Alternative Designs Report

Electronic Circuit to Mimic the Neural Network for the Saccade Controller

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Project 12

for

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**Introduction**

In order to provide a valuable teaching tool, a controller for a robot with realistic eye movements, and an aid to diagnosing mild traumatic brain injuries in the future, the proposed device will be an electronic circuit that mimics the neural network controlling horizontal saccades. An exterior view of the proposed device is shown in figure 1.

![Figure 1](image)

Figure 1. A proposed exterior for the device. The input will be processed information about desired saccade direction and magnitude.

In all alternative designs, the exterior of the device and the neural network remain the same. This network consists of several connected neuron groups that fire in synchrony, based on external feedback, to cause an eye movement. The network, with diagrams indicating relative firing times and rates, is shown in figure 2.
Figure 2. The neural network for horizontal saccade control with timing and relative firing rate indicated. For feasibility, the parts of the cerebellum (S. Nigra, Vermis, Fastigial Nucleus) will not be considered in the device. Also, the left and right eye plants are not part of the design, but are shown for completeness.

Circuits to simulate excitatory and inhibitory synapses will be used to connect neurons. The circuit model used to simulate individual neurons is the topic of discussion in the alternative designs. Neurons will be built using one of the alternative models, modified to resemble the properties of the desired neuron population, and printed on individual circuit boards. They will be interfaced according to the connections in figure 1 with synaptic circuits. If noise becomes an issue, filters will be implemented appropriately.

Budget information is outlined in table 1.
<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 – Acrylic Case</td>
<td>$50</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$670</strong></td>
</tr>
</tbody>
</table>

Table 1. Budget information is shown.

Since the differences between alternative designs are between circuit components, the costs of each design will be similar.
Alternate Design 1

This design makes use of the circuit proposed by L.D. Harmon in 1961. Two models were identified: a preliminary model and a more complex one. This design will opt for the simpler model in order to develop a more cost-effective and consistent circuit, as the more advanced model contains a variable component that could alter the function of the circuit if shifted. Figure 3 depicts the simple Harmon circuit model proposed.

Figure 3. The preliminary Harmon neuron model circuit schematic. 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 neuron model. In order to satisfy the requirements of the project, some of the resistor and capacitor values may need to be changed in order to adjust the behavior of the individual subcircuits, particularly in regards to the firing rate. The model is empirical, and as such does not have defined sections for the various ion channels. Therefore, the changes would have to be made exclusively based on the final output of the circuit.

Harmon’s design allows for explicit definition of excitatory and inhibitory inputs, making it significantly easier to incorporate the multiple signals coming to some of the neuron populations. Some properties of the circuit, such as its refractory period and behavior under repetitive excitation (or the circuit’s ability to develop output pulses based on a constant input
voltage and frequency) are altered through the use of redundancy at these inputs. The general trend is that as more redundant inputs are used, the refractory period decreases and the repetitive excitation more closely matches the input’s frequency at lower voltages. Further experimentation can provide an appropriate balance between input voltage, input frequency, and the subcircuit’s firing rate. Figure 4 describes Harmon’s analysis of the circuit’s refractory recovery and reaction to repetitive excitation, among other properties.

Figure 4. The behavior of the Harmon neuron model based on Harmon’s 1961 analysis.

Using the documented properties of the circuit in its current form, 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. The primary focus would be in modifying the input as it reaches the circuit, particularly in the form of amplification. This would mean that the circuits developing the action potentials would remain relatively unchanged, but the output of the previous neuron(s) would not necessarily be exactly the same as the input of the neurons following it.
Alternative Design 2

In 1971, Guy Roy proposed a simple model to reproduce the electrical properties of an axonal membrane\(^2\). Roy’s circuits accurately reproduce the time and voltage dependence of the sodium, potassium, and leak conductance in the membrane. The conductance of each is represented by a simple circuit involving transistors, resistors, capacitors, and operational amplifiers. The circuits are shown in figure 5.

![Potassium Conductance Circuit](image1)

![Sodium Conductance Circuit](image2)

**Figure 5.** 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.
Under certain biasing conditions, field effect transistors (FETs) may be made to behave as variable resistances, which can accurately mimic the time dependence of actual ion channels and are thus used in this model. 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 figure 6.

Figure 6. 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 \( \Omega \) and \( C_M \) has a value of 0.0047 \( \mu F \).

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 will need to be modified in order to achieve the firing characteristics given in Enderle and Zhou (2010). Current pulses will be delivered by a microcontroller, and the output of an excited neuron may be used as the excitatory or inhibitory input to another neuron. Circuitry for such synapses is shown in figure 7.
Figure 7. The circuitry for an excitatory and an inhibitory synapse are shown. These may be used to connect the output of one neuron to the input of another.

All of the neuron groups from Enderle and Zhou (2010) will be represented. The device will be packaged in a moderately sized case, and contacts to record and observe any neuron’s activity will be accessible.
Alternative Design 3

For the construction of the proposed electronic neuron, this alternative design incorporates the FitzHugh-Nagumo (FHN) type neuron. This model is based on the work of Hodgkin and Huxley, where the behavior of the ion channels of the neuron cell membrane is expressed as an electrical circuit. A circuit schematic can be found in figure 1.

This design provides a low cost solution to an otherwise complex problem, consisting of relatively few components, no function generators, and requires little physical space for construction. But if this circuit is to be used, there are several factors to consider. For one, the output is several magnitudes larger than its physiological equivalent. Simulated action potentials are output at approximately five volts, as opposed to the more realistic 100 mV. This is not of great concern, as the output voltage may be dampened or amplified through additional subcircuits based on what is needed.

Each circuit also requires multiple voltage and/or current inputs, which must be accounted for on a per neuron basis or through the use of a central power distribution network for the entire system. Again, this is not a serious problem, inputs may be amplified or dampened in order to accommodate for these requirements.
Overall, this circuit design allows for extensive property manipulation for each of the neuron populations at low cost. In figure 2, the input current source is removed and an additional resistor is supplied to allow for an autonomous oscillating circuit.

![Circuit Diagram](image)

Figure 2. An autonomous FitzHugh-Nagumo schematic is shown. This circuit fires repeatedly without a constant current input with the addition of $R_L$.

Adjustments of this nature allow for the circuit to behave in a similar fashion to such populations as the excitatory burst neuron (EBN), long lead burst neuron (LLBN), and others. Use of this model will require some experimentation in order to ensure the desired firing rates and output voltages, though this will be facilitated by research and design already performed.

References