Optimal Design Report

Electronic Circuit to Mimic the Neural Network for the Saccade Controller

Team 8
Justin Morse, Dean Poulos & Edward Ryan

Project 12

for
Dr. John Enderle
University of Connecticut
Department of Biomedical Engineering
A. B. Bronwell Building, Room 209
260 Glenbrook Road
Storrs, CT 06269-2247

Phone: (860) 486-5521
Email: jenderle@bme.uconn.edu
1.1 Introduction

The proposed device is an electronic circuit analog for the neural network that controls fast horizontal eye movements known as saccades. It will provide a valuable teaching tool in the field of neurobiology since it will mimic the neuron populations involved with eye movement, and the signals produced will be observable. Furthermore, using the device as a model of healthy physiology may provide a way to diagnose mild traumatic brain injuries, or concussions, which may go unnoticed otherwise. The device will also be used to control a robot that can realistically and accurately move its eyes to a light in front of itself. An exterior view of the device is shown in Figure 1.

![Figure 1. An exterior view of the device is shown. The input will be processed information about desired saccade direction and magnitude.](image)

The eye movement robot will provide input from eye-mounted cameras. A light in an array in front of the robot will turn on, and the captured image will provide information about the direction and magnitude of the desired saccade. A LabVIEW program running on a computer, and eventually a microcontroller, will imitate the superior colliculus, determining the degree of error on eye position, and then sending a signal to the circuit to move the eyes to the
new desired position. The circuit will contain the major populations of neurons in the horizontal saccade network presented in [1], and all neuron circuits will produce action potentials at a rate and duration consistent with physiological data for a given saccade magnitude and direction. The layout of the network, as well as relative timing and firing rates, are illustrated in Figure 2.

Figure 2. The neural network for horizontal saccade generation is shown¹. Times zero and T represent saccade initiation and termination, respectively. For feasibility, the cerebellum components will not be included.
Table 1 quantitatively outlines the timing and firing rates of the neuron groups involved in the movement of the eye in one direction. The term ipsilateral indicates the same side as saccade direction, and contralateral indicates the opposite side.

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

Table 1. Neuron groups and their timing and firing rates are shown. The neuron groups in the proposed circuit will fire according to these observations.

The neuron circuits will be built using the FitzHugh-Nagumo model, modified to achieve a constant train of action potentials when stimulated. This model is presented in the next section and provides a simple and customizable electric circuit that produces results similar to the Hodgkin-Huxley model.

Each neuron population will be connected with excitatory and inhibitory synapses as seen in Figure 2. Timing circuits will be placed between neuron groups to achieve realistic delays in signal propagation. Filters will be implemented between each neuron circuit to eliminate the possible 60 Hz noise in the signal. The signals from the abducens and oculomotor nuclei will be used to stimulate the eye movement robot to fix its gaze onto the given light.

At the moment, the current budget outlook remains fluid. The current proposal utilizes basic electrical circuit components that are readily available and low in cost. The Fitz-Hugh-
The Nigumo model contains resistors, capacitors, transistors, and diodes. From the quantities of components in 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 boards 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 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 budget is outlined in table 2.

<table>
<thead>
<tr>
<th>Part</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circuit Components</td>
<td>$320 – approximately $20 per neuron</td>
</tr>
<tr>
<td>Printed Circuit Boards</td>
<td>$300</td>
</tr>
<tr>
<td>Aluminum – Plastic Case</td>
<td>$50</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$670</strong></td>
</tr>
</tbody>
</table>

Table 2. Budget information is shown.

1.2.1 Neural Circuit Design

For the construction of the optimal 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 empirical Hodgkin-Huxley model. This analog design provides a robust, cost-effective solution for the range of behaviors exhibited by each neuron population of interest. As shown in Figure 3 below, the modified design of this circuit is relatively simple and provides a train of action potentials at approximately 1000 Hz. Modification of this circuit, namely adjusting capacitance
values, can vary several circuit parameters, including action potential amplitude, length of bursts and frequency of bursts.

Figure 3. The schematic for a stock FitzHugh-Nagumo neuron with burst-firing capabilities.

The behavior of this model is displayed in the NI Multisim trace available in Figure 4 below.

Figure 4. A FitzHugh-Nagumo neuron model modified to fire at roughly 1 kHz is shown.

Though the FitzHugh-Nagumo model provides an easily adaptable neuron that is capable of accurately mimicking the physiological behavior of the neuron populations of interest, it does not describe the interactions between independent neural subsystems. The communication between these burst-firing populations is the backbone of the saccadic control system, and without proper connectivity, gross orchestrated motion is impossible. Therefore, in addition to these basic neuron subcircuits, additional accessory circuits must be employed to supplement the otherwise independent systems.
Both analog excitatory and inhibitory synapses have been developed to allow connectivity and communication between independent neural subsystems, mimicking physiological behavior. The excitatory synapse, displayed in Figure 5, connects two independent neurons by modifying the delayed outward depolarizing current channel of the FitzHugh-Nagumo neuron to depend on a presynaptic voltage. As shown, the excitatory synapse has a variable resistance that can be adjusted to a desired synaptic strength or threshold voltage for further customization.

