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Electronic Circuit to Mimic the Neural Network for the Saccade Controller

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Electronic Circuit to Mimic the Neural Network for the Saccade Controller

A Thesis Submitted to Fulfill the Requirements for Graduation as a University of Connecticut Honors Scholar

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Abstract

The proposed device is an electronic circuit that mimics the neural network controlling fast eye movements, or saccades. The device simulates the signals produced by each neuronal population during the control of a horizontal saccade and allows for observing and recording. It will serve as a valuable teaching tool in the field of neural control. Furthermore, the device will have applications 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 FitzHugh-Nagumo 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 provides a simple empirical model that can be customized according to the properties of a given neuron. Each neuron will be printed on a circuit board that can be bypassed to simulate a lesion. A current pulse will serve as an input, but in the future, this may be replaced with feedback from a robot. This product is unique in that an analog circuit model of this neural network has not been built before.

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1 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 that 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 that mimics its behavior. The Hodgkin-Huxley model of the action potential is used as a framework. This is an empirical model that 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 these 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 Project Purpose

The device is 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 are 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 that must exhibit realistic eye movements. Finally, this product would potentially be a component of a future project that diagnoses mild traumatic brain injuries. This would be 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 Done by Others

In 1952, Alan Hodgkin and Andrew Huxley described an empirical model that explains the propagation of action potentials though the behavior of ion channels in the cell membrane. It comprises many differential equations which may be evaluated with a numerical approach to yield a voltage-versus-time plot of an action potential, which can be seen in figure 2. 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 since in modeling neuron behavior. In 1961, Richard FitzHugh and J. Nagumo, et al. developed the FitzHugh-Nagumo model, a simplified version of the Hodgkin-Huxley model. It is important because it retains accuracy despite its simplicity, and it is better suited for implementation in circuitry.

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 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 demonstrated the possibilities of modifying a previous empirical neuron model to simulate any kind of neuron.

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, these choices have not been verified by physiological experimentation. The connections between parts of the neural network also differ from that proposed by Enderle and Zhou.

Recently, 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 is created after Enderle's vision of the neural network from Enderle and Zhou (2010) and will serve as the basis for the proposed device. However, the device will use the simpler FitzHugh-Nagumo model for modeling individual neurons.

Land (2011) lists several important circuit models of neurons. The model most important to the design of this device is the FitzHugh-Nagumo model, which provides a simplified model of the action potential adapted from Hodgkin and Huxley that is well suited to implementation in analog circuitry.

1.3.1 Products

Electronic neuron models have been built into 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 Patents

There are no patents for similar devices that will need to be considered when designing this product.

1.4 Report Outline

The optimal design of the device will be described in detail. Additionally, discussion of the alternative designs and their shortcomings will be included. All subunits of the device will be described, beginning with the parts of each neuron circuit model: the dendrite, axon, and synapse. A description of each neuron population and propagation of signals will follow. Finally, the construction of the device and methods of data acquisition will be addressed.

Constraints due to the environment, sustainability, and manufacturability will be discussed, as well as safety concerns, the impact of this design on society, and life-long learning from this project. A description of the budget, timeline, and individual team member contributions, and a summary will conclude the report.

2 Project Design

2.1 Background

The saccade controller consists of several connected neuron groups that fire in synchrony, based on external feedback, to cause an eye movement. The device will consist of separate printed circuit boards for each neuron, connected in the manner presented in Enderle and Zhou (2010). In all of the alternative designs that were developed, the construction of the device and the modeled neural network remained the same. The variable in the design was the axon, the action potential producing component. The three alternative designs under consideration were based on the Harmon, Roy, and FitzHugh-Nagumo models. In considering which model to use, we were concerned with complexity, cost, and accuracy. Safety, environmental, and sustainability issues do not differ between models, and are also minimal.

In 1971, Guy Roy proposed a simple model to reproduce the electrical properties of an axonal membrane. The conductance of each is represented by a simple circuit involving transistors, resistors, capacitors, and operational amplifiers. The circuits are shown in Fig. 1.

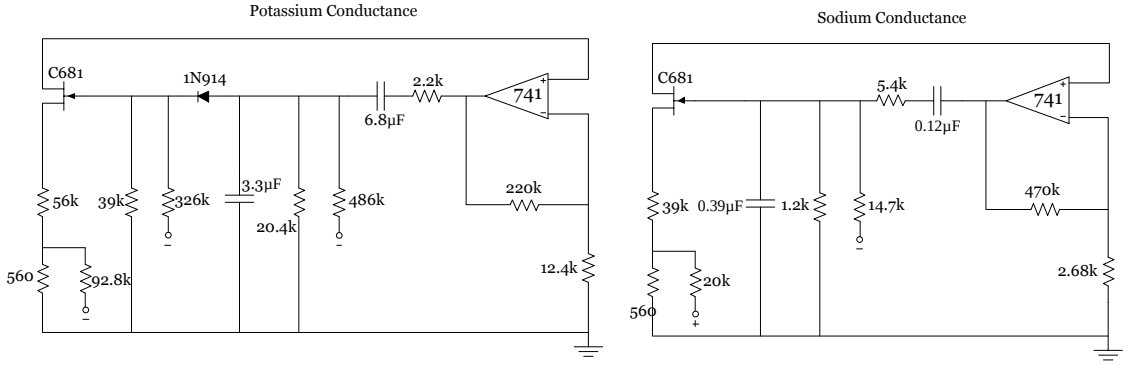

Figure 1. The potassium and sodium conductance circuits from the Roy model are shown. Supply voltages are ± 15 Volts. The output is defined across the source and drain of the transistor in each.

The field effect transistors (FETs) in this model are made to accurately mimic the time dependence of actual ion channels. According to the model circuit proposed by Hodgkin and Huxley for the capacitive properties of a patch of membrane, the conductance circuits are placed in parallel with a capacitor, and in series with a battery simulating the resting potential of each ion. This is shown in Fig. 2.

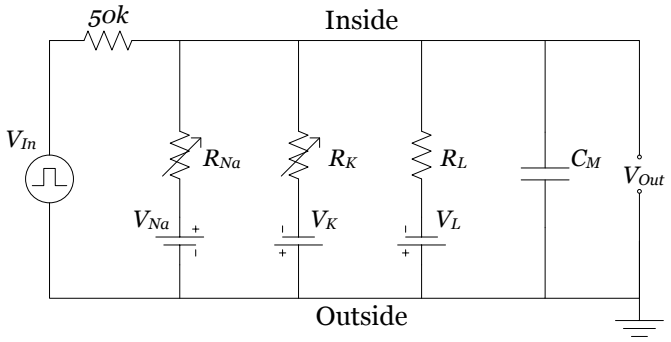

Figure 2. The assembled membrane patch circuit is shown. The conductance circuits are substituted in the place of R_{Na} and R_K. R_L is a constant resistance of 220 Ω and C_M has a value of 0.0047 μF.

The results have been compared to data from the experiments of Hodgkin and Huxley on the squid giant axon, and the circuit is shown to be a suitable analog of the membrane. A realistic looking action potential is produced when a current pulse is applied across the membrane, and voltages are biologically realistic. To be implemented in the proposed neural network, the circuit would need to be modified in order to achieve the firing characteristics given in Enderle and Zhou (2010). This circuit, however, is relatively complicated and there was no success in modifying its characteristics. This circuit was not robust in that small modifications caused total failure. A possible reason is that the circuit was designed around the C681 transistor, which is no longer in production and has no freely available documentation. Substitutes for this component do not match its characteristic perfectly, so the circuit does not work as intended. In the interest of having a simple design with less room for failure, this design was rejected.

The second alternative design makes use of the circuit proposed by L.D. Harmon in 1961. Figure 3 depicts a simplified version of the Harmon circuit model.

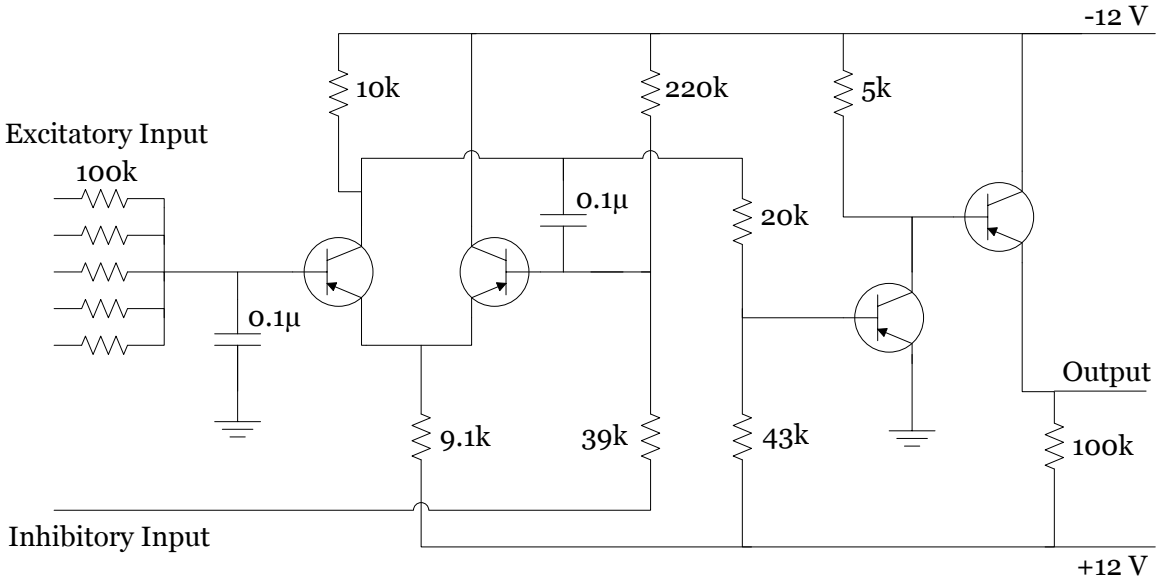

Figure 3. The preliminary Harmon neuron model circuit schematic is shown. The circuit is not limited to having only the specified number of inputs; more can be added as needed.

This circuit, using the parameters given above, yields a signal resembling that of the Hodgkin-Huxley model of the action potential. The design also allows for explicit definition of excitatory and inhibitory inputs, making it significantly easier to accommodate the multiple input signals of some neuron populations. Using the documented properties of the circuit, modifications can be made in order to develop the unique behaviors of the neuron populations being included in the neural network for the saccade controller. Though modification of this circuit is more feasible than for the Roy model, it is still not as flexible as the FitzHugh-Nagumo circuit.

Finally, the FitzHugh-Nagumo (FHN) neuron model was considered. This model is based on the work of Hodgkin and Huxley, and produces similar results with a simpler design. A circuit schematic is found in Fig. 4.

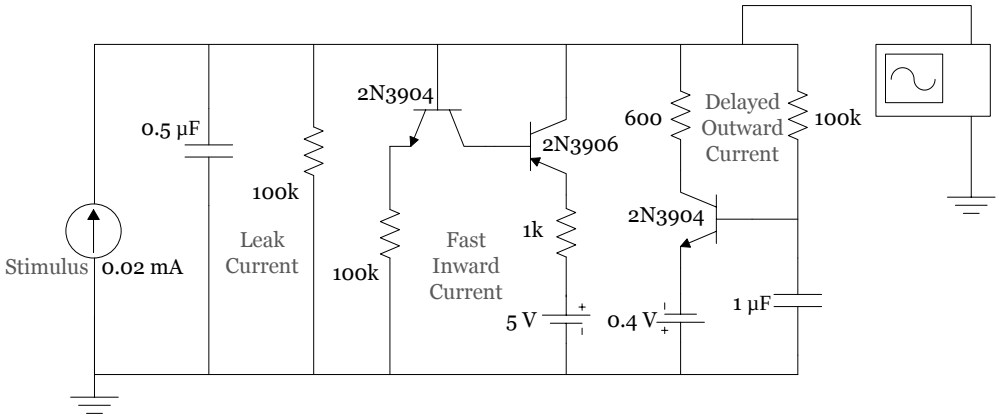

Figure 4. A basic FitzHugh-Nagumo axon model is shown.

