Submitted to 31st Annual Northeast Bioengineering Conference, Hoboken, NJ, April 2-3, 2005

On the Chaotic Nature of Biological Signals: Linear and Nonlinear Data Analysis of Neuronal Action Potentials

John DiCecco, BS, Anna Wagner, Rachel Bartels, and Ying Sun, PhD,
Department of Electrical and Computer Engineering, University of Rhode Island, Kingston, RI 02881-0805 USA

Abstract- Linear time invariant system analysis represents the educational core of the contemporary electrical engineer. While many of the analytical tools that are employed to perform linear analysis, i.e., mean, standard deviation, Fourier transforms, and the like, establish reliable and effective measures of prediction with regard to linear signals, biological signals such as those generated by the central nervous system, require additional considerations. Since the very nature of analysis is to make sense of what is and to apply it to what will be, the concept of predictability is of paramount concern. It has been established that various biological signals, including those used in neuronal communication, are in fact chaotic, making predictability a much more complex issue. A method of decomposing nonstationary and chaotic signals into stationary signals is proposed. By separating nonstationary signals into smaller time intervals, the segmented signal can be evaluated as a stationary signal. As a result, the stationary signal can be studied using linear and nonlinear analysis methodology, since observed chaotic parameters could otherwise be attributed to the nonstationarity. Using the neuronal signals from the pond snail *Lymnaea stagnalis* as a biological signal source, this research identifies and examines the relationships between linear and nonlinear systems.

***Index Terms*— Biomedical engineering, electrophysiology, microelectrode, neurophysiology, nonlinearity, chaos.**

I. Introduction

NONLINEAR systems require special treatment that is superfluous in the analysis of linear systems. Similarly, many of the analytical tools which are considered essential in analyzing linear systems reveal little insight to the nonlinear system. However, many techniques such as signal conditioning, segmentation, and filtering are common to both types of systems and, as such, provide a starting point for analysis.

Biological signals are decidedly nonlinear [1]. At any given moment, the communicatory action of the nervous system is influenced by physical stimuli, chemical stimuli, and electrical stimuli. It is precisely these nonlinear contributions that make analysis difficult, since it is problematic to account for the exact contribution of each underlying system. Stochastic process analysis provides some measure of predictability, but this approach provides only the *probability* of an outcome. For a more concrete treatment, one needs to turn to the mathematics of nonlinearity.

II. Methods

Action Potential Recording Using Microelectrode Methodology

Intracellular recording of neuronal action potentials is a well established, and well documented, procedure [2]. The briefest of descriptions is provided for orientation.

The dissection of *Lymnaea stagnalis* begins with the administration of 0.36M MgCl to anesthetize the animal. The snail is removed from its shell and pinned to a Sylgard lined Petri dish in a solution of snail saline. Microscissors are used to expose the central nervous system (CNS), and the ganglia are removed intact and transferred to a smaller Sylgard lined Petri dish. The structure is stretched and pinned securely for ease of insertion of the microelectrode.

Using a three plane micromanipulator, the tip of the microelectrode is positioned on the surface of a cell membrane. A light tap of the microelectrode headstage eases the microelectrode into the cell and the recording begins.

II. Calculations

As stated previously, some analysis techniques are common to both linear and nonlinear signals. Figure 1a and 1b show a signal and its corresponding Fourier transform. Recall that a discrete time Fourier transform (DTFT) allows a time series

Manuscript received February 14, 2005. This work was supported as a cooperative between the College of Engineering and the College of Arts and Sciences.

John DiCecco is an electrical engineering graduate student at the University of Rhode Island, Kingston, RI 02881 USA (phone: 401-219-1021; e-mail: diceccoj@ ele.uri.edu).

