Reading Neural Encodings using Phase Space Methods

Henry D. I. Abarbanel
Evren Tumer

To Larry Sirovich, on the occasion of his 70th birthday.

ABSTRACT
Environmental signals sensed by nervous systems are often represented in spike trains carried from sensory neurons to higher neural functions where decisions and functional actions occur. Information about the environmental stimulus is contained (encoded) in the train of spikes. We show how to "read" the encoding using state space methods of nonlinear dynamics. We create a mapping from spike signals which are output from the neural processing system back to an estimate of the analog input signal. This mapping is realized locally in a reconstructed state space embodying both the dynamics of the source of the sensory signal and the dynamics of the neural circuit doing the processing. We explore this idea using a Hodgkin–Huxley conductance based neuron model and input from a low dimensional dynamical system, the Lorenz system. We show that one may accurately learn the dynamical input/output connection and estimate with high precision the details of the input signals from spike timing output alone. This form of "reading the neural code" has a focus on the neural circuitry as a dynamical system and emphasizes how one interprets the dynamical degrees of freedom in the neural circuit as they transform analog environmental information into spike trains.

Contents

1 Introduction ................................................. 2
2 Input Estimation from State Space Reconstruction .... 3
3 R15 Neuron Model ........................................ 6
   3.1 Input Signals to Model Neuron ...................... 10
   3.2 Numerical Results .................................. 11
4 Discussion ............................................... 18
References ................................................ 20

E. Kaplan et al. (eds.), Perspectives and Problems in Nonlinear Science
© Springer-Verlag New York, Inc. 2003
1 Introduction

A primary task of nervous systems is the collection at its periphery of information from the environment and the distribution of that stimulus input to central nervous system functions. This is often accomplished through the production and transmission of action potentials or spike trains Rieke, Warland, de Ruyter van Steveninck, and Bialek [1997].

The book Rieke, Warland, de Ruyter van Steveninck, and Bialek [1997] and subsequent papers by its authors and their collaborators Brenner, Strong, Koberle, Bialek, and de Ruyter van Steveninck [2000] carefully lay out a program for interpreting the analog stimulus of a nervous system using ideas from probability theory and information theory, as well as a representation of the input/output or stimulus/response relation in terms of Volterra kernel functions. In Rieke, Warland, de Ruyter van Steveninck, and Bialek [1997] the authors note that when presenting a stimulus to a neuron, it is common “that the response spike train is not identical on each trial.” Also they observe that “Since there is no unique response, the most we can say is that there is some probability of observing each of the different possible responses.” This viewpoint then underlies the wide use of probabilistic ideas in describing how one can “read the neural code” through interpreting the response spike trains to infer the stimulus.

In this paper we take a different point of view and recognize that the neuron into which one sends a stimulus is itself a dynamical system with a time dependent state which will typically be different upon receipt of different realizations of identical stimulus inputs. Viewing the transformation of the stimulus waveform into the observed response sequence, as a result of deterministic dynamical action of the neuron one can attribute the variation in the response to identical stimuli to differing neuron states when the stimulus arrives. This allows us to view the entire transduction process of analog input (stimulus) to spike train output (response) as a deterministic process which can be addressed by methods developed in nonlinear dynamics for dealing with input/output systems Rhodes and Morari [1998].

Previous research on information encoding in spike trains has concentrated on nonlinear filters that convert analog input signals into spike trains. It has been shown that these models can be used to reconstruct the dynamical phase space of chaotic inputs to the filters using the spike timing information Sauer [1994]; Castro and Sauer [1997]; Pavlov, Sosnovtseva, Mosekilde, and Anishchenko [2000, 2001]. Using simple dynamical neuron models, Castro and Sauer Castro and Sauer [1999] have shown that aspects of a dynamical system can be reconstructed using interspike intervals (ISIs) properties. Experimental work has demonstrated the ability to discriminate between chaotic and stochastic inputs to a neuron Richardson, Imhoff, Grigg, and Collins [1998], as well as showing that decoding sensory information from a spike train through linear filtering Volterra series techniques can allow for large amounts of information to be carried by