This design provides a low cost solution, consists of few components, and requires little space for construction. One issue is that the output is larger than the true physiological signal, but this is acceptable according to the specifications, and amplifier circuits may be used to scale outputs as desired. Adjustments of the capacitors of the leak and outward current sections allow for the circuit to fire at an identical rate to any documented neural population. The documentation of this design is extensive, the model is very flexible, and matching of the specifications is feasible. In comparison to the Roy and Harmon models, this circuit is a robust and simple choice and was selected for use in the optimal design. Further discussion of the FitzHugh-Nagumo model is in the section of this report describing the axon.

The neural network, with diagrams indicating relative firing times and rates are shown in the proceeding section. Additionally, all aspects of the device will be described: the dendrite, the axon, and synapse of a neuron, the different neuron populations in the neural network, the method of observing and recording output, and the physical structure of the device. Analyses of circuits performed with the National Instruments Multisim circuit simulation suite are included.

2.2 Optimal Design

2.2.1 Objective

The objective of this final design is to provide a cost-effective system that is capable of mimicking the physiological properties of the horizontal saccade controller of the brain. The complete system consists of a series of subsystems designed to imitate the behavior of actual neuronal populations in the horizontal saccade controller (see Fig. 5).

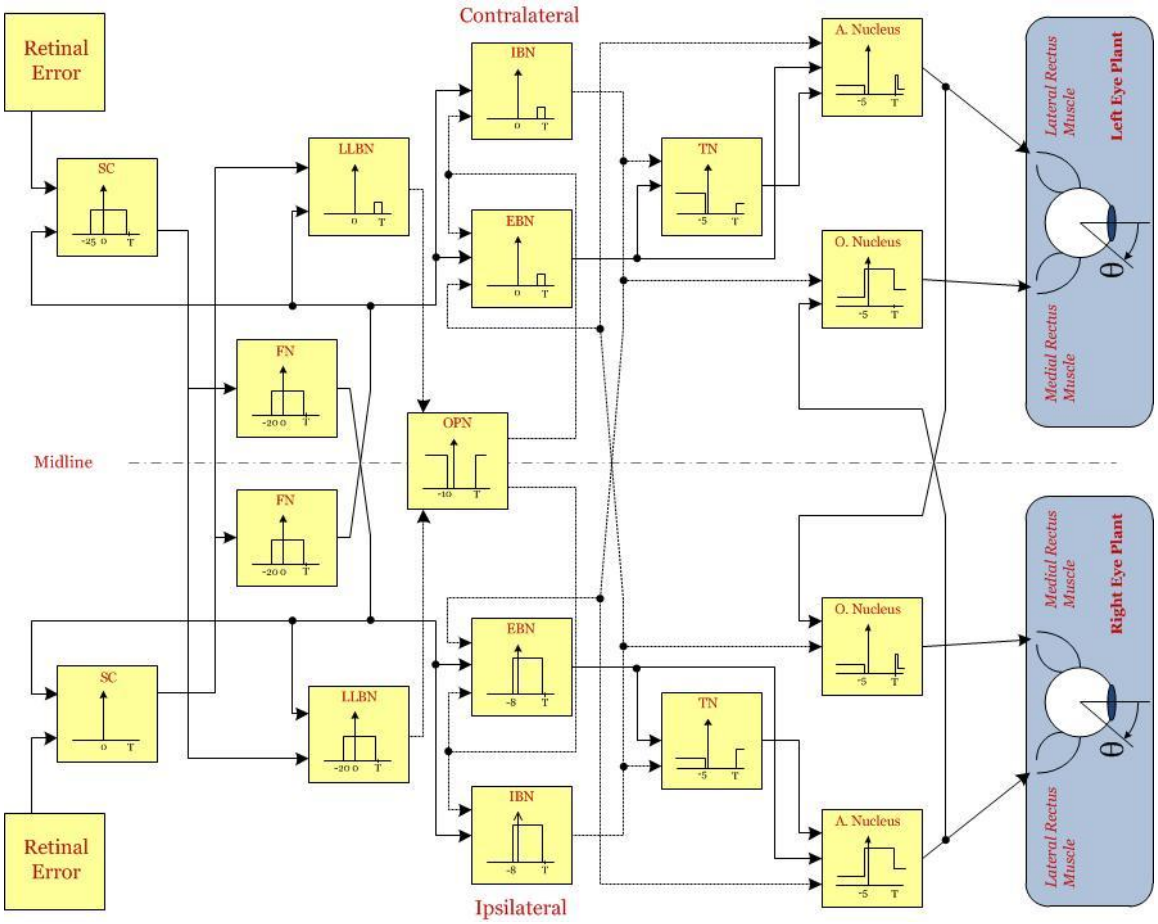

Figure 5. The neural network for the horizontal saccade generation is shown. Times zero and T represent saccade initiation and termination, respectively.

Each of these subsystems is further divided into neural components that function as analogues for different neural structures. In Fig. 6, a diagram of these components and their interrelations can be found.

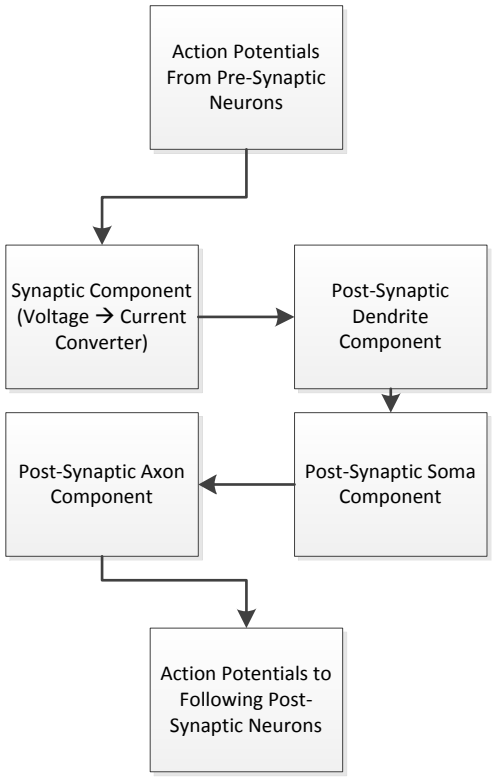

Figure 6. Flow chart describing the propagation and interpretation of signals through the individual neuron populations.

Following this general pattern, each neuron can be modified from a series of "stock" components developed to provide readily available machinery that, as a whole, can provide acceptable descriptions of all neural populations in the horizontal saccade system. One of these components is the synapse, which is responsible for passing the output of a pre-synaptic neuron to the input mechanisms of the following post-synaptic neuron. Here, the voltage action potential signal is converted to a current pulse which can be used to excite the following neuron in a specific manner. This current pulse passes through the dendritic compartments which function as a filter to provide desired input-output relationships. Next, this signal passes to the neural cell soma, which prevents current backflow and primes the axon for excitation. Finally, this signal

reaches the post-synaptic axon, which restarts the entire cycle by generating signature action potential firing patterns dependent on the type of neural population.

2.2.2 Generalized Neuron Circuit

Dendrite

The dendrite is the first component of the neuron circuit that the input signal interacts with. Its implementation uses a compartmental modeling approach, which is a discrete approximation of the equations used in dendrite cable theory. Unlike the axon and synapse, the dendrite is designed to be a passive subcircuit. The circuit is also iterative, with the signal passing through multiple, similar, if not identical compartments. Fig. 7 describes the format of an unbranched dendrite using generic component values.

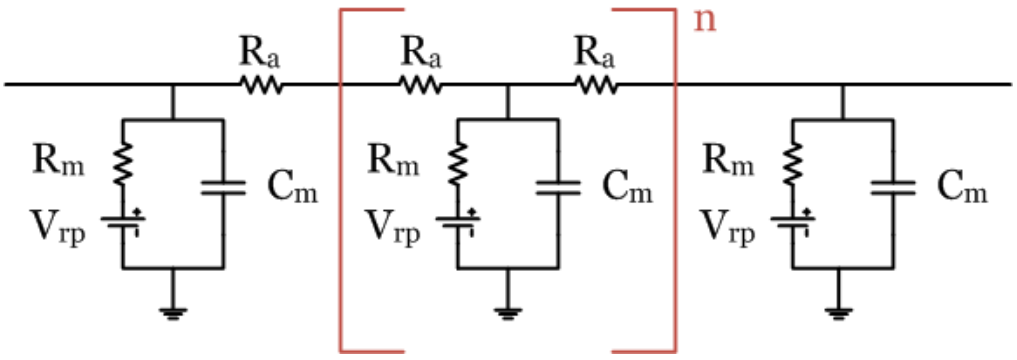

Figure 7. A generalized, unbranched dendrite schematic is shown. The intermediate compartment design (bracketed in red) may be repeated in order to extend the length of the dendrite. Note that the only differences between the three circuits shown are the number of times the axial resistance (R_a) is accounted for in the design.

The dendrite is composed of three types of compartments: an initial segment, intermediate segment(s), and a soma. The initial compartment only has one axial resistor, the intermediate compartments have two, and the soma is designed such that it has no axial resistance.

The dendrite is designed using only four components iterated as is needed to create the desired compartment. The axial resistance (R_a) represents the resistance of the

dendrite in regards to its behavior as a wire. The membrane resistance (R_m) and membrane capacitance (C_m) describe the membranes behavior as an RC circuit and allow for the manipulation of the membrane time constant (τ_m), which in turn controls the responsiveness of the neuron as a whole (see Equation 1). The fourth component is a battery representing the resting membrane potential (V_{rp}), which is included in order to add to the physiological realism of the model.

$$t_m = R_m C_m = R_M C_M \quad (1)$$

Equation 1: Determining the membrane time constant of a given dendrite compartment.

The model used for the neuron circuits in this device have opted for an empirical model in order to decrease PCB size and improve cost effectiveness. However, it is possible to account for the length and diameter of the dendrite compartment in order to further increase the physiological realism. This can be done by calculating the circuit element values using Equations 2-4.

$$R_a = \frac{4lR_A}{\rho d^2} \quad (2)$$

$$R_m = \frac{R_M}{\rho dl} \quad (3)$$

$$C_m = \rho dl C_M \quad (4)$$

Equations 2-4: Determining the axial resistance, membrane resistance, and membrane capacitance, respectively, using the compartment length, diameter, and specific component values.

The increased physiological realism is beneficial, but no significant behavior change is seen provided that the components used in the actual circuit maintain the membrane time constant.

As previously stated, the compartmental modeling approach for the design of the dendrite is based on cable theory, which describes the electrical behavior of the dendrite using partial differential equations. However, as this cannot be feasibly modeled using analog circuitry, the compartmental approach is the only option. The

model more closely resembles the cable equations as more compartments are added. For this design, ten dendrite compartments were used along with a single soma compartment (n=9 based on Fig. 7).

Another major component of the dendrite subsystem is the current stop. As per the client's request, a subcircuit needed to be placed between the dendrite and the axon in order to provide adequate signal isolation. Due to the empirical nature of the axon model, this also required that the signal leaving the final dendrite compartment be amplified to such a point that an adequate current source could be provided. This was done by recalibrating the dendrite signal to a resting potential of 0 mV, amplifying it, and then passing it through a diode to the axon circuit (see Fig. 8).

