This study has demonstrated that the electronic models of a neuron and a synapse are capable of forming a reciprocal inhibitory oscillator. The advantages of the proposed neuron emulator and artificial synapse pertain to their representation of realistic electrical properties typically observed in an experimental setting with microelectrodes. The high impedance from the microelectrode often introduce noise, which can play in important role in controlling the neuronal signals. This work paves the way for studying control mechanisms in biological nervous systems. For future work we intend to use the neurons from the pond snail (*Lymnaea stagnalis*) in conjunction with the neuron emulators and artificial synapses. By replacing one or both neuron emulators with neurons from the pond snail, it will be possible to study the mechanisms of interaction between live neurons and electronics.

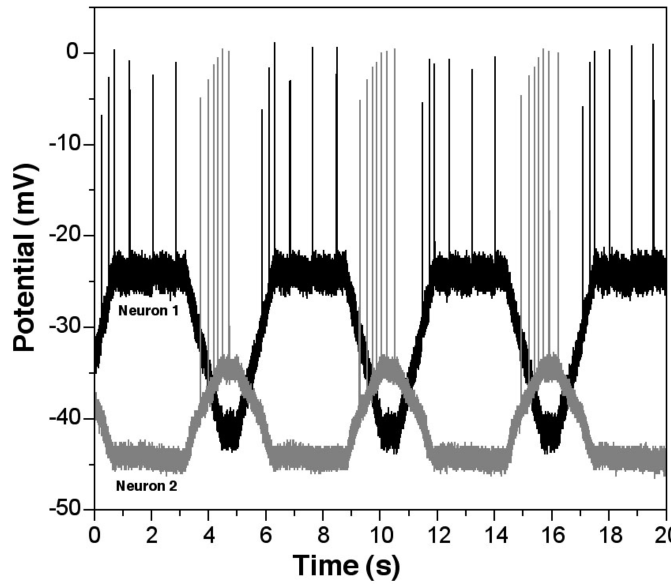

Fig. 3. Bursting patterns of action potentials in neuron emulator 1 (dark) and neuron emulator 2 (light) configured as a reciprocal inhibitory oscillator.

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