![Figure 5. The schematic for a generic excitatory synapse subcircuit.](image)

These excitatory synapses allow for stimulatory communication between connected neural populations. In the most general cases, the presynaptic neuron fires autonomously as if stimulated by an outside input or control. This, in turns, functions as an input for the postsynaptic neuron, which fires at a rate determined by the synaptic strength resistance.

In addition to the excitatory synapse, the proposed inhibitory synapse, found below in Figure 6, is another inter-neuron communication tool. As opposed to the excitatory synapse, where the firing of the presynaptic neuron forces the firing of the postsynaptic neuron, an inhibitory junction allows for a presynaptic neuron to silence its postsynaptic complement.
In this case, both neurons are firing autonomously as if stimulated by independent, outside stimuli. However, whenever the presynaptic neuron fires, the postsynaptic neuron is silenced via inhibition.

The last component for the complete analog saccadic control system is a dendrite model. In physiological systems, dendrites are necessary for signal transduction and communication, but also cause some inherent signal dampening and time delay. As such, to keep our analog system as physiologically accurate as possible, dendrites and their resulting time delays must be modeled using an arrangement of subcircuits. The dendrite subcircuit is relatively simple, as shown in Figure 7 below, and can be repeated, as necessary, to achieve the desired behavior.
These subcircuits may also be arranged in parallel in order to accommodate for multiple inputs to a single neuron circuit.

### 1.2.2 Superior Colliculus

The superior colliculus receives information from other portions of the brain about how far the eye should move. It outputs a signal whose length is proportional to the magnitude of the desired movement and initiates the action of the rest of the neurons. This part of the device will be created after the rest of the circuit has been successfully built because of its dependence on several other factors. It will receive information from the cameras in the eye movement robot, process this, and determine the distance the eyes should move. The cameras will continuously capture images of the LED array in front of it. When a new LED is lit, the goal is to accurately fix the robot’s eyes onto it.

Figure 8 outlines the procedure for mimicking the superior colliculus.

![Figure 8. A flowchart illustrating the operation of the superior colliculus is shown. The process is initiated with information provided by the robot, indicated in red.](image)

Images will be input into a script written with LabVIEW and NI Vision Assistant and ported to continuously run on a microcontroller. Various filters will be applied so that the LEDs are isolated and located precisely. The difference in position between the previously and newly lit LED will be found and the difference in direction and angle calculated based on distance of the LED from the camera. Once the angle and direction have been obtained, it will be used to generate a proportional signal with the microcontroller’s waveform generator to stimulate the
rest of the neural network. This signal will need to be amplified with a simple operational amplifier circuit.

1.2.3 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.

1.2.4 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 population will employ the FitzHugh-Nagumo model attached to both an excitatory and inhibitory synapse. These synapses will provide excitatory inputs to the tonic neurons and the abducens nucleus, and inhibit the inhibitory burst neuron during firing.

1.2.5 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 circuit representation of the long-lead burst neuron will contain a FitzHugh-Nagumo model with both an excitatory and an inhibitory synapse, with the excitatory signal being sent to the inhibitory burst neuron and the inhibitory signal being relayed to the omnipause neuron.
1.2.6 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. The tonic neurons will be represented in the circuit system by a FitzHugh-Nagumo model with an excitatory synapse, which will transmit the appropriate signal to the abducens nucleus.

1.2.7 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 FitzHugh-Nagumo model with an inhibitory synapse that will deliver the appropriate signal to the inhibitory burst neuron circuits.

1.2.8 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 via the use of the FitzHugh-Nagumo model with an inhibitory synapse in order to provide the proper inputs to the system.
**1.2.9 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. The circuit model for the abducens nucleus will contain the FitzHugh-Nagumo model with an excitatory synapse.

**1.2.10 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 this element will include a FitzHugh-Nagumo model and a single excitatory synapse, giving the output to the muscle analog.

**1.2.11 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.

1.2.12 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, seven analog inputs are available. Thus, there will be seven “channels” which will be able to record any of the neuron outputs simultaneously. Figure 9 illustrates the data acquisition process for this device.

![Figure 9. A flowchart for the data acquisition process is shown.](image)

The signals from multiple neurons may be acquired with the NI DAQ hardware. Once the signal has been acquired by LabVIEW, software filters will be applied as necessary to eliminate noise from the signal(s). The treated signal(s) will be displayed on a graph with an appropriate time and voltage scale. A spike counting virtual instrument (VI) will be used to calculate the firing rate of the signal, and it will be displayed on the front panel.
2. **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.
3. 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 neural network circuit.

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.

The only other safety hazard that would apply to this design involves the actual movement of the device. The completed circuit network will not be particularly large, and will be relatively easy to move. However, the fact that it is mobile means that it may also be dropped or prone to falling if not handled properly. Handling this risk is feasible, requiring that the operator and anyone involved in moving device make sure that they place it on a stable surface.
4. 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.
5. 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 constantly 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 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 of neurons that are not physiologically analogous to real neurons, but perform analogous actions.

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. This device will provide a course in proper technique in 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, and this device provides a learning experience in this. The device will have a thorough owner's manual, the progress and design are documented in periodic reports and presentations, and time and resources will be 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.

6. References


