Final Project Report

Intro to Neural and Cognitive Modelling, IIIT-H
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Aim

We intend to use computer simulations to implement Hodgkin-Huxley models of various cells. These cells are drawn from various regions of the brain (like the visual and somatosensory cortices) and from various animals (ferrets, rats, etc.).
We also plot the voltages and the various constituent ion currents, along with their gating variables. We analyse the periodicity of these currents under a repetitive spiking behaviour.

Introduction

The model is an ordinary Hodgkin-Huxley model, implemented for four different types of cells. These are described as regular spiking (RS), fast spiking (FS), intrinsically bursting (IB), and low-threshold spiking (LTS).
We have a set of ion currents (sodium, potassium, and high- and low-threshold calcium), from which we draw terms to add to the models of each of the above types. Thus, each cell type's model consists of a different set of currents, added together to give the final current.

We analyse the composition of the current according to each of the ion currents, for all the models implemented. We correlate their behaviour with the values of the gating variables, and consider how this corresponds to the biological model of the neuron.

The equations used are as follows:

$$C_m \frac{\mathrm{d}V}{\mathrm{d}t} = -g_{\text{leak}}(V - E_{\text{leak}}) - I_{\text{Na}} - I_{\text{Kd}} - I_M - I_T - I_L,$$

$$I_{\text{Na}} = \bar{g}_{\text{Na}}\, m^3 h\, (V - E_{\text{Na}})$$

$$I_{\text{Kd}} = \bar{g}_{\text{Kd}}\, n^4\, (V - E_K)$$

$$I_M = \bar{g}_M\, p\, (V - E_K)$$

$$I_L = \bar{g}_L\, q^2 r (V - E_{\text{Ca}})$$

$$I_T = \bar{g}_T \, s_\infty^2 u \, (V - E_{\mathrm{Ca}})$$

Methods

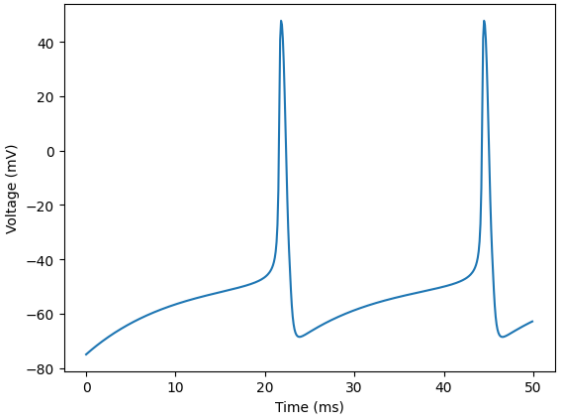
We use the brian2 Python library to simulate the above models. All the relevant code and plots can be found here.
We run the simulation under conditions that create repetitive spiking (the limit cycle stage), but only consider a time period having 2 spikes. This makes the plots easier to read.

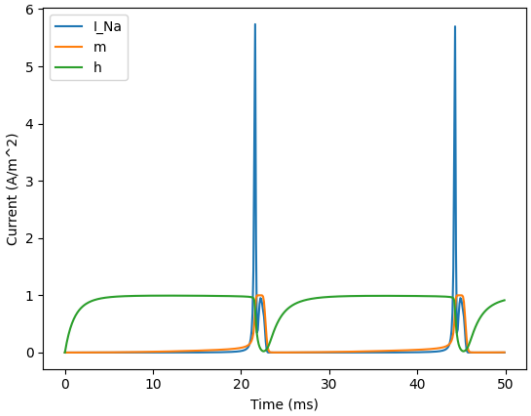
Results

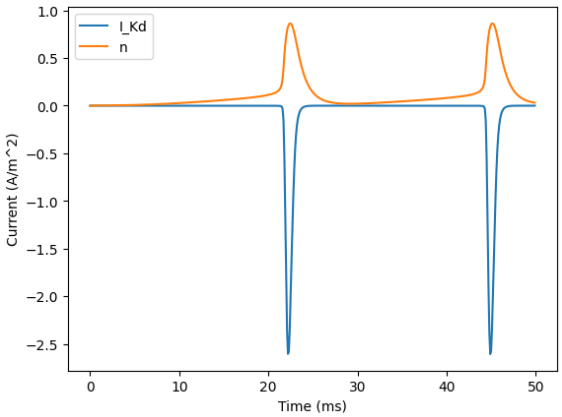
Plots

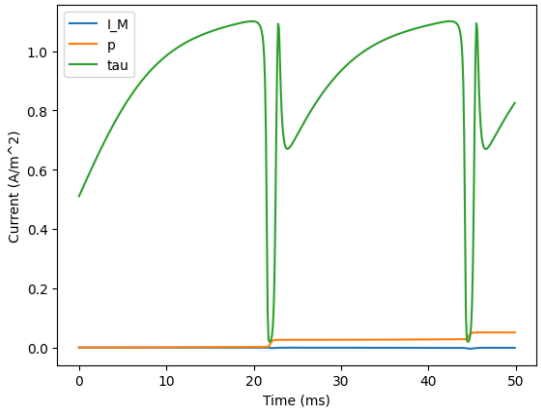
Each cell type has, on average, 2-3 models that we have implemented. For each model, we have plotted the voltage and all the component currents in separate plots.
Thus, for economy of space, we present the plots corresponding to a single model for each cell type.
NB: The axes show the units of current only. Gating variables are dimensionless; τ is plotted in units of seconds.