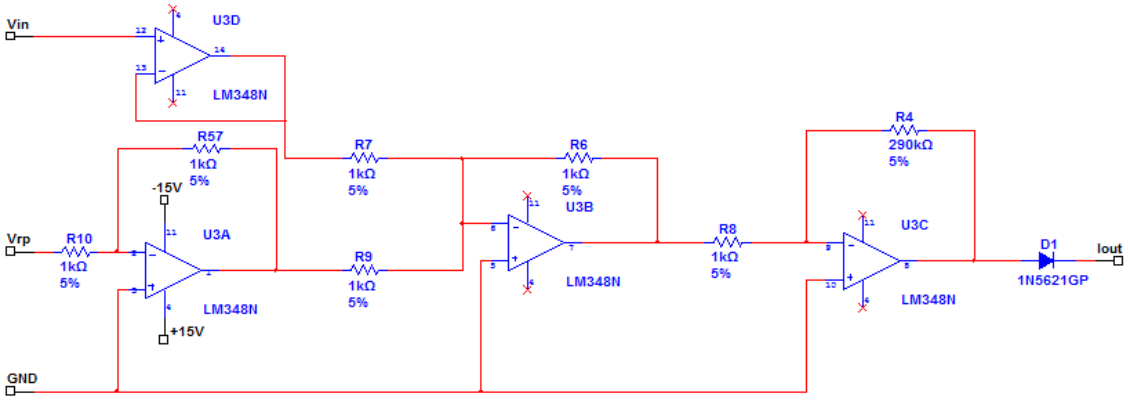

Figure 8. The schematic for the current stop subcircuit is shown. Resistor values may be changed in order to allow for autonomous firing and for manipulating the reaction time of the neuron as a whole.

The current stop also allowed for the creation of autonomously firing neurons. By increasing R57 (based on the Fig. 8 schematic), the axon could be kept above threshold when the dendrite was at rest, allowing for continual production of action potentials. This could then be interrupted through the use of an inhibitory input. Overall, the current stop allowed for increased customization of the neuron's behavior through simple resistor value alterations.

Axon

The axon is second component of the neural unit and is the site of action potential generation and propagation. The pre-synaptic input, which crosses the synapse and is conducted by the post-synaptic dendrites, finally reaches the neuron axon where a resulting neural action is produced. In the context of our final design, several basic subcircuit designs can be repeated, with modification, to mimic the desired behavior of each neuron population. The design relies on the FitzHugh-Nagumo circuit model of a neuron, which is an adaptation of the empirically-defined Hodgkin-Huxley model. This analog design provides a robust, cost-effective solution for the range of behaviors exhibited by each neuron population of interest.

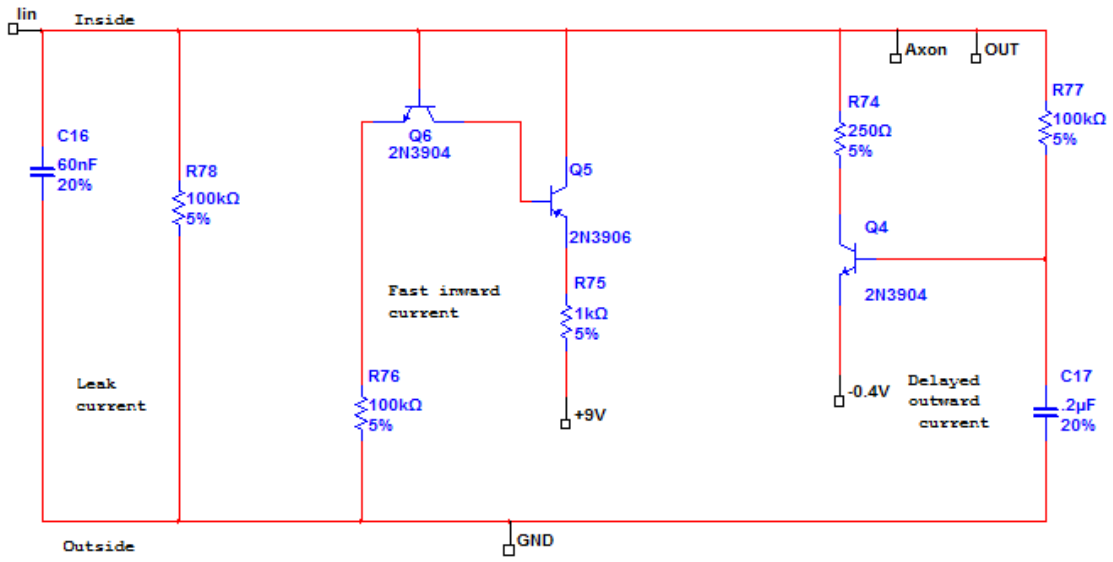

Figure 9. The schematic for the modified FitzHugh-Nagumo axon is shown.

While the FitzHugh-Nagumo model provides a simplistic means for simulating neural axon behavior, its implementation comes by the sacrifice of realism. The current FHN model rests at 0 V and generates action potentials of 5 V in amplitude. These parameters differ greatly from physiological analogs, which typically rest at -60 mV with action potentials of approximately 100 mV in amplitude. As a result, a post-processing unit was implemented to correct output voltages to physiological levels by scaling and

offset mechanisms. A circuit schematic of the axon post-processing unit can be seen below in Figure 10.

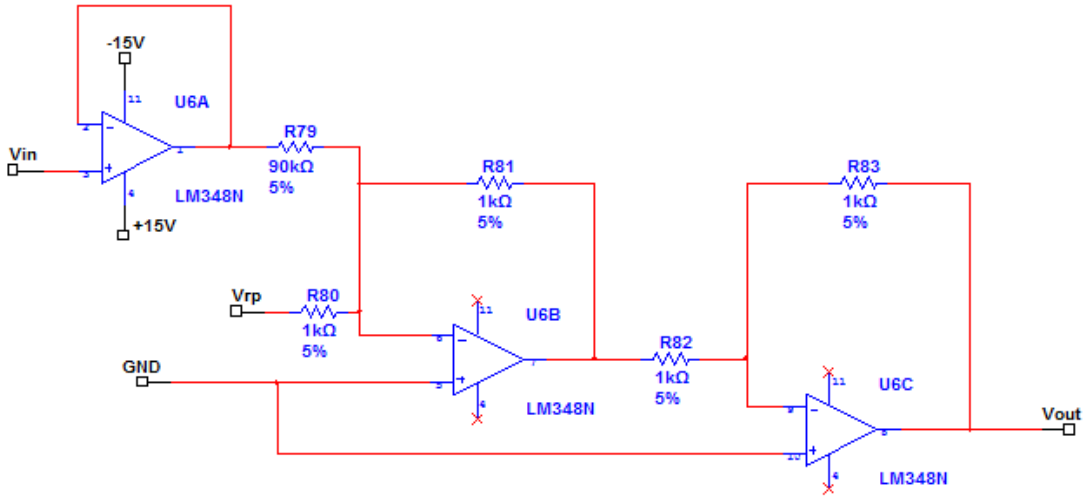

Figure 10. The general schematic for the axon's post-processing unit is shown.

The output signal of the FHN neuron, alongside the post-processed output signal is shown below if Figure 11. In this example, the raw axon output signal is displayed in green, while the post-processed output signal is displayed in red. It is also important to note that the raw signal is plotted on a vertical axis of 5 V per division, while the post-processed signal is plotted on a vertical axis of 50 mV per division.

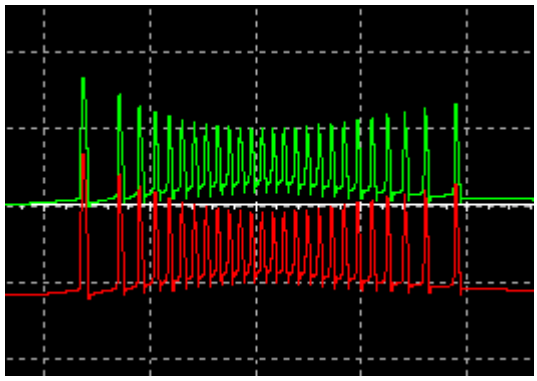

Figure 11. Two axon outputs are show. The green signal is the axon without any post processing, and has a peak-to-peak voltage of approximately 8 V. The post-processed signal is shown in red, with a peak-to-peak voltage of approximately 100 mV.

While this "stock" model functions properly for autonomously firing 1000 Hz neurons, some additional work is necessary to describe the desired physiologically

accurate neuronal populations. To encompass all of the desired neural behaviors of each of these populations, several modifications are necessary which directly impact the firing rate. These modifications include modifications to the axon itself, as well as modifications to the current stop of the dendrite. By manipulating the current stop of the dendrite, specifically R4 and R57 of Fig. 8, an artificial increase in resting potential can be achieved. Changes in the axon typically revolve around the C16 capacitor of Fig. 9. Changes in the capacitance of this value allow some manipulation of firing rate. Together, these changes allow for a variable firing rate between 200 – 1300 Hz, depending on the input current pulse.

In the end, these modifications allow us to easily generate axon components that are capable of mimicking all the desired behaviors of each neural population. Table 1 contains the pertinent frequency data that describes each of the neuron populations being modeled.

Neural Site	Onset Before Saccade	Peak Firing Rate	Approximate End Time
Abducens Nucleus	5 ms	400-800 Hz	5 ms before saccade ends
Contralateral Superior Colliculus (SC)	20-25 ms	800-1000 Hz	At saccade termination
Ipsilateral Excitatory Burst Neurons (EBN)	6-8 ms	600-800 Hz	10 ms before saccade ends
Ipsilateral Inhibitory Burst Neurons (IBN)	6-8 ms	600-800 Hz	10 ms before saccade ends
Ipsilateral Long-Lead Burst Neurons (LLBN)	20 ms	800-1000 Hz	At saccade termination
Omnipause Neurons (OPN)	6-8 ms	150-200 Hz (before and after)	At saccade termination

Table 1: The neuron populations being modeled and their associated timings and frequencies.

Synapse

The synapse is the chemical or electrical connection between two neurons. In the pre-synaptic terminal, which is the part of the neuron following the axon, action potentials cause the release of neurotransmitter into the synaptic cleft. Depending on

the type of neurotransmitter, certain ion channels in the dendrite open to cause an excitatory or inhibitory post-synaptic potential. In a circuit model, this may be modeled as a positive or negative current that is injected into the next neuron's dendrite. The pre-synaptic terminal is modeled with two circuits: the comparator and the inverting amplifier, both shown in Fig. 12. Behavior in the synaptic cleft is modeled with the inverting summing amplifier and the bilateral current source.

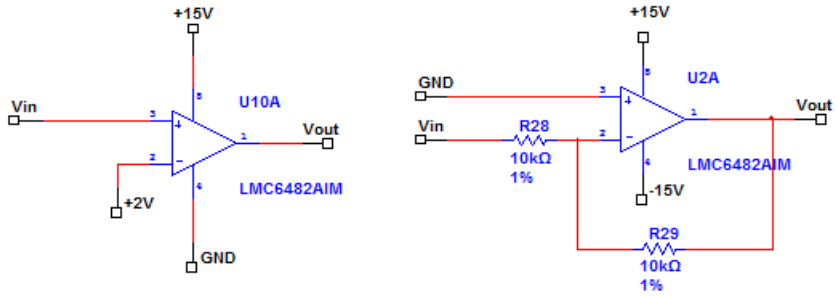

Figure 12. The comparator and inverting amplifier circuits, both using the LMC6482AIM high-precision, rail-to-rail operational amplifier, is shown.

