

Model Predictive Control Strategies for Hodgkin–Huxley Neuron Models in Closed-Loop Neuromodulation – A Simulation Study

Proposal for a Master's or Bachelor's Thesis

Closed-loop neurostimulation and neuromorphic control systems are emerging paradigms in which neural activity is continuously monitored and precisely modulated in real time, offering transformative potential for treating neurological disorders, enabling brain–computer interfaces, and advancing adaptive neuromodulation technologies. The goal of this project is to develop and compare model predictive control (MPC) strategies for regulating neuronal membrane potential in a simulated Hodgkin–Huxley (HH) neuron model, as a step toward such systems. In this setting, the controller continuously monitors neuronal activity and adjusts a biologically meaningful control parameter—the injected current (I_{inj})—which can be positive to depolarize or negative to hyperpolarize the neuron. Adjusting pulse timing, amplitude, and width changes membrane potential trajectories and firing rate, and the control objective is tied to physiological targets such as maintaining a healthy firing rate, preventing sustained depolarization that could damage cells, or inducing specific spike patterns.

Two approaches will be explored: a direct HH-in-the-loop MPC using the full HH equations with short prediction horizons and numerical integration for high accuracy, and a surrogate or reduced-model MPC employing faster approximations to achieve lower computational load. The simulation campaign will compare these methods in terms of stability, tracking accuracy, and computational efficiency, while also accounting for practical constraints, since MPC requires fast optimization where delays may cause instability or missed spikes, and the amplitude and duration of the injected current must remain within safe ranges to avoid tissue damage or unrealistic excitation. Although this study will be conducted entirely in simulation without experimental validation, the results are expected to provide valuable insights for the design of real-time closed-loop neuromodulation systems, bridging the gap from computational modeling to future hardware implementations in applications such as brain–computer interfaces, seizure suppression, and adaptive deep brain stimulation.

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Requirements:

- Strong proficiency in Python programming with experience in numerical simulations, dynamic system modeling, and data analysis
- Understanding of control theory, particularly Model Predictive Control (MPC), and familiarity with neuronal modeling such as the Hodgkin–Huxley model
- Good problem-solving and communication skills in English