Regular Spiking (ferret visual cortex)

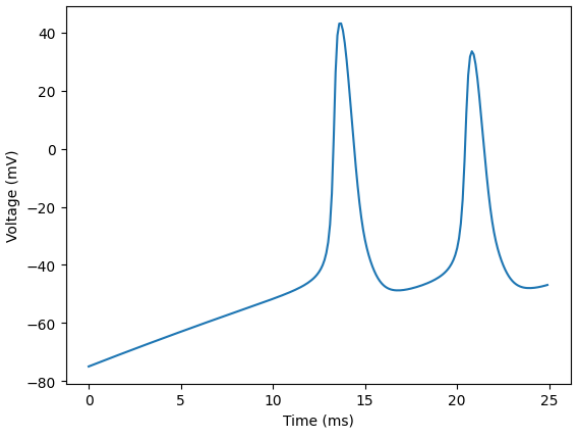


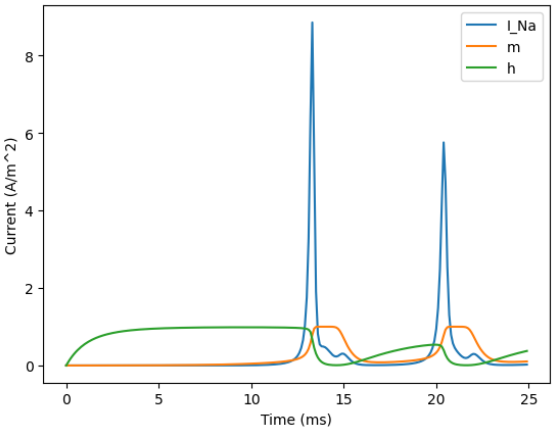


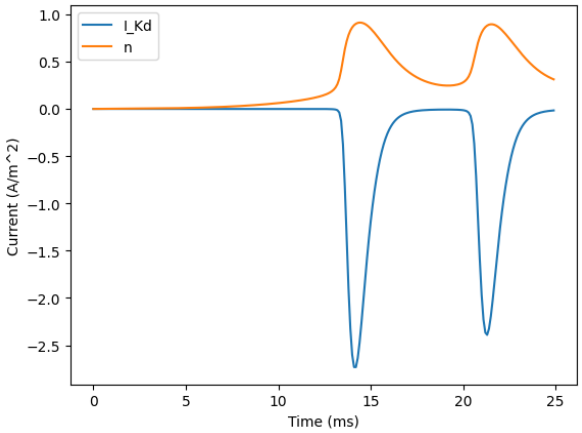


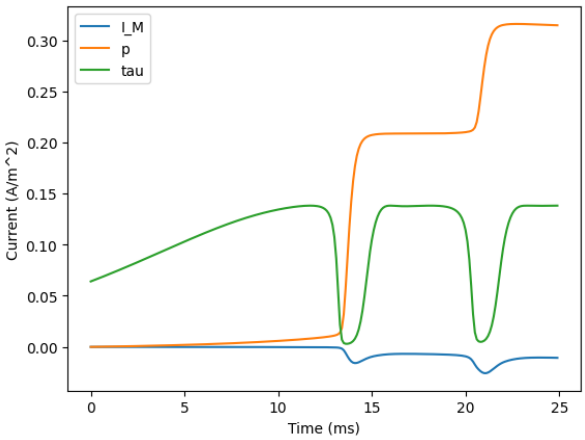


Fast Spiking (rat somatosensory cortex)