The left part of the circuit in Fig. 12 is a comparator, and the reference voltage is set to 2 Volts because it is a point that the action potentials reliably cross each time and will provide a reliable count. Positive, square voltage pulses are produced with each action potential. This models the pulsatile release of neurotransmitter as each action potential arrives at the pre-synaptic terminal. If the synapse is inhibitory, negative voltage pulses are created by adding the inverting amplifier after the comparator. This is demonstrated in Fig. 13.

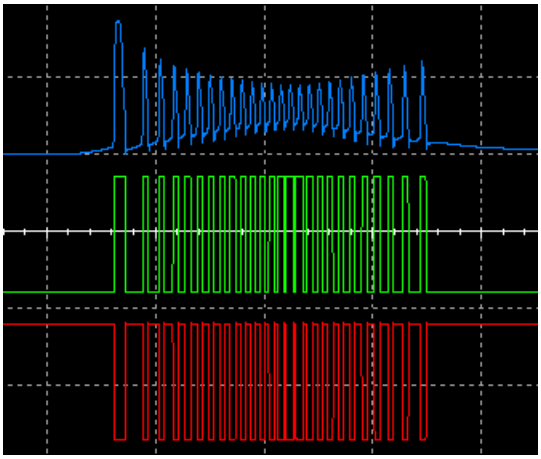

Figure 13. This generic neuron is generating action potentials, which may be seen on the top row. The second row shows positive, excitatory voltage pulses from 0 to 15 V generated by the comparator. The bottom row shows negative, inhibitory voltage pulses from 0 to -15V generated by the comparator and inverter.

The summing amplifier and bilateral current source is shown in Fig. 14.

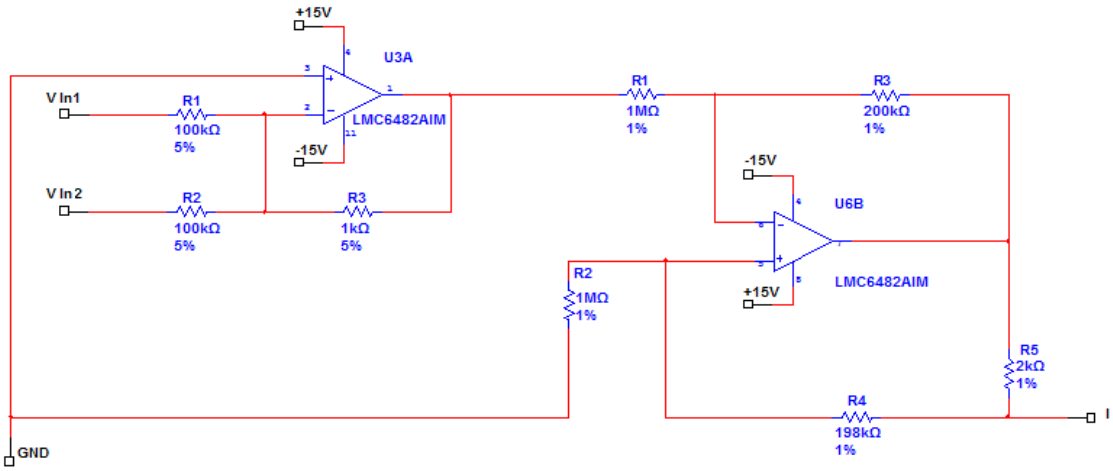

Figure 14. The inverting summing amplifier, left, and bilateral current source, right, are shown.

In the case of a neuron receiving input from multiple other neurons, the voltage pulses are added together with a summing amplifier. The relative strength of each input and the overall strength may be adjusted by setting the gain of the amplifier according to Equation 5.

$$V_{out} = -R_3\left(\frac{V_{in1}}{R_1} + \frac{V_{in2}}{R_2}\right)$$

Equation 5. The relationship between output and input voltage for the summing amplifier.

The current leaving the bilateral current source may also be customized to provide an appropriate stimulation of about 10 μA when active. Current is related to the voltage at the input by the relationship in Equation 3.

$$I_{out} = -\frac{R_3 V_{in}}{R_1 R_5}$$

Equation 6. Determining the output current of the bilateral current source. Note that for this equation, $R_3 \approx R_4 + R_5$ and $R_1 = R_2$.

The current will be injected into the dendrite of the post-synaptic neuron and will either stimulate or inhibit it, depending if it is positive or negative.

Central Board

The neuron circuits, on their own, are only capable of producing action potentials in response to a given stimulus; they lack any sort of networking capabilities. The neuron boards also require access to multiple DC voltage supplies in order to function properly. In order to meet all of these needs, a central board was developed in order to allow for proper networking, power supply, and expansion via future work.

The central board is designed to be powered via a standard wall outlet (120 Vrms, 60 Hz) and converts this AC source into three major DC sources: 15 V, -15V, and 5 V. These are then manipulated as need to obtain the other DC voltage sources required by the neurons. This is then networked with the input and output signals for the various neurons so that everything is sent to the appropriate location. The component that allows for this networking to occur is ribbon cable. Using a 24-pin connector for each neuron population, all the necessary signals may be sent, retrieved, and manipulated as deemed necessary by the network layout. Figure 15 shows this arrangement, using the long-least burst neuron (LLBN) as an example.

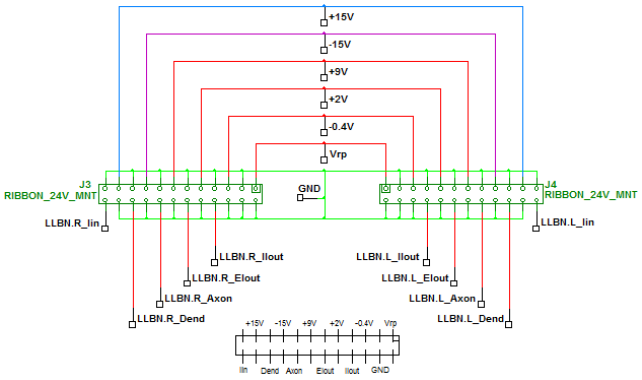

Figure 15. The connection scheme for the ribbon cable connectors that attach the neuron circuits to the central board are shown. The individual pin labels are found on the diagram at the bottom of the figure.

In order to create the necessary input for each neuron population, the excitatory and inhibitory signals must be combined and then passed on to the appropriate neuron with any sort of backflow. This was achieved by moving the bilateral current source, once located in the synapse subcircuit on the neuron boards, to a networking portion of the central board. This left the neurons outputting a voltage signal that could be taken and combined with the other signals using a summing amplifier. The resulting signal then entered the bilateral current source, which developed a proper signal to send to the dendrite of the corresponding neuron (see Fig. 16).

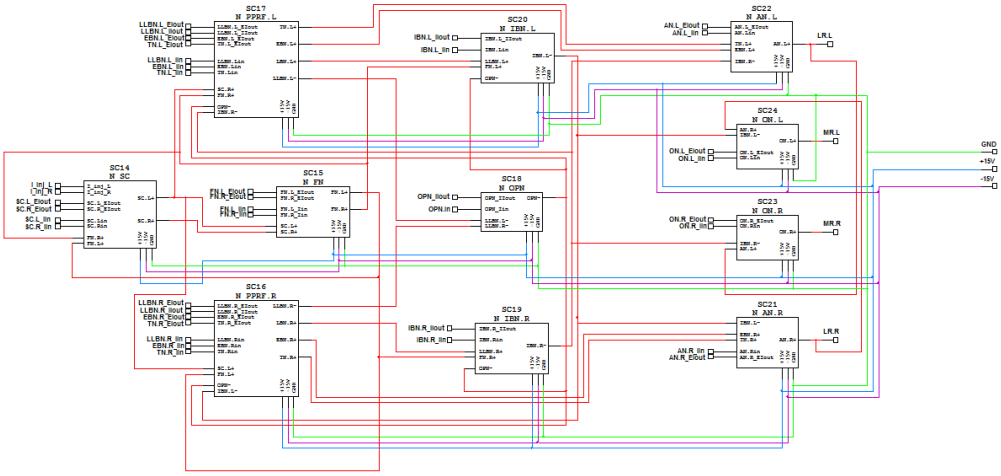

Figure 16. The schematic for the networking portion of the central board is shown. This allows for the excitatory and inhibitory signals of the various neuron populations to travel to their intended locations to develop a proper current source.

Ribbon cable connectors were also employed for the signal observation component of the central board. This allows for either direct measurement via oscilloscope probe or a wire connected to NI DAQ hardware, or connection to a separate board that can have another observation method implemented. This allows for further expansion to the device by opening the possibility for Bluetooth connectivity. This could allow for the user to rapidly select which signals that they wish to view, and with further modification to the central board, allow for lesioning of certain neuron populations in order to simulate various form of traumatic brain injury.

2.2.3 Superior Colliculus

The superior colliculus is a neuron populatin that receives information from other portions of the brain about how far the eye should move. In general, it outputs a signal with a length proportional to the magnitude of the desired movement and initiates the action of the rest of the neurons. This is a simplified description of the population adequate for the purposes of this model; a more detailed view is provided in Enderle and Zhou (2010).

In the device's current state, a user-initiated current pulse begins the signal cascade and serves as the superior colliculus. However, this part of the device can be customized in the future to receive input from the eye movement robot. A possible general procedure is outlined below.

Information from the robot's cameras will be processed and the distance and direction the eyes must move will be supplied by the robot. The appropriate half of the superior colliculus will fire for a period of time related to this information. Neural output from the Abducens and Oculomotor nuclei will be interpreted by the robot and eye movement will take place. The cameras will continuously monitor the LED array before it. When a new LED is lit, the robot will shift its gaze to it.

Fig. 17 outlines the procedure for mimicking the superior colliculus.

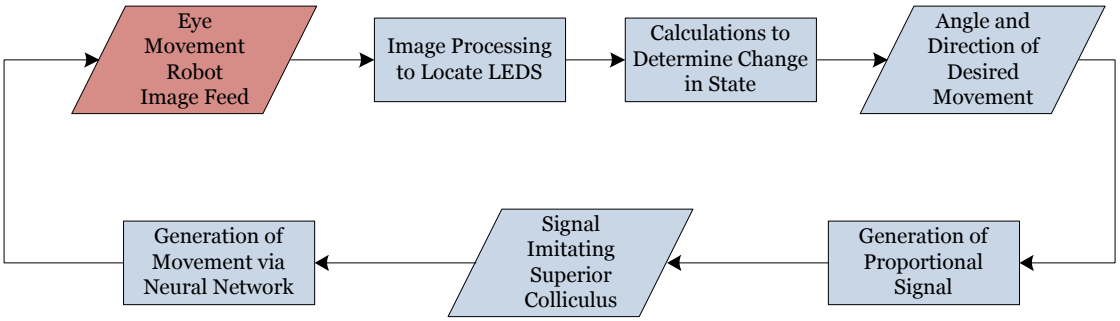

Figure 17. A flowchart illustrating the operation of the fully realized superior colliculus is shown. The process is initiated with information provided by the robot, indicated in red.

2.2.4 Cerebellum

At the request of the client, the cerebellum elements of the neural network, notably the fastigial nucleus, will not be included in the circuit design. The superior colliculus will function such that it will fulfill the role of the input to the neural populations that would otherwise be connected to the fastigial nucleus. This substitution will be referred to when describing the inputs and outputs of the other neuron populations.

