ABSTRACT

A SIMULINK network that models a Hodgkin - Huxley neuron has been generated. It is a simulation tool that can be used by a neuroscientist that wishes to investigate the expected behaviour of a real neuron when different parameters are systematically changed, or by a neural networks researcher that may wish to investigate the response of a realistic neuron prior to incorporating it in a more complicated neural network. Graphs of the time dependency of membrane potentials, for different operational parameters, have been produced and presented. These show the general, global time response of the neuron.

INTRODUCTION

The Hodgkin and Huxley model of a single neuron is a well-known and extensively used model, especially in computational-neurophysiological studies [(Deutsch & Micheli-Tzanacou, 1987), (Holden et al, 1991)]. It has been generated using measured data from the axon of the giant squid and is considered to describe the voltage-dependent kinetics of real biological neurons with acceptable accuracy (Holden et al, 1991). It is however considerably complicated and thus difficult to use. For this reason, simpler models have been proposed [(FitzHugh, 1961), (Nagumo, et al., 1962), (Troy, 1978), (Chay, 1985), (Bressloff & Taylor, 1991), (Abbott & Kepler, 1991)]. The FitzHugh-Nagumo model is a simplification that has been extensively used as a simple model of biological neurons. Recently, new complicated models of artificial neurons have been proposed that respond in a similar manner as real neurons in pattern identification. Some of these have been used for explorations into artificial neural system computational schemes [(Matsugu & Yuille, 1994), (Petkov & Kruizinga, 1997)]. Since such units are useful in building complicated neural networks, it would be of significant utility if the user had a clear view of the dynamical behaviour of these models. Such a view may be obtained through the use of the proposed implementation.

The input in a network could be continuously varying. Thus a large library of possible input excitations need to be investigated. Furthermore, there exist a multitude of operational parameters that could affect the neuron response. Some of these have been investigated in a systematic manner.

THE HODGKIN AND HUXLEY NEURON MODEL

This model, originally proposed by Hodgkin and Huxley in a seminal paper (Hodgkin & Huxley, 1952), is described by a system of nonlinear-coupled equations. These are shown as equation 1. They are considerably involved and difficult to incorporate in an artificial neural
network. Recently, they have been extended to the 2-dimensional space (Hirose, 1997). For someone to gain a deep understanding of the neuron dynamics, a systematic simulation is preferably needed. Such simulations have been done and presented in the next section of the work.

\[ C_m \frac{dV}{dt} = I - I_m = I - g_{Na} m^3 h(V - V_{Na}) - g_K n^4 (V - V_K) - g_L (V - V_L) \]  

(1a)

\[ \frac{dm}{dt} = \alpha_m (1-m) - \beta_m m \]  

(1b)

\[ \frac{dn}{dt} = \alpha_n (1-n) - \beta_n n \]  

(1c)

\[ \frac{dh}{dt} = \alpha_h (1-h) - \beta_h h \]  

(1d)

where,

- \( V \) = Membrane potential
- \( I \) = Sum of external and synaptic currents entering the cell
- \( I_m \) = Membrane current
- \( m, n, h \) = State variables
- \( V_{Na} \) = Equilibrium (or reversal) potential at which the net flow of Na ions is zero
- \( V_K \) = Equilibrium (or reversal) potential at which the net flow of K ions is zero
- \( V_L \) = Equilibrium (or reversal) potential at which leakage is zero
- \( C_m \) = Membrane capacitance
- \( g_{Na} \) = Sodium channel conductivity
- \( g_K \) = Potassium channel conductivity
- \( g_L \) = Leakage channel conductivity
- \( \alpha_m, n, h \) = Suitable rate coefficients
- \( \beta_{m, n, h} \) = Suitable rate coefficients

Realistic values of the various parameters have been obtained by fitting experimental data. They are:

- \( V_{rest} = -60 \text{ mV} \)
- \( V_{Na} = 50 \text{ mV} \)
- \( V_K = -77 \text{ mV} \)
- \( V_L = -54.402 \text{ mV} \)
- \( g_{Na} = 120 \text{ mmho/cm}^2 \)
- \( g_K = 36 \text{ mmho/cm}^2 \)
- \( g_L = 0.3 \text{ mmho/cm}^2 \)
- \( E = V - V_{rest} \)
- \( \alpha_m = 0.1(25-E)/(e^{(25-E)/10} - 1) \)
- \( \beta_m = 4e^{E/18} \)
- \( \alpha_n = 0.01(10-E)/(e^{(10-E)/10} - 1) \)
- \( \beta_n = 0.125e^{E/80} \)
- \( \alpha_h = 0.07e^{E/20} \)
- \( \beta_h = 1/(1 + e^{(30-E)/10}) \)
Inserting these values the Hodgkin- Huxley equations become as shown below (equations 2).

\[
d\frac{V}{dt} = - 120m^3h(V - 50) - 36n^4(V + 77) - 0.3(V + 54.402) + I \\
\frac{dm}{dt} = 0.1(V + 35)(1 - m)/(1 - e^{-(V+35)/10}) - 4me^{-(V+60)/18} \\
\frac{dh}{dt} = 0.07(1 - h)e^{-(V+60)/20} - h/(1 + e^{-(V+30)/10}) \\
\frac{dn}{dt} = 0.01(1 - n)(V+50)/(1 - e^{-(V+50)/10}) - 0.125ne^{-(V+60)/80}
\]

**NEURON SIMULATIONS**

The set of coupled equations 1 and 2 have been simulated in MATLAB. A SIMULINK block diagram, shown in Figure 1, has been prepared so that a user may have an instant response to different types of inputs. The various operational parameters (\(V_{\text{rest}}\), \(V_{\text{Na}}\), \(V_{\text{K}}\), \(V_{\text{L}}\), \(g_{\text{Na}}\), \(g_{\text{K}}\), \(g_{\text{L}}\)) can be set by the user. This provides flexibility in conducting different simulations, with different operational conditions.

To demonstrate the usability of the network, typical graphs for the time response of the membrane potential for different membrane current inputs is shown in Figure 2.

Similarly the effect of different channel conductivities may be investigated by systematic variation of their values, as shown for the sodium channel in Figure 3.
Figure 1. A SIMULINK block diagram for the Hodgkin - Huxley neuron
Figure 2. Membrane potential for different current inputs

Figure 3. Membrane potential for different membrane sodium channel conductivities
CONCLUDING REMARKS

A SIMULINK network of the Hodgkin-Huxley neuron can be very useful to scientists working in the general area of artificial neural networks, when they would like to use a realistic neuron as a single-neuron model. Also it can be of use to neurophysiologists that may be interested to attain an alternate view of the parametric response of the Hodgkin-Huxley neuron. Figures 2 and 3 show the power of the simulator. Such figures can be generated for a multitude of diverse operational parameters.

REFERENCES