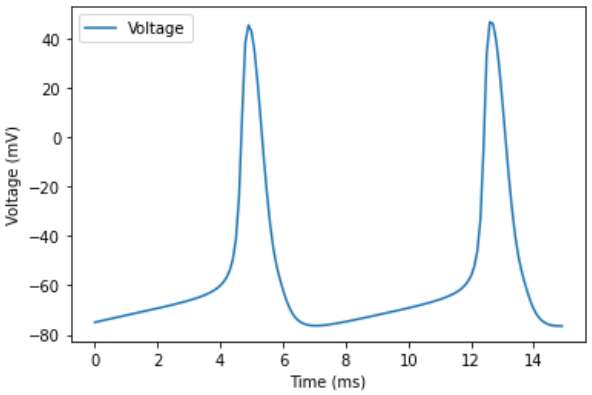


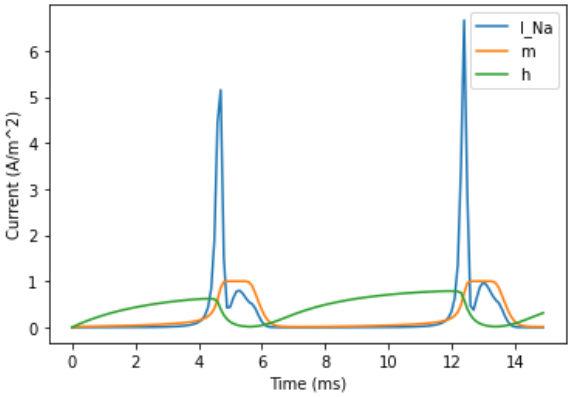


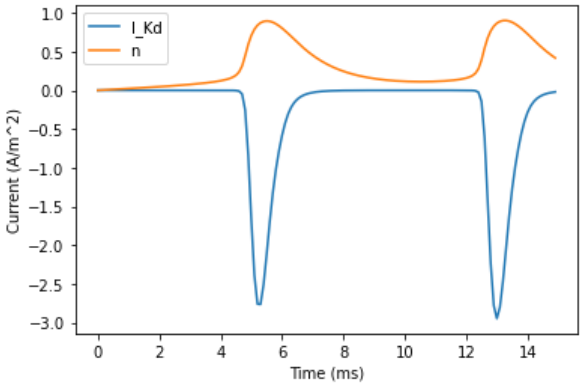


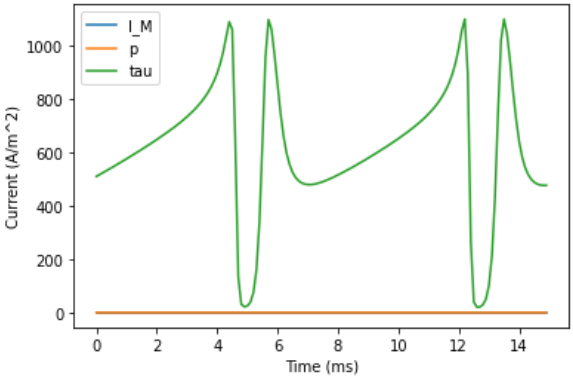


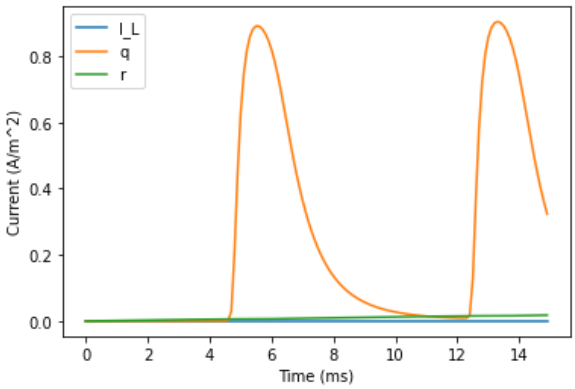
Intrinsically Bursting (guinea pig somatosensory cortex)