2.2.5 Excitatory Burst Neuron

The excitatory burst neuron, located in the paramedian pontine reticular formation, serves as one of the major excitatory inputs for the saccade controller. Firing at a rate of approximately 1000 Hz, this neuron fires spontaneously upon release from inhibition. The primary inputs for this neuron population, based on the model being simulated, are the excitatory input of the superior colliculus and the inhibitory inputs of the inhibitory burst and omnipause neurons. The circuit design for this neuron employs the same dendritic, axonal and synaptic components as the non-autonomous populations. With modification to the current stop of the dendrite, as was done to adjust the axon firing rate, artificial increase of resting potential can be achieved. With an increase of proper magnitude, the axon can be forced to fire autonomously at a preset

firing rate. When properly inhibited by the inhibitory burst and omnipause neurons, this artificial increase in resting potential is forced back towards inadequate levels. When these signals are terminated upon saccade initiation, the excitatory burst neuron is released from inhibition and fires spontaneously. Other than these relatively minor changes, no additional modification is necessary to create a neural unit that functions as desired. The synapses of the excitatory burst neuron will provide excitatory inputs to the tonic neurons and the abducens nucleus, and inhibit the inhibitory burst neuron during firing.

2.2.6 Long-Lead Burst Neuron

The long-lead burst neuron shares a location and similar function to the excitatory burst neuron, but is instead responsible for controlling the behavior of the omnipause and inhibitory burst neurons. This neuron population, in the proposed model, will be controlled exclusively by the superior colliculus. The long lead burst neuron circuit represents the most elementary of any population and is simply a dendrite, axon and synapse of no remarkable change. In fact, the long lead burst neuron was used as the starting point from which all other neural populations were designed. The output of the long lead burst neuron forms an excitatory synapse with the inhibitory burst neuron and an inhibitory synapse with the omnipause neuron.

2.2.7 Omnipause Neuron

The omnipause neuron serves as an inhibitory signal to keep the neural network at rest in between saccades. It receives exclusively inhibitory inputs from both of the long lead burst neuron groups (one on either side of the system). This neuron population also provides only inhibitory outputs, one going to each of the inhibitory burst neuron groups. The omnipause neuron will be represented electronically by a modification of the FHN axon and dendritic current stop. Similar to the excitatory burst neuron, autonomous function arises from modifications of the dendritic current stop. These

modifications result in an artificial increase in resting potential, which is later corrected by the axon post-processing unit. From here, the appropriate firing rate is acquired by further modification.

2.2.8 Tonic Neuron

The tonic neurons are responsible for fixing the rectus eye muscles in place once the saccade completes. This neuron population receives excitatory and inhibitory inputs from the excitatory and inhibitory burst neurons, respectively. During saccades, the tonic neuron remains inactivated until saccade termination. At this point, the tonic neuron generates a signal of variable frequency, depending on how far the eye has moved from its initial position. Uniquely, the tonic neuron functions as an integrator, generating an action potential train of frequency proportional to the integrated excitatory burst signal. As a result of its unique behavior, the design of the tonic neuron required a number of specific modifications. An integrator was built using a basic op amp configuration, along with several supplementary accessory circuits that are necessary for achieving the desired behavior. These accessory circuits allow for the correction of non-zero resting potentials, evaluation of the compound integrals of both contralateral and ipsilateral excitatory burst neuron signals and subsequent signal integration. A schematic of the integrator accessory circuit of the tonic neuron can be found in Figure 18.

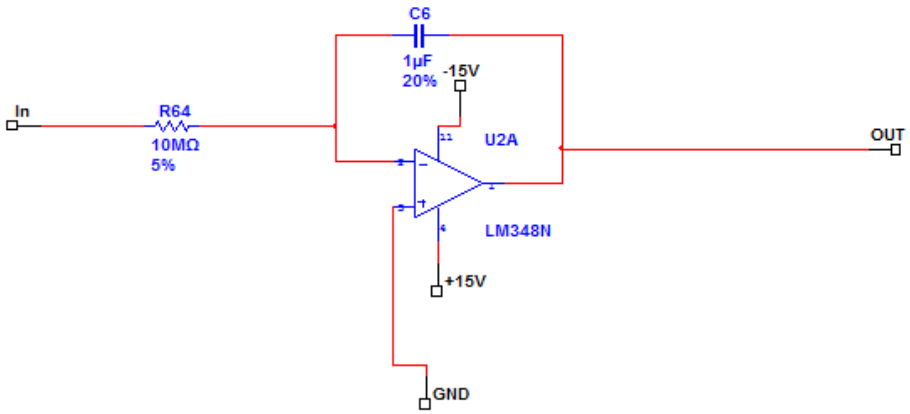

Figure 18. The tonic neuron's integrator subcircuit is shown.

Following these preliminary accessory circuits, the actual neural unit is modeled from a modified omnipause neuron. This neuron fires autonomously at a basal rate, similar to the omnipause neuron, but can be adjusted by integration of excitatory burst signals. This output signal is then translated to the abducens nuclei and oculomotor nuclei as an input.

2.2.9 Inhibitory Burst Neuron

The inhibitory burst neuron controls the firing of the excitatory burst neuron as well as the tonic neuron, both of which are on the opposite side of the system to the corresponding inhibitory burst neuron. This neuron population receives excitatory input, in this model, from the superior colliculus and the long-lead burst neuron, and an inhibitory input from the omnipause neuron. The inhibitory burst neuron will be implemented almost identically to the long lead burst neuron, but will function as an inhibitory input, rather than excitatory, to the following post-synaptic neuron.

2.2.10 Abducens Nucleus

The abducens nucleus functions as the input for the lateral rectus eye muscles, while also influencing the behavior of the oculomotor nucleus of the opposite side. The abducens nucleus is excited by the excitatory burst neuron during the saccade and by the tonic neuron once the saccade has completed. The inhibitory burst neuron inhibits this portion of the system outside of the saccade execution period. Modifications will allow for a broad input current range with appropriate frequency response.

2.2.11 Oculomotor Nucleus

The oculomotor nucleus is solely responsible for the control of the medial rectus eye muscles. This nucleus receives excitatory input from the abducens nucleus and inhibitory input from the inhibitory burst neuron. The circuit implementation of the oculomotor nucleus will be identical to the abducens nucleus.

2.2.12 Circuitry Case

In order to allow for feasible movement and management of the neural network circuitry, the circuit boards will be connected inside a case. However, due to the currently unknown size of the circuit boards being produced, the actual dimensions of this enclosure have yet to be determined. The case will be made of opaque acrylic, allowing for a clean finish and easy manufacturing. The structure will be reinforced with aluminum angle to provide additional structural integrity. There will also be openings allowing for assisted ventilation from the cooling system as well as access to the circuit boards themselves.

Upon construction, the case will have locations for the user to connect leads to observe the action potentials developed by each of the neuron populations in the circuit, including the final outputs for the medial and lateral rectus eye muscles. The user may connect to as many or as few leads as desired, allowing for selective analysis of the system.

2.2.13 Observation of Signals

There will be 15 neuron groups represented in the device, and the output signals of all of them will be observable. The contacts on the case may be observed with an oscilloscope or connected to NI Data Acquisition (DAQ) hardware so the signal may be processed in LabVIEW. With the NI hardware at hand, eight analog inputs are available. Thus, there will be eight “channels” which will be able to record any of the neuron outputs simultaneously.

Currently, a VI for this purpose has not been written. Future work will entail creating such a program to view outputs and graph firing rates versus time. Additionally, Bluetooth transmission of signals and control of neuron lesions could be implemented. Fig. 19 illustrates a general procedure of data acquisition for this device.

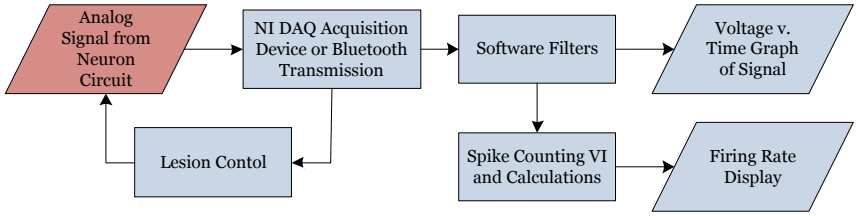

Figure 19. A flowchart for the data acquisition process is shown.

2.3 Prototype

2.3.1 Multisim

Though a physical prototype is not complete at this point, the Multisim models of all neurons have been completed, and the neural network may be modeled in segments to overcome the speed concerns that arise when many neurons are part of one simulation. An overview of operation of the Multisim prototype is now given.

The first file contains the current sources representing the superior colliculi and the left and right LLBN models. A full view of the first demonstration file is shown in Fig. 20.

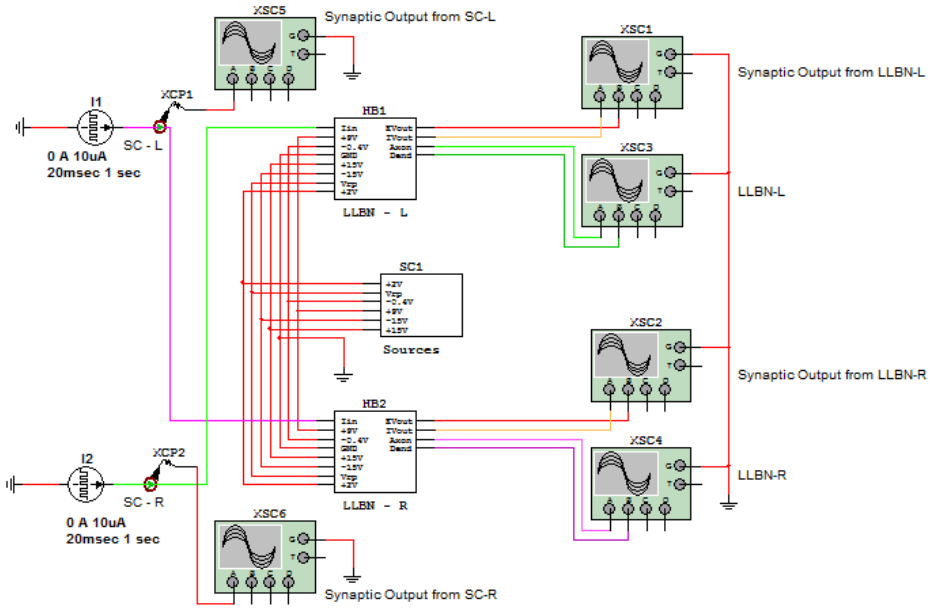

Figure 20. The first Multisim demonstration file is shown.

It is crucial that the demonstration file be in a folder with the individual neuron files. The neuron files are imported into the demonstration as a hierarchical block. The

voltage ports on the neuron block are supplied for proper function, and all operational amplifiers are checked for proper supply voltage connections before running the model. Mishaps occur when neuron files are opened independently, or demonstration files are opened while there is already an open file in Multisim. These cause the operational amplifiers to be renamed and stripped of their supply voltages.

One may select a time and length for a saccade by changing the properties of the superior colliculus current sources, but the default is a 20 millisecond pulse of 10 μA initiating in the left superior colliculus. The current probe attached to each superior colliculus output coverts current to voltage for viewing on an oscilloscope, and its conversion ratio is set such that 0 – 10 μA appear are 0 – 15 Volts.

To operate the demonstration, the simulation is run for a period of time that allows for all activity to take place; 400 milliseconds should suffice. The oscilloscopes attached to the pins labeled “Axon” and “Dend” show physiologically accurate axon and dendrite membrane voltage, respectively. The pins labeled “EVout” and “IVout” output synaptic pulses of voltage between 0 and ±15 Volts that are used to excite or inhibit the next neurons.

The synaptic output simulation data is saved in the .LVM file format by pressing the “Save” button within the oscilloscope window, highlighted in Fig. 21.

