Proposal

Electronic Circuit to Mimic the Neural Network for the Saccade Controller

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Project 12
for
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Executive Summary

The proposed device is an electronic circuit that mimics the neural network controlling fast eye movements, or saccades. The device will simulate the signals produced by each neuronal population during the control of a horizontal saccade, and will allow for observing and recording. It will serve as a valuable teaching tool in the field of neural control, since the timing and synchrony of signals will be precisely demonstrated. Furthermore, the device will provide possibilities in the realm of diagnosing and properly treating brain injury. Finally, this device could be incorporated into a system for controlling the eye movements of a realistic, artificially intelligent robot.

The Hodgkin-Huxley model of the action potential will be used as a foundation to mimic the signals produced by the neurons in question. This is a proven framework, and will provide a precise empirical model that can be customized according to the properties of a given neuron. The device will be created on printed circuit boards and will be reasonably priced. This product will be versatile as well as unique, in that this neural network has not been simulated by a physical electronic circuit before.

1.0 Introduction

1.1 Background

Dr. John Enderle is a professor of biomedical engineering at the University of Connecticut. His research focuses in part on the neural network controlling fast eye movements, or saccades. These movements are performed during such activities as reading and scanning one’s environment. Though the control system behind these movements is not completely understood, several parts of the brain are known to have a role. These neuron populations make up a neural network which exhibits coordinated activities in the initiation and
control of saccades. The model of the network controlling horizontal saccades is provided in Enderle and Zhou (2010).

The research involves investigating this neural network to understand it more fully, and to build a computer model which mimics its behavior. The Hodgkin-Huxley model of the action potential is used as a framework. This is an empirical model which describes the behavior of ion channels in the cell membrane that cause potential changes.

The research is intended to culminate in the development of a way to quantitatively diagnose mild traumatic brain injuries, or concussions. Athletes and construction workers are at high risk for this kind of injury, but it can happen to anyone. The effects of multiple, untreated injuries can be additive, leading to a more serious condition. In many cases, concussions are difficult to differentiate from normal head pain and dizziness, so the injuries go untreated. The development of a way to definitively diagnose the injuries would be a great advancement.

This research also has its role in the realm of artificial intelligence. Models of the neural network controlling eye movements can drive the development of robots with realistic head and eye behavior. The possibilities of such a robot are vast.

1.2 Purpose

The device will be an electronic circuit that mimics the timing and synchrony of the neuronal populations involved in the execution of horizontal saccades. The signals from each neuron center will be observable and recordable. Such a device will be a valuable tool to enhance the understanding of this, and similar, neural networks. This device could also serve as an input to a robot which must exhibit realistic eye movements. Finally, this product would potentially be a component of a future project which could diagnose mild traumatic brain injuries. This project would culminate in a device that could observe a patient’s eye movements
and compare them to those of an ideal, uninjured model to detect the presence of an injury. This product would serve as the reference model of the neural network.

1.3 Previous Work by Others

In 1952, Alan Hodgkin and Andrew Huxley described an empirical model that explains the propagation of action potentials through the behavior of ion channels in the cell membrane. It comprises many differential equations which may be evaluated with a numerical approach, and yield a voltage-versus-time plot of an action potential. There are parameters that can be changed to yield plots that approximate action potentials of neurons with different properties, such as the firing rate and refractory period.

Much work has been done in modeling neuron behavior. More recently, in 1995, a model of the excitatory burst neuron (EBN) was created by Enderle (Enderle and Zhou, 2010). It was based on the Hodgkin-Huxley model, but with a modified sodium ion channel equation to achieve a firing rate of about 1000 Hz. The EBN model also differs from the original model in that it does not require a current impulse for a stimulus, but rather a release from inhibition. This model showed that modifying the Hodgkin-Huxley model in similar ways can be a method of modeling other neuron populations in the network.

In 2006, Dr. Lance Optican described a model of the complete network controlling saccades in Miura and Optican (2006). This work took a different approach in that it included several more membrane channels and a different, biochemically-based scheme for excitation and inhibition of neurons, as opposed to viewing these signals as current pulses. The EBN portion of the model sacrificed simplicity for physiological realism. However, the realism has not been verified by physiological experimentation. The connections between parts of the neural network differ from that proposed by Enderle and Zhou.