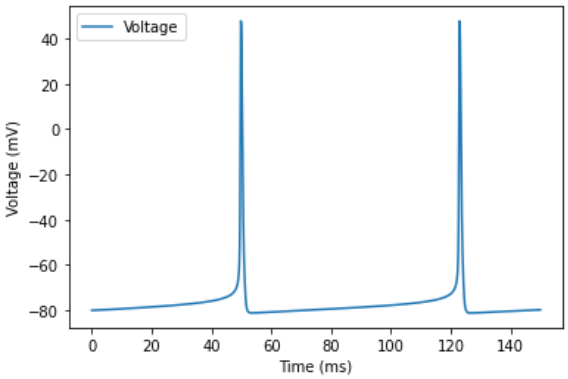


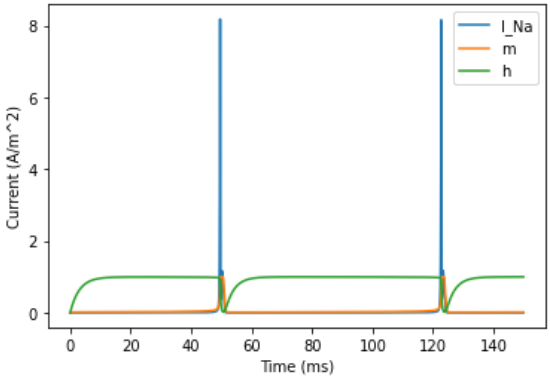


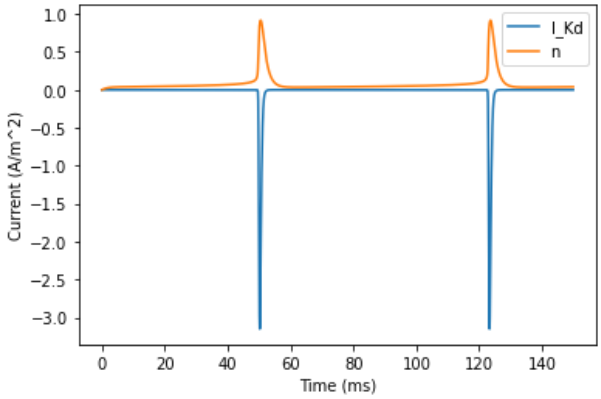


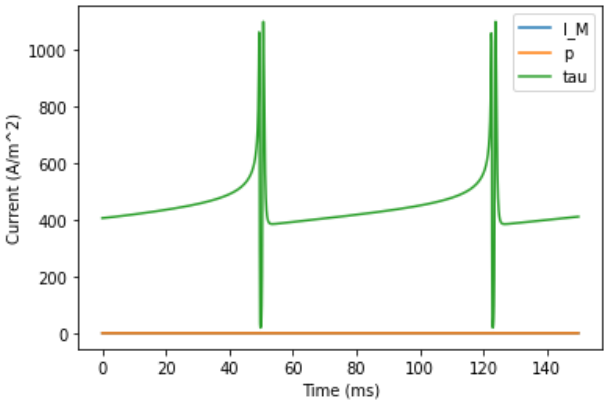


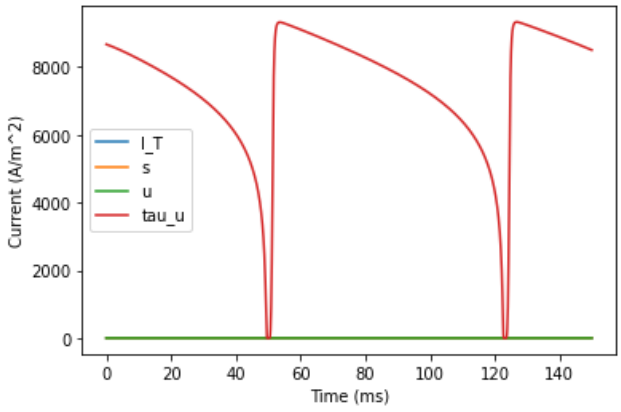
Low-Threshold Spiking (cat association cortex)











Observations

We make the following observations from the above plots:

- The current in most cases is dominated by the sodium current – the spikes in this component correspond exactly to the spikes in the main voltage.
- The potassium and calcium currents play an inhibitory part in the main spike; their values never rise above 0.
- All the component currents model the decrease/increase in the peak of the second spike.

- The second observation that motivates the FHN model – that the gating variables n and h mirror each other – is supported by the graphs.
- The gating variable p (which controls the slow non-inactivating potassium current) is not periodic. It monotonically increases in steps at each spike.

Discussion

We have simulated models of four classes of neurons according to the Hodgkin-Huxley paradigm. We have plotted and analysed the behaviours of the sub-components of the currents, as well as the gating variables controlling them.

The observations correspond to the biological significance of the various components. Across all types, the sodium current is the main component – its spikes correlate exactly with the spikes in the voltage. The potassium currents counteract the effect of the sodium current slightly, as their values remain below 0 consistently.

The second spike may have a lower or higher peak than the first. This models synaptic depression (intrinsically bursting neurons) and facilitation (fast spiking neurons), and is consistently controlled by certain specific gating variables – h in the case of the sodium current and p in the case of the slow non-inactivating potassium current.
The p gating variable plays a huge effect on the value of the non-inactivating potassium current, since its value is not bounded – it keeps increasing monotonically, taking a “step” at each spike, thus pushing the current value further down.

We know that the FHN model is based on the observation that the gating variables h (for sodium) and n (for potassium) have values that “mirror” each other. Our graphs also bear out this assumption, since we can see that n stays close to zero for as long as h is near 1, and they rise and fall (respectively) at the same instants. Thus we can represent them as $w(t) = 1 – h(t) = an(t)$, as assumed in the FHN model.

Thus, the simulations and analyses conducted above have helped to solidify our understanding of single-compartment Hodgkin-Huxley models and how they bring biological realism into the modelling process by modelling each current separately and adding gating variables to simulate ion channels.

References

Pospischil, Martin, et al. "Minimal Hodgkin–Huxley type models for different classes of cortical and thalamic neurons." *Biological cybernetics* 99.4 (2008): 427-441.