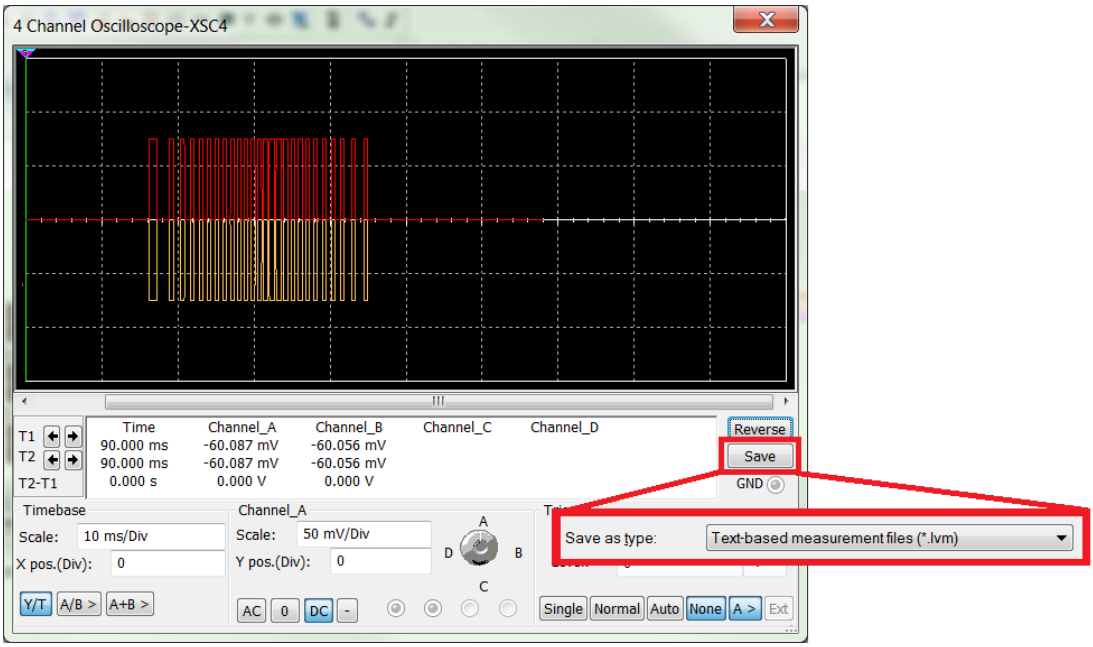

Figure 21. The oscilloscope window with simulation data and "Save" button highlighted is shown. The subset shows the appropriate file format for saving data.

The default options in the second dialog are satisfactory. The axon and dendrite simulation data may be saved under a different name or location for viewing in parallel with a LabVIEW VI discussed later, but this is optional.

The next demonstration file is opened when the required simulation data is saved. The second file is shown in Fig. 22.

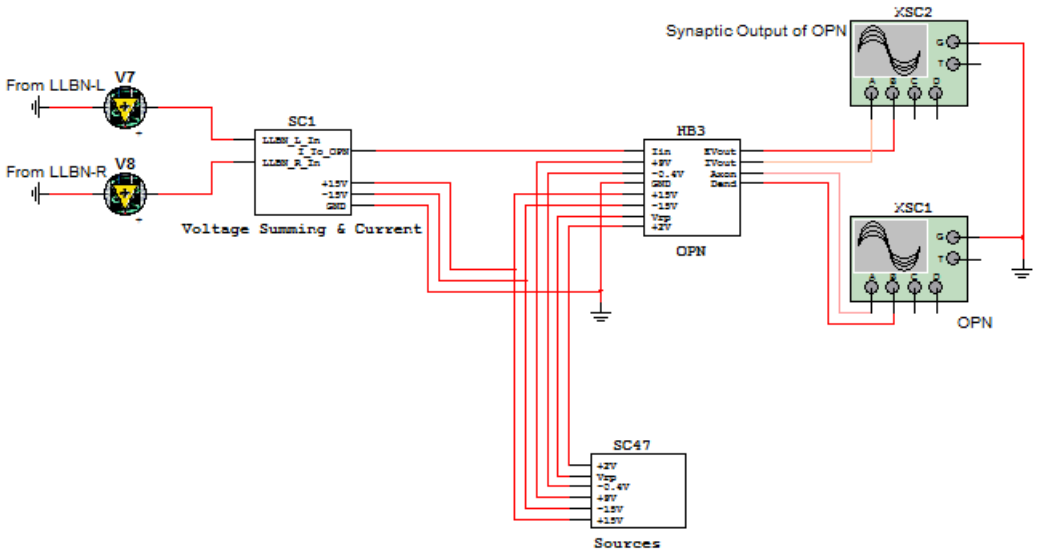

Figure 22. The second demonstration file is shown.

The .LVM files from the synaptic outputs of the LLBNs in the previous files are used as inputs for the .LVM controlled voltage sources seen in the left side of Fig. 21. Besides file location, the default voltage source options are acceptable, as the appropriate synaptic output was attached to channel A in the previous file. The same steps are repeated, saving synaptic outputs and using them as voltage sources for the appropriate post-synaptic neurons in the proceeding files. These steps effectively bridge the gap between Multisim files and allow for the network to be run in increments.

2.3.2 NI Ultiboard and PCB Design

With the neuron circuit schematics finalized in Multisim, the process of developing them into functional circuit boards may occur. The overall goals for this process were to group components involved in similar sections of the neuron (i.e. dendrite components in one area, axon components in another), as well as trying to minimize the board space while not requiring an excessive number of layer changes.

With the exception of the tonic neuron, all of the neuron populations can be represented by the same setup of circuit elements, with some resistor and capacitor values changing order to allow for the customized behavior. As a result, only a single neuron needed to be developed in Ultiboard in order to order the PCBs for all but the tonic neuron populations.

The neuron boards were constructed using a two layer PCB with the dimensions of 6 inches by 3 inches. Space was left in each of the four corners in order to allow for mechanical holes to be included. These holes would allow for the PCBs to be stacked (provided they were separated via an appropriate spacer), allowing for the device to take up a smaller amount of horizontal space. Extra space was also left on either side of the ribbon cable connector in order to allow for some deviation in size from the footprint available in Ultiboard. However, special care was taken to ensure that the holes for the pins were spaced properly so that the ordered part would still function properly.

The parts were arranged such that connected leads would be close to each other, and as such decrease the physical distance the signal had to travel on the board. This also made the design more simplistic, and as a result, cheaper and easier to duplicate. The final schematic for a generic neuron board is show in Figure 22.

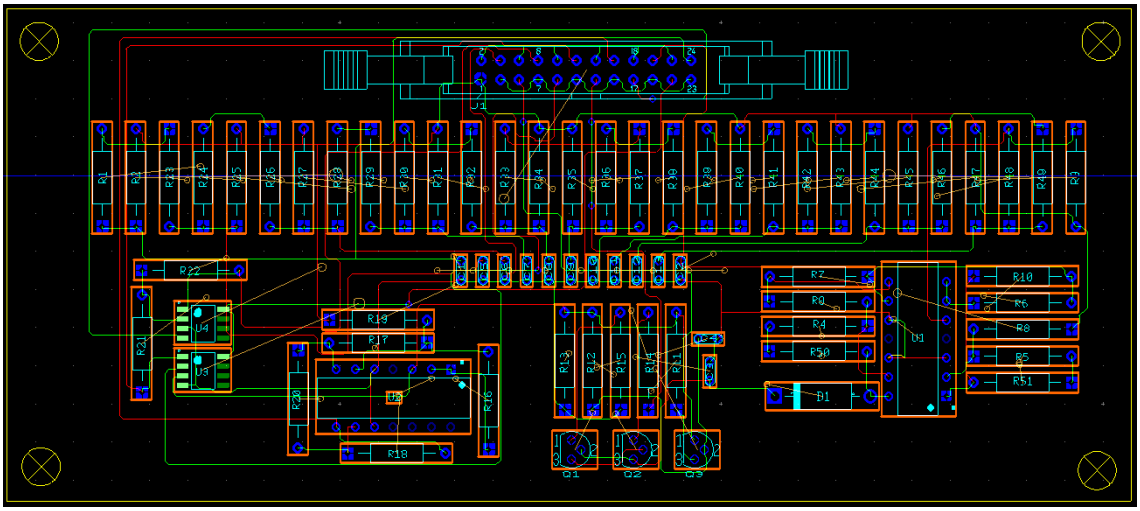

Figure 22. The schematic for a generic neuron PCB is shown. The green connectors show those routes on the top layer of the board, and those in red denote that the connection is made via the bottom of the board.

At this time, an Ultiboard implementation of the central board will not be produced, and a placeholder model on a protoboard will be used instead.

2.3.3 LabVIEW Acquisition Program

The LabVIEW Acquisition Program was designed during the simulation phase to allow signal visualization without using Multisim. Signals are exported from Multisim as LabVIEW .LVM data files. These data files can be loaded individually into LabVIEW and visualized on graphs. The program is useful for comparing the relative timing and interactions between neural populations while avoiding the simulation overhead that is associated with Multisim. Additionally, it provides a tool for comparing previously simulated output signals without having access to the original circuit schematics.

3 Realistic Constraints

Due to the size and application of this neural network, there are no organizations that must approve the manner in which the project is performed. The circuit is not to be implanted in an individual, and therefore does not need to be approved by the FDA. The final product will also not be of such a size that structural or mechanical issues pose a serious concern, and require no certification in that regard. The constraints on the project are subtle, but do limit its functionality in some aspects.

The design of the circuit model is such that it represents the major populations of neurons involved in producing the signals for the lateral and medial rectus models, yielding a certain degree of physiological realism. The resulting signals do resemble the actual action potential with regards to their firing rates, though the amplitudes immediately produced are not as accurate. The functionality of the circuit has been given priority of the physiological realism of the amplitude. The measurable signals can be dampened in order to yield more appropriate amplitudes, but the fact still remains that the circuits, on their own, do not yield the expected physiological voltages.

The circuits for the individual neuron populations are designed such that they cannot be altered once connected to the printed circuit board. This property means that if additional information becomes available that would suggest altering the behavior of neuron, the circuit board is more likely to need to be completely replaced. However, this design choice gives more reliable, durable neuron circuits. Allowing for interchangeable parts would result in the inability to solder components into place, greatly increasing the possibility of parts becoming loose during handling, causing the entire neural network to yield inaccurate signals.

Beyond these implementation constraints, the device does not create any sort of controversy with regards to its production. Of all the proposed designs, this method involved the least quantity of parts, ultimately yielding the least expensive model. This

will allow for the project to be completed with a lower budget, as less circuit components and circuit board space would be required.

No controversy is expected to arise with regards to the device itself either. Being completely comprised of circuitry, there is no need for any sort of *in vitro* or *in vivo* testing, meaning that no animals or cells need be harmed in order to develop the product. It is true that animal testing has been performed in order to obtain some of the physiological data used to estimate the parameters that the device is based on; no additional testing is needed in this form. The device also is not meant to alter a human or animal in any fashion, so ethical concerns related to this are expected to be nonexistent.

The device, if used properly, should not be difficult to maintain. The circuit elements remain static on the appropriate circuit boards, and should not come loose during regular use. The connections between boards should also remain connected, as the cables contain clips within their structures that encourage the connections to remain tight when placed in the appropriate receptacle. The circuits and connections should be examined, however, in the event of the case being dropped.

4 Safety Issues

This design, due to its extensive use of electronic components, requires proper handling of two major safety concerns: electrical and thermal. The circuits being designed require specific voltage levels in order to function, but these all occur at or below five volts. Harm to the operator related to electrical, if any, would likely be the result of misuse of the circuitry, resulting in minor electrical shock. The signals developed by the model will also be processed by a computer, which brings about its own safety concerns. The safety issues to be addressed in this regard, however, are largely dependent upon the model computer being used. Operators should consult the manual(s) for that device in order to ensure they are following safety protocol. Generalized safety issues would generally be the result of connecting the wrong leads for signal transmission, which again would possibly lead to minor electrical shock. More serious injury could result if the operator decides to manipulate the computer parts during use, though this is in no way required or recommended when using the device.

