REAL-TIME NEURAL SIGNAL FILTERING VIA HODGKIN-HUXLEY SIMULATION MODELS

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ABSTRACT

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1 INTRODUCTION

2 MOTIVATION & RELEVANCE

In the field of biomedical engineering, extracting action potential timings from noisy extraceulluar recordings is essential in advancing brain-computer interfaces and neuroscience research. While spike detection itself is a signal processing task, the underlying signal can be described and approximated by the Hodgkin-Huxley (H-H) model. This set of non-linear ordinary differential equations models the ionic conductance changes that generate the action potential waveform. Our challenge is to adapt the H-H waveforms to mimic the noise present in real-life data.

Beyond common EEG readings or microelectrode arrays, neural signal filtering and spike detection is relevant to other closed-loop systems such as epileptic seizure prediction (Addai-Domfe & Daoud, 2024) or adaptive deep brain stimulation for Parkinson's disease (Aljalal et al., 2022). Advancements in filtering are further motivated by the advent of high-density neural probes which generate large data streams requiring efficient, accurate processing solutions (Ye et al., 2024). This project aims to develop a spike detection algorithm based on the H-H model to improve accuracy in low signal-to-noise ratio (SNR) environments.

3 SCOPE & FEASIBILITY

The scope of this project builds upon concepts from ESC103: Engineering Mathematics & Computation and MAT292: Ordinary Differential Equations. The work is divided into three primary phases: (1) generating synthetic neural data by solving the Hodgkin-Huxley equations, (2) processing this data with a digital filter, and (3) developing a spike detection algorithm.

3.1 PROJECT OBJECTIVES

The primary objectives of this project are:

1. **Data Generation:** To implement numerical solvers for the Hodgkin-Huxley (H-H) model to generate realistic synthetic action potential data.

2. **Signal Processing:** To design and apply a digital band-pass filter to isolate the spike waveform from the generated signal and added synthetic noise.

3. **Spike Detection:** To develop an algorithm that detects action potentials using an adaptive threshold, calculated from the estimated noise floor of the processed signal.

4. **Validation:** To qualitatively and quantitatively assess the performance of the detection algorithm on the noisy synthetic data.

3.2 Project Milestones & Timeline

4 Technical Background

4.1 The Biological Basis: Ion Channels and Currents

4.1.1 The Cell Membrane and Resting Potential

4.1.2 Voltage-Gated Ion Channels

4.1.3 Sodium-Potassium Pump

4.2 Modeling Neurons as Electrical Circuits

4.2.1 The Parallel Conductance Model

4.2.2 Circuit Analogs: Capacitors, Resistors, and Batteries

4.3 Hodgkin-Huxley Equations

4.3.1 Model Components and Equations

4.3.2 Gating Variables and Activation/Inactivation

4.4 Numerical Methods

4.4.1 Euler's Methods

4.4.2 Runge-Kutta Methods

4.4.3 Comparison of Methods

5 Conclusion

References

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