Modelling neural dynamics on neuromorphic hardware

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1. Background and motivation

Mathematical models of individual brain cells called neurons can be used in neural networks to simulate large-scale brain activity. Brain-inspired neuromorphic computing systems such as SpiNNaker[1] provide platforms for simulation of complex spiking neural networks (SNNs) incorporating neural models. A wide variety of mathematical models of neurons exist varying in complexity and biological plausibility. SpINNaker currently use a simple single-compartment mathematical model of neurons called Leaky Integrate and Fire (LIF) which contains a single term summarising neural membrane conductance.

Biologically, this conductance is comprised of a number of individual currents flowing through ion-channels within the neural membrane. A more complex model called the Hodgkin-Huxley[2] (HH) neuron model incorporates complex ion-channel models to model membrane conductance, more accurately representing biological neurons. HH neural models have not yet been modelled on SpiNNaker due to the complex mathematical nature of integrating the additional ion-channel components; SpiNNaker is typically limited in terms of precision and restricted in certain mathematical operations, limiting the accuracy and precision of resulting membrane voltage calculations.

2. Mathematical neural models

General equation for calculation of membrane voltage over time for a single compartment neuron:

$$c_m \frac{dV}{dt} = -i_m + \frac{Ie}{A}$$

Where c_m = specific membrane capacitance , V = membrane voltage, i_m = membrane conductance , Ie = injected current and A = area.

The LIF neural model has individual membrane conductance modelled in a single passive leakage term:

$$i_m = \bar{g}_L(V - E_L)$$

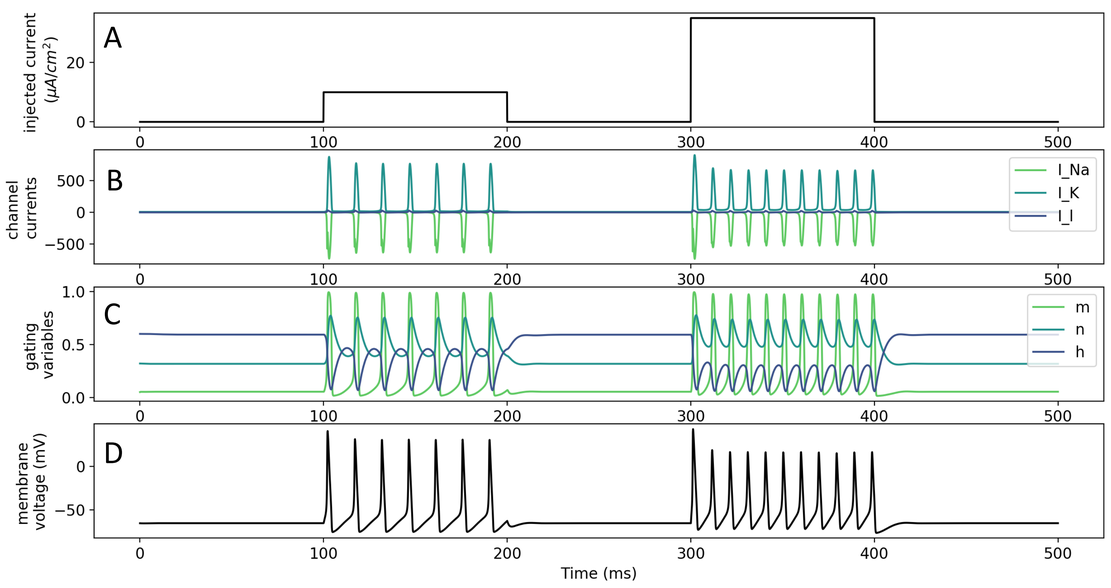
Where $\bar{g}_L$= leakage conductance and E_L= resting potential of cell

HH neurons model the membrane current as the sum of three ion channels: leakage current, delayed rectified K+ channel, and a transient Na+ channel with:

$$i_m = \bar{g}_L(V - E_L) + \bar{g}_K n^4(V - E_K) + \bar{g}_{Na} m^3 h(V - E_{Na})$$