Thermodynamics dictate that during the use of electric circuit components, heat is generated. With numerous circuits running simultaneously, the amount of heat generated increases significantly. The operator should not have to touch any of the circuit components during operation, though if this were to occur, any injury would like be seen in the form of first degree burns. Any further injuries (more serious burns) would suggest severe misuse of the product. In order to minimize the possibility of this occurring, the container for the circuitry will include a fan (or multiple fans if necessary) in order to keep the parts cool, avoiding operator injury and failure of circuit elements.

For a more comprehensive analysis of possible safety issues, how to identify them, and troubleshooting suggestions, please read the Operator's Manual associated with this device.

5 Impact of Engineering Solutions

As a whole, the development of an analog electronic neuron does have some potential implications that can be discussed. The proposed device allows for the construction of a physiologically accurate eye saccade control system. Assuming that the accompanying muscular system can be developed elsewhere, these models combined would provide a complete functioning eye control system that could be exported and extrapolated to other robotic designs with minimal change being required. This is convenient for any biomimetic system that requires eye control and motion. However, the benefits of this design are not limited to strictly robotic applications.

Because the system is physiologically accurate, a complete robotic human eye analog can be used to diagnose mild traumatic brain injuries, often referred to as concussions. When an individual suffers a mild traumatic brain injury, there are generally few or no symptoms of any brain damage that may be noticed qualitatively during examination. Using this device as an input benchmark, the neural signals and resulting eye motions may be compared to that of a physiologically “normal” saccade. Deviation from this control can suggest the extent of brain damage for the patient, allowing for early diagnosis and treatment. This early action can help to avoid long-term pain, brain-related illness, and possibly even death due to injuries sustained during the mild traumatic brain injury.

All of these applications entail realistic prospect for the finished device. A complete, easy-to-manage saccadic control system can revolutionize modern robotics. On the opposite end of the spectrum, a complete system can also be used in medicine to aid in the diagnosis of traumatic brain injury.

6 Life-Long Learning

Brain physiology and anatomy, the empirical model, control systems, the art of circuit building and troubleshooting, and the design process are all topics in which knowledge will be and has been acquired due to the creation of this device. These are critical pieces of information and skills in engineering, and they will continue to be valuable.

The complexity of the neural network for the control of such a simple task, the horizontal saccade, is staggering. An appreciation of the beauty of this naturally evolved control system can be gained from this project. Even the fastest computers cannot outperform the brain. An understanding of the brain's systems, and thinking about how man-made systems can more closely mirror them, could lead to improved efficiency and power in systems.

In the neural network, the difference between desired eye location and actual eye location is encoded in a signal sent to the superior colliculus, and the amount and location of neurons firing there initiate a chain of relayed signals to the rest of the network. The populations on each side of the midline excite and inhibit each other appropriately to guarantee movement between the eyes is coordinated. The error is fed back to the superior colliculus, ensuring the proper outcome is reached. This kind of scheme is used universally in control systems, and is vital to understand.

On a lower level, simply an understanding of brain physiology and anatomy, such as the neuron populations involved in various tasks, the nature of membrane potentials, and the behavior of ion channels, is a useful thing. The value of the empirical model is brought to light in this project. The model is not an analog to the actual physiological process, in that it does not replicate the behavior of every component of the real system. However, it provides results that match the outcome of the process. The Hodgkin-Huxley model, the basis for the simpler FitzHugh-Nagumo model, is an apt example,

describing the electrical behavior of the neuron membrane during an action potential using differential equations. It was built by matching experimental data from a squid axon, not by building a replica of the axon in an attempt to make it behave the same way. The Hodgkin-Huxley model remains an extremely important contribution, and demonstrates the importance of applying empirical models. The device will use empirical circuit models that are not physiologically analogous to real neurons, but perform analogous functions.

Circuit design is a meticulous process because all aspects of the circuit must be absolutely correct and when malfunction occurs, it is often difficult and frustrating to find the cause. The building of this device will be a lesson in proper technique for creating and troubleshooting complicated circuits. Complementary to this is the design process in general. Proper documentation of steps, planning and budgeting time, money, and resources are necessary in a successful project. The device has thorough owner's manual, the progress and design are documented in periodic reports and presentations, and time and resources are tracked in a Microsoft Project file. The process of building this device mirrors the engineering process in industry and will provide valuable life-long skills.

7 Budget

For the majority of this project, all activity was confined to simulations and development of circuitry within NI Multisim. As a result, the budget remained largely unused. However, once the generic neuron circuit was finalized, several large orders were placed. Though this used approximately 85 percent of the original budget, there is no concern about exceeding the original budget of $1,000. However, these orders have shown that the original projection of the project only costing about $700 was too low.

In order to expand on the project, namely the production of a power grid and central board PCB, additional funds would likely be required, as these PCBs would be significantly larger and more complex. The development and implementation of a Bluetooth module for signal transmission and device control would also be an expensive addition, and would again require exceeding the original budget. If any future work is desired, it would be advisable to request for a budget increase. The amount for said increase would vary based on the extent of the work that would be desired, but to include both the central board and the Bluetooth module as the client described, the additional costs would require a budget increase of approximately $750 to $1,000. These numbers may change based on additional alterations made to the circuit schematics as well as part availability and PCB design.

Table 2 outlines all spending thus far with regards to the project. No money has been spent on the case at this point due to the fact that one will not yet be made.

Category	Amount Spent	% Total Spent	% Budget		
Circuit Elements	$281.99	31.76%	28.20%		
PCBs	$494.67	55.71%	49.47%		
Case	$0.00	0.00%	0.00%		
Miscellaneous	$18.78	2.12%	1.88%		
Shipping	$92.48	10.42%	9.25%	**% Budget Used:**	**88.79%**
Totals:	**$887.92**	**100.00%**	**100.00%**	**Total Budget:**	**$1,000.00**

Table 2: The breakdown of the items purchased for the project.

8 Team Member Contributions

8.1 Justin Morse

Justin has done much exploratory work, and has found the existing neuron models from which the project is being based. His contribution to the documentation is equal to that of the other team members, and he has taken part in upkeep of the website. He also modified a FitzHugh-Nagumo model to fire at 1000 Hz, and this opened the door for customizing axons. There was also a period of three weeks where the Fitz-Hugh Nagumo model was brought into question by our client because of physiological realism, and Justin built and troubleshot the Roy model, sought and built more alternatives, and concluded these models were not feasible.

Though his early work focused on characterizing the dendrite, Ed has taken these reigns and Justin became the leader of the work on the synapse, which later came to light as a challenging and important portion of the neuron to model. He focused on developing the tachometer-bilateral current source synapse scheme. However, this scheme proved to be too slow, and he later developed the scheme now implemented in the project. After the synapse, he worked on customizing neurons into specific populations and overcoming limitations in Multisim to test and demonstrate the network as a whole.

8.2 Dean Poulos

Most of Dean's early work revolved around the construction of an appropriate axon unit. At first, this entailed heavy research into the previous works of other academic scholars who have focused on mimicking the physiological behavior of basic neurons using analog components. In the beginning, the work was focused around the FHN model, but other models were also considered. Despite the extensive investigation of alternative models, in the end the FHN model was chosen as the best, albeit non-ideal,

option. Once a viable model was chosen, further work pursued regarding the perfection of this behavior and providing readily available alternatives that could be utilized for the construction of all neural populations in the system. This was achieved by weeks of testing and experimentation to further the understanding of the workings of these axon units, primarily focusing on how these variable components could be modified to mimic the desired firing rates for each population.

In addition, Dean also played a major role in the development of the primitive synaptic units, prior to the changes installed by Justin and Edward later in the year. Again, this portion of the project focused on understanding how these pre-built synapse units functioned, what controlled their behavior and how this behavior could be modified and prepared in a readily available manner. In comparison, this work was minimal and was later abandoned as other group members developed much more effective alternatives for establishing synaptic relationships.

Dean was responsible for the design of the tonic neuron. Due to time constraints the neuron was never able to be fully implemented, as his focus was directed towards the customization of other neurons. A complete tonic neuron was constructed, but still experiences problems that require manual manipulation.

8.3 Edward Ryan

Edward's work has been distributed between the development and optimization of the dendrite portion of the system as well as providing support circuits for the other two portions. The dendrite circuit, originally spearheaded by Justin, but then transferred to Edward as Justin's focus shifted to the synapse, was compared to the information available from "The Book of GENESIS" and its simulation of the cable model. From this data, Edward was able to confirm that the proposed dendrite circuit could be accurately

compared to the cable behavior, and developed that and an appropriate current stop subcircuit in order to provide the signal isolation desired by the client.

As for the support circuits, Edward developed the post-processing unit for the axon, which was then manipulated by Dean in order to customize individual neurons. The support network for the synapse was the central board, which converted the voltage output to a current source using a bilateral current source model proposed by Justin. The central board also added components for signal observation and the generation of DC voltage sources using the AC power supply of a standard wall socket. In addition, Edward also contributed to website maintenance and copy editing of many submitted reports and presentations.

9 Conclusion

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

10 References

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11 Acknowledgements

There are a number of individuals who have been necessary for this project's natural progression and eventual completion. The first, and perhaps most obvious of these, is Dr. John Enderle of the University of Connecticut's Biomedical Engineering Department. Doubling as both our project's sponsor and mentor, Dr. Enderle has provided us with clear directions, supplementary help and zealous support that has made our job as painless as possible. On this note, Marek Wartenberg has fulfilled his role as our advisor by providing guidance and assistance during our project development. Both Dr. John Enderle and associate Marek Wartenberg were consistently supportive and helpful, serving as a source of inspiration for all three of the current group members.

In the same manner as the above, David Kaputa has supplied our group with logistic guidance and moral support that has gone unrivaled. Dave was also a great source of information about electronic circuit construction and has never hesitated to point our group in the proper direction. His extensive knowledge has saved our group precious time by limiting the amount of searching and testing necessary when choosing electrical components with little experience.

Thirdly, Bruce R. Land of Cornell University has posted an invaluable source on the construction of analog neurons that has given us a starting point for everything. From here, we were able to gather the basics of analog neurons and gather enough data to construct our own neural analogs. Dr. Land provided us with basic neural components that have been further modified to construct our own specific alternatives. Dr. Land's work saved us from a lot of theoretical and research-based work, allowing us to focus on more design-oriented aspects. While Dr. Land was unable to provide us with source files for his simulations, his contributions cannot go unmentioned.

Lastly, James M. Bower and David Beeman, authors of *The Book of GENESIS*, supplied us with some theoretical physiology and modeling techniques which have proved to be absolutely essential to the construction of our analog system. *The Book of GENESIS,* in and of itself, has provided our team with a "gold standard" to ensure that our developing system as close as possible to this already accepted theory and description of natural phenomena.

12 Appendix

12.1 Project Specifications

Mechanical:	
Size:	Not specific; small enough to move by hand.
Electrical:	
Maximum Input Current:	150 microamps (μA) (scalable if necessary)
Maximum Output Voltage:	100 millivolts (mV) (scalable if necessary)
Environmental:	
Storage Temperature:	60 - 90 °F
Operating Temperature:	60 - 90 °F
Operating Environment:	Indoors (Laboratory, Clinical)
Software (for data acquisition):	
User interface:	Oscilloscope, Keyboard, Mouse, LabVIEW
Hardware Interfaces:	Oscilloscope, Monitor, NI DAQ inputs
Computer Requirements:	
Operating System:	Windows 7/Vista/XP SP2, Mac OS X 10.5 or later
Processor:	Pentium 4/M or better (Windows) Intel-based processor (Mac OS X)
Memory (RAM):	1 GB
Safety:	Damage to the device or user may occur if inputs are not properly connected to the system. Primary dangers include electrocution, destroying circuit components, and minor burns. No special safety equipment should be required.
Maintenance:	The circuitry should be kept clean, particularly of dust or residues forming on circuit elements or contacts for inputs, wires, or nodes.

