Parameter estimation in hybrid dynamical systems with application to neuronal spiking models

Oral Defense of Doctoral Dissertation
by
Anish Mitra

Master of Science, George Mason University, 2011
Bachelor of Engineering, Birla Institute of Technology, 2007

Committee
Dr. Andre Manitius, Dissertation Director
Dr. Tim Sauer, Member
Dr. Janos Gertler, Member
Dr. Gerald Cook, Member

July 23rd, 2014 at 10:00am
Room 3507, Nguyen Engineering Building

Abstract

Analysis and recreation of brain dynamics has been identified as one of the greatest scientific challenge of this century. Detection of electrical impulses in the brain was the first step towards understanding how it functions. An interconnected network of neurons relay information and communicate with one another through these impulses also referred to as ‘spikes’. Knowledge of the spiking behavior and connectivity in different regions of the brain will help in the diagnosis and treatment of neurological disorders such as epilepsy and Parkinsons disease. There are also efforts to develop intelligent algorithms inspired by the functioning of the brain and build efficient processing and computing units.

Mathematical modeling of neuronal spiking and the different observed phenomenon has helped researchers study the properties of neurons and understand their physiological attributes. Scientists have been able to use these models to develop input-output characteristics. This has enabled us to draw conclusions about brain functionality. Mathematical models can also be used to estimate parameters and neuronal connections that allow the prediction of neuronal spiking activity. Over the last few decades better and more efficient models have been designed. Coupled with the improvement in computing resources, the objective of building a brain simulator is slowly turning into
reality. As models are now able to successfully reproduce cognitive tasks, there is the need of algorithms that can use such models to interpret and analyze biological neurons and connectivity in the brain.

The theory of nonlinear dynamical systems plays an important role in reconstructing brain dynamics. There are various dynamic models, linear and nonlinear, that attempt to generate the neuronal spiking patterns observed experimentally. More recently, discontinuous resets have been introduced in otherwise continuous time models to expand the range of the spiking phenomenon that the model can produce. This also reduces the computational complexity of the system allowing for simulation of larger networks.

This doctoral dissertation focuses on two such hybrid neuron models and describes new methods of system identification based on observations of the neuron. Parameter estimation in a single neuron is achieved by designing a novel spike train comparison technique. The optimal parameters of the model are the computed by using the steepest descent method to locate the minima of the squared error between the model and the experimental spikes. Results show that the optimized model is then able to predict the spiking of the biological neuron. This is indicative of not only the accuracy of the model but also the success of the optimization algorithm that enables the automatic fitting of models to experimental data. For networks of neurons, the least squares estimation technique is implemented to identify the connections. This method proves to be robust and accurate in estimation the connectivity even in the presence of significant model error and observation noise. The sensitivity and specificity measures show that the synaptic connections from excitatory as well as inhibitory neurons are identified correctly. The evolution of the neuronal connectivity is also observed by tracking the generation of new synapses and degeneration of existing ones.