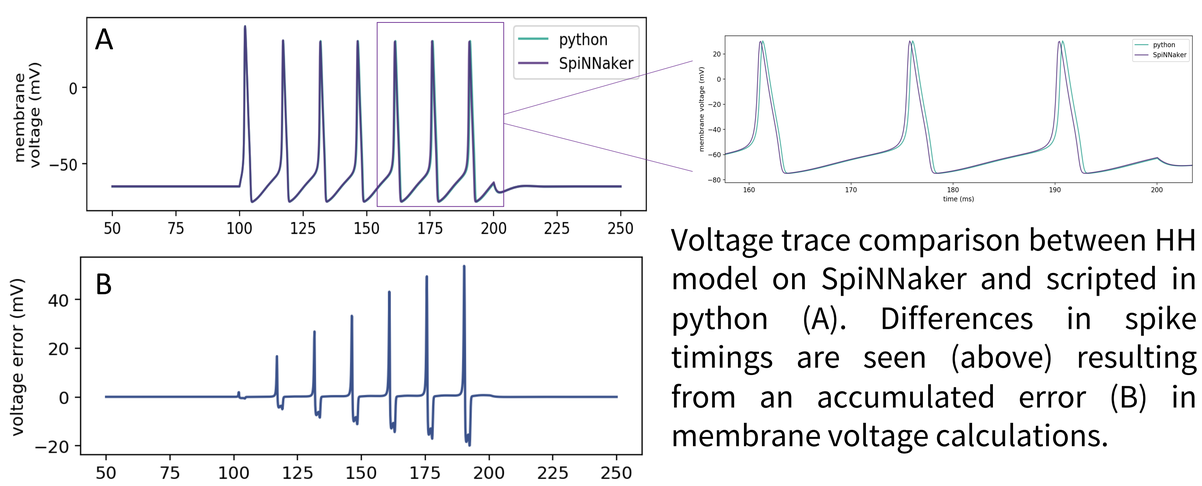
Where *n*, *m* and *h* are voltage-dependent gating variables which vary over time: *r* and *m* are activation variables for K+ and Na+ channels respectively and *h* is ar inactivation variable for Na+ channels. $\bar{g}_K, \bar{g}_{Na}$ = leakage conductances and E_K E_{Na} = reversal potentials.

3. Implementation of HH on SpiNNaker



Current injection (A) into a Hodgkin-Huxley model neuron on SpiNNaker. Resulting traces of current flow through sodium (I_Na), potassium (I_k) and leakage channels (B), activation parameters m, n and h (C) and resulting membrane voltage traces (D).

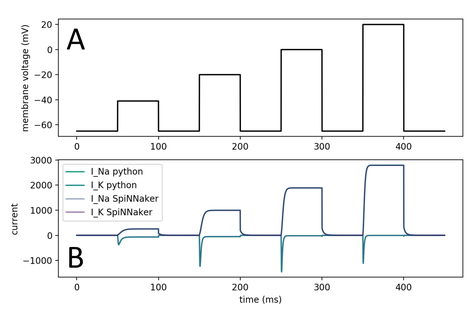
Comparisons with Python



Voltage trace comparison between HH model on SpiNNaker and scripted in python (A). Differences in spike timings are seen (above) resulting from an accumulated error (B) in membrane voltage calculations.

Voltage clamp

Clamping membrane voltage at constant values (A) allows comparison between calculated current values flowing through the sodium and potassium channels (B). Errors observed in membrane voltage calculations (above) are not observed here.



4. Conclusions and future direction

- A Hodgkin-Huxley[2] neural model has been built on SpiNNaker neuromorphic hardware and demonstrates spiking neural activity governed by ion-channel currents flowing through sodium and potassium channels.
- Despite this, error in membrane voltage is accumulated leading to differences in spike timings in comparison with similar models in Python
- Investigation and minimisation of errors is required before incorporation of HH models into complex neural networks.

References

[1] Steve Furber et al. (2013). *Overview of the SpiNNaker System Architecture* , 10.1109/TC.2012.142

[2] Hodgkin, A. L. and Huxley, A. F. (1952). *A quantitative description of membrane current and its application to conduction and excitation in nerve*. The Journal of Physiology, 117(4):500

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