12.2 Purchase Requisitions and Price Quotes

PURCHASE ORDER REQUISITION - UCONN BME SENIOR DESIGN LAB

Instructions: Students are to fill out boxed areas with white background
Each Vendor will require a different purchase requisition

Date:	October 12, 2011	Team #	8
Student Name:	Edward Ryan	Total Expenses	$0.00
Ship to:	University of Connecticut Biomedical Engineering U-2247, 260 Glenbrook Road Storrs, CT 06269-2247	Lab Admin only: FRS # Student Initial Budget Student Current Budget Project Sponsor	
Attn:	Edward Ryan		
Project Name:	Neural Network for the Saccade Controller		

ONLY ONE COMPANY PER REQUISITION

Catalog #	Description	Unit	QTY	Unit Price	Amount
512-2N3904TA	Bipolar Small Signal NPN Transistor (General Purpose)		100	$0.034	$3.40
512-2N3906TFR	Bipolar Small Signal NPN Transistor (General Purpose)		100	$0.05	$5.00
602-3051/1-100-03	Wire - Single Conductor - 22AWG Solid PVC 100' Spool Red		1	$18.78	$18.78
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
				Shipping	$7.48
				Total:	$27.18

Comments: Shipping is based on weight. The cost based on an estimated weight of 2 lbs. is shown.

Price Quote File Name: (Yes or No)

Vendor Accepts Purchase Orders?

Vendor: Mouser Electronics
Address: http://www.mouser.com
Phone: N/A
Contact Name: N/A

Authorization: _____

PURCHASE ORDER REQUISITION - UCONN BME SENIOR DESIGN LAB

Instructions: Students are to fill out boxed areas with white background
Each Vendor will require a different purchase requisition

Date:	April 13, 2012	Team #	8	
Student Name:	Edward Ryan	Total Expenses	$34.66	
Ship to:	University of Connecticut Biomedical Engineering U-2247, 260 Glenbrook Road Storrs, CT 06269-2247	Lab Admin only: FRS # Student Initial Budget Student Current Budget Project Sponsor		
Attn:	Edward Ryan			
Project Name:	Neural Network for the Saccade Controller			

ONLY ONE COMPANY PER REQUISITION

Catalog #	Description	Unit	QTY	Unit Price	Amount
71-CCF0710K0JKE36	Metal Film Resistors - Through Hole 1/4watt 10Kohms 5% Rated to 1/2watt		100	$0.037	$3.70
660-MFS1/4LCT52R122J	Metal Film Resistors - Through Hole 1.2K ohm 5%		15	$0.08	$1.20
660-MF1/4LCT52R123J	Metal Film Resistors - Through Hole 1/4 WATT 12K OHM 5%		50	$0.07	$3.50
594-5073NW200K0J	Metal Film Resistors - Through Hole 1watt 200Kohms 5%		10	$0.16	$1.60
270-10K-RC	Metal Film Resistors - Through Hole 10Kohms 1% 50PPM		10	$0.11	$1.10
271-18K-RC	Metal Film Resistors - Through Hole 18Kohms 1% 50PPM		10	$0.09	$0.90
71-RN60D4001FTR	Metal Film Resistors - Through Hole 1/4watt 4Kohms 1% 100ppm		5	$0.13	$0.65
71-RN60D1251F	Metal Film Resistors - Through Hole 1/4watt 1.25Kohms 1% 100ppm		5	$0.13	$0.65
273-1.6K-RC	Metal Film Resistors - Through Hole 1.6Kohms 1% 50PPM		5	$0.14	$0.70
71-CCF60-20K-E3	Metal Film Resistors - Through Hole 1/2watt 20Kohms 1% Rated to 1watt		5	$0.10	$0.50
71-RN60D1703F	Metal Film Resistors - Through Hole 1/4watt 170Kohms 1% 100ppm		10	$0.13	$1.30
660-MF1/4DC1303F	Metal Film Resistors - Through Hole 130K 1% 100PPM		30	$0.06	$1.80
660-MF1/4DCT52R6802F	Metal Film Resistors - Through Hole 1/4 WATT 68K OHM 1%		30	$0.06	$1.80
271-1.2K-RC	Metal Film Resistors - Through Hole 1.2Kohms 1% 50PPM		10	$0.09	$0.90
					$0.00
Comments	Shipping is based on weight. The cost based on an estimated weight of 2 lbs. is shown.				
Price Quote File Name:				Shipping	$0.00
				Total:	$20.30
Yes or No	*Vendor Accepts Purchase Orders?*				
Vendor:	Mouser Electronics				
Address:	http://www.mouser.com				
Phone:	N/A				
Contact Name:	N/A				

Authorization:

_____

PURCHASE ORDER REQUISITION - UCONN BME SENIOR DESIGN LAB

Instructions: Students are to fill out boxed areas with white background
Each Vendor will require a different purchase requisition

Date:	April 13, 2012	Team #	8	
Student Name:	Edward Ryan	Total Expenses	$34.66	
Ship to:	University of Connecticut Biomedical Engineering U-2247, 260 Glenbrook Road Storrs, CT 06269-2247	Lab Admin only: FRS # Student Initial Budget Student Current Budget Project Sponsor		
Attn:	Edward Ryan			
Project Name:	Neural Network for the Saccade Controller			

ONLY ONE COMPANY PER REQUISITION

Catalog #	Description	Unit	QTY	Unit Price	Amount
71-CCF07100RJKE36	Metal Film Resistors - Through Hole 1/4watt 100ohms 5% Rated to 1/2watt		300	$0.040	$12.00
71-CCF0715K0JKE36	Metal Film Resistors - Through Hole 1/4watt 15Kohms 5% Rated to 1/2watt		100	$0.04	$4.00
71-CCF071K00JKE36	Metal Film Resistors - Through Hole 1/4watt 1Kohms 5% Rated to 1/2watt		150	$0.04	$5.55
71-RN55E5002B	Metal Film Resistors - Through Hole 1/10watt 50Kohms .1% 25ppm		5	$0.74	$3.70
571-2-746610-3	Headers & Wire Housings .1CL IDC PLG 2X12P		40	$1.33	$53.20
270-90K-RC	Metal Film Resistors - Through Hole 90Kohms 1% 50PPM		30	$0.11	$3.30
71-CCF07100KJKE36	Metal Film Resistors - Through Hole 1/4watt 100Kohms 5% 100ppm		100	$0.04	$4.00
271-249-RC	Metal Film Resistors - Through Hole 249ohms 1% 50PPM		20	$0.09	$1.80
71-CMF075K0000JNEK	Metal Film Resistors - Through Hole 1/4watt 5Kohms 5%		20	$0.07	$1.40
594-5083NW62K00J	Metal Film Resistors - Through Hole 2watts 62Kohms 5%		5	$0.32	$1.60
594-5073NW1K300J	Metal Film Resistors - Through Hole 1watt 1.3Kohms 5%		5	$0.16	$0.80
71-CCF55200KFKE36	Metal Film Resistors - Through Hole 1/4watt 200Kohms 1% Rated to 1/2watt		30	$0.08	$2.40
271-1.0M-RC	Metal Film Resistors - Through Hole 1.0Mohms 1% 50PPM		200	$0.02	$4.00
71-CCF552K00FKE36	Metal Film Resistors - Through Hole 1/4watt 2Kohms 1% Rated to 1/2watt		30	$0.08	$2.40
					$0.00

Comments	Shipping is based on weight. The cost based on an estimated weight of 2 lbs. is shown.		
Price Quote File Name:		Shipping	$8.00
		Total:	$108.15
Yes or No	*Vendor Accepts Purchase Orders?*		
Vendor:	Mouser Electronics		
Address:	http://www.mouser.com	Authorization:	
Phone:	N/A		
Contact Name:	N/A	_____	

PURCHASE ORDER REQUISITION - UCONN BME SENIOR DESIGN LAB

Instructions: Students are to fill out boxed areas with white background
Each Vendor will require a different purchase requisition

Date:	April 13, 2012	Team #	8	
Student Name:	Edward Ryan	Total Expenses	$34.66	
Ship to:	University of Connecticut Biomedical Engineering U-2247, 260 Glenbrook Road Storrs, CT 06269-2247	Lab Admin only: FRS # Student Initial Budget Student Current Budget Project Sponsor		
Attn:	Edward Ryan			
Project Name:	Neural Network for the Saccade Controller			

ONLY ONE COMPANY PER REQUISITION

Catalog #	Description	Unit	QTY	Unit Price	Amount
810-FK18X7R1C105K	Multilayer Ceramic Capacitors (MLCC) - Leaded 1.0uF 16volts X7R +/-10%		150	$0.118	$17.70
598-DMM2P22K-F	Polyester Film Capacitors .22UF 250V 10%		20	$0.47	$9.34
595-LM348N	Op Amps Quad GP Op Amp		30	$0.45	$13.50
926-LMC6482AIM/NOPB	Op Amps CMOS Dual R/R I/O Op Amp		50	$1.87	$93.50
625-1N5621GP-E3/54	Diodes (General Purpose, Power, Switching) 1.0 Amp 800 Volt Glass Passivated		20	$0.17	$3.40
DMM4S33-1K-F	Polyester Film Capacitors .033UF 400V 10%		10	$0.51	$5.10
71-CMF551K1000FKEK	Metal Film Resistors - Through Hole 1/4watt 1.1Kohms 1%		10	$0.14	$1.40
71-CMF6060R000BHEB	Metal Film Resistors - Through Hole 1/2watt 60ohms .1%		20	$0.46	$9.20
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00

Comments	Shipping is based on weight. The cost based on an estimated weight of 2 lbs. is shown.		
Price Quote File Name:		Shipping	$0.00
Yes or No	*Vendor Accepts Purchase Orders?*	Total:	$153.14
Vendor:	Mouser Electronics		
Address:	http://www.mouser.com	Authorization:	
Phone:	N/A		
Contact Name:	N/A	_____	

PURCHASE ORDER REQUISITION - UCONN BME SENIOR DESIGN LAB

Instructions: Students are to fill out boxed areas with white background
Each Vendor will require a different purchase requisition

Date:	April 16, 2012	Team #	8	
Student Name:	Edward Ryan	Total Expenses	$316.25	
Ship to:	University of Connecticut Biomedical Engineering U-2247, 260 Glenbrook Road Storrs, CT 06269-2247	Lab Admin only: FRS # Student Initial Budget Student Current Budget Project Sponsor		
Attn:	Edward Ryan			
Project Name:	Neural Network for the Saccade Controller			

ONLY ONE COMPANY PER REQUISITION

Catalog #	Description	Unit	QTY	Unit Price	Amount
Neuron001	Sunstone Circuits PCB Order - 11 PCBs		1	$494.750	$494.75
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00
					$0.00

Comments

Price Quote		Shipping	$77.00
File Name:	GenericNeuron.ewproj	Total:	$571.75
Yes or No	*Vendor Accepts Purchase Orders?*		
Vendor:	Sunstone Circuits		
Address:	http://www.sunstone.com	Authorization:	
Phone:	N/A		
Contact Name:	N/A	_____	

12.3 Circuit Schematics

Due to the complexity of the circuits, particularly with regards to subcircuits, it is impractical to try and include a complete set of schematics for the entire device, as it would take several hundred pages to describe all the components of the various neuron populations and the central board. The function of each of the subcircuits is explained in detail in their respective report sections, and if complete models are desired, the Multisim (and/or Ultiboard) files are available upon request.