In 2007, Zhou had started a model of the complete saccadic neural network using SIMULINK, a simulation tool provided in the MathWorks’ MATLAB suite, and the C++
programming language to ensure a reasonably fast simulation. This model was created after Enderle's vision of the neural network, from Enderle and Zhou (2010) and will serve as the basis for the proposed device.

Malmivuo and Plonsey (1995) list several circuit models that have been built using the Hodgkin-Huxley equations as a framework. The Lewis and Roy membrane models provide a realistic and a simple solution, respectively. Other models which are of concern to this product, such as the Harmon neuron model, describe a single neuron that produces signals in response to a stimulus without the use of compartments.

1.3.1 Products

Electronic neuron models have been built onto integrated circuits. In one case, a single neuron was represented on a chip with an area of 4.5 by 5 millimeters (Malmivuo and Plonsey, 1995). With this size, high volumes may be produced, and neural networks may be created easily. Other neurons with different characteristics have been built based on existing theoretical models as well. However, these do not seem to be commercially available, and an integrated circuit provides very little customizability.

1.3.2 Patent Search Results

United States patent number 3351773 is a product that is similar to a component of the proposed device. It is held by Horst F. Wolf et al. and was filed in 1967. The model in this patent appears significantly different than the proposed device, and as such, patent infringement is not a concern.
2.0 Project Description

2.1 Objective

The primary objective of this project is to implement an electrical circuit model of the neural system for the saccade controller. The circuit network must be able to be stimulated in the region representing the superior colliculus, propagate through the necessary pathways, and ultimately yield an output at the nodes representing the medial and lateral rectus eye muscles. These must demonstrate agonist/antagonist behavior such that if the electrical signal were applied to an appropriately scaled eye, the eye would be able to successfully perform a horizontal saccade. The behavior of the neuronal populations involved in the execution of a horizontal saccade will be individually observable during the simulation.

The device will consist of a printed circuit for each neuron population enclosed in an attractive and protective case. There will be a contact at the input and output of each neuron, allowing the signals to be observed. A National Instruments LabVIEW program will be designed to acquire and record signals.

2.2 Methods

In order to develop a practical model of the neural network for the saccade controller, each type of neuron will be modeled as a single neuron. These neurons will be implemented as its own circuit, yielding a single-compartment model of each. These circuits can then be connected as per the inputs, outputs, and intermediate connections described in the original figure. Trivial portions of the system (represented by those regions shaded grey) will not be included. As a result, any inputs or outputs related to these regions will not be implemented in the design. Figure 1 provides a block diagram displaying the active neuronal regions during horizontal saccades and the signal pathways by which the action potentials are transferred between regions.
Figure 1: A Simulink block diagram representing the primary regions involved in the neural network for the saccade controller. Identical regions are shaded the same color and are denoted right or left based on anatomical conventions.
The superior colliculus circuit will require an external source in order to initiate activity in the system. External inputs are generally defined as either voltage or current inputs, but these can be altered to become a combination of these input types via resistor networks. Keeping the amplitude of this input in physiological ranges would be ideal, but if necessary, the current and voltage may be scaled to allow for the circuit to function properly. Two identical subcircuits will represent the right and left halves of the superior colliculus, allowing for independent stimulation of each section. Once the desired stimulus is achieved, the signal will pass through the superior colliculus circuit and move to the pair of circuits representing the cerebellum. Each side of the superior colliculus also transmits its output to the paramedian pontine reticular formation (PPRF) on the opposite side of the system.

Figure 2: A Simulink block diagram of the superior colliculus where only one side of the superior colliculus is receiving an initial stimulation. By only stimulating a single side, the abducens and oculomotor nuclei will define agonist/antagonist behavior for the median and lateral rectus eye muscles.

The fastigial nucleus represents the cerebellum in the neural network, which will be separated into two identical circuits representing the right and left halves in a similar manner to
the superior colliculus. The outputs are then transferred to the PPRF and inhibitory neurons of the opposite side, and form a feedback loop with the opposite side of the superior colliculus.

The PPRFs contain three neuron species pertinent to the implementation of the system: long lead burst neurons (LLBN), excitatory burst neurons (EBN), and tonic neurons. A PPRF exists for both the right and left sides of the system, resulting in a total of six subcircuits: two for each neuron species. The LLBN provides inputs for the omnipause and inhibitory neurons, while the EBNs and the tonic neurons output signals to the abducens nucleus.

The omnipause neuron region will be constructed like the fastigial nucleus and superior colliculus in that there will be two identical subcircuits. The omnipause neurons feed both the excitatory burst neurons as well as the inhibitory neurons on that side.

The inhibitory neurons exist as a pair of regions, one for each side of the neural system. These circuits will be responsible for providing inputs for both the oculomotor nucleus of the same side and the abducens nucleus of the opposite side. These neurons also form feedback loops with the PPRF of the opposite side of the system.
The abducens and oculomotor nuclei are the final regions the signal passes through before terminating at the rectus eye muscle nodes. The oculomotor nuclei are responsible for the medial rectus muscles, and the abducens nuclei control the lateral rectus muscles and also provide an output to the oculomotor nuclei. The model will not contain any circuit representation of the muscles, but rather will allow for these signals to be observed, acquired, and analyzed. By recording the signal being transmitted to muscle regions, firing rate and agonist/antagonist muscle behavior analysis can be performed.

The subcircuits used to represent each neuron population will be contained on a single circuit board per neuron, with locations available to observe the input and output of the subcircuit, effectively showing the input and output of the given neuron. The circuits themselves will act as empirical models of the neurons they represent, and as such do not necessarily contain leads to observe ion channel activity.

Once all the neuron circuits have been constructed, they will be arranged and connected within a container in order to protect the circuitry as well as provide adequate cooling and facilitate the use of the system. The individual subcircuits will be arranged as necessary to contain the complete network in a manageable space, but the overall functionality of the device and access to locations for signal analysis will remain the highest priority. If deemed reasonable to do within time and budget constraints, an overlay will also be created in order to assist users in identifying the various neuron species.

The LabVIEW program associated with this model will use National Instruments Data Acquisition (DAQ) hardware in order to transmit the terminal signals from the abducens and oculomotor nuclei into an environment where the data can be more easily manipulated. In its simplest form, the LabVIEW program will function as a modified oscilloscope, displaying the signal as is it obtained. From there, firing rates can be determined, and the muscle stimuli can be monitored to see when each muscle is inhibited or excited, defining the agonist/antagonist behavior of the muscle pairs.
3.0 Budget

At the moment, the current budget outlook remains highly fluid. The current proposal utilizes basic electrical circuit components that are readily available and low in cost. The specifics of the current design remain a topic of discussion and, as a result, the best estimate can be derived from the previous constructions of similar products. Malmivuo and Plonsey discuss three different electronic neuron models in their article, each using a similar quantity of circuit components. In order to construct any of the proposed models, the circuits must contain resistors, capacitors, transistors, and diodes. From the relative quantities in each of the models, it would cost roughly $20 in circuit elements per neuron population. This would give a total cost of $320 in parts.

The largest expenditure for the project would be purchasing the circuit board(s) to layout the design. The current estimate places this cost at approximately $300 total, and is subject to change based on layout decisions. An enclosure for the circuitry, comprised of an aluminum skeleton with acrylic walls, would cost an additional $50.

Several portions of the project will be available at no cost. Access to machines to manufacture the enclosure is available, as is the LabVIEW software that may be used to develop the signal analysis program. Input sources may also be available at no cost.

These estimates lead to an exact total of $670. The requested budget for the project is $700, allowing for some flexibility in the estimates provided. The budget is outlined in table 1.

<table>
<thead>
<tr>
<th>Part</th>
<th>Cost</th>
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<tr>
<td>Circuit Components</td>
<td>$320 – approximately $20 per neuron</td>
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<tr>
<td>Printed Circuit Boards</td>
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</tr>
<tr>
<td>Aluminum – Plastic Case</td>
<td>$50</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$670</strong></td>
</tr>
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Table 1. Budget information is shown.
4.0 Conclusion

This device will use an electronic circuit to mimic the neural network controlling horizontal fast eye movements, or saccades. The signals produced by every neuron population involved will be observable and recordable. The product will incorporate previous work on neuron models into a neural network that has not been represented in this manner before. It will provide an enhanced understanding of this neural network and will be a stepping stone for other projects, such as the control of a robot’s eye movements, and diagnosing mild traumatic brain injuries. The possibilities this device holds for the fields of artificial intelligence and neural medicine are great. Additionally, the device will use traditional analog circuit components and repeated design elements, keeping it affordable. The funding and subsequent creation of this product will be a step forward in the field of neural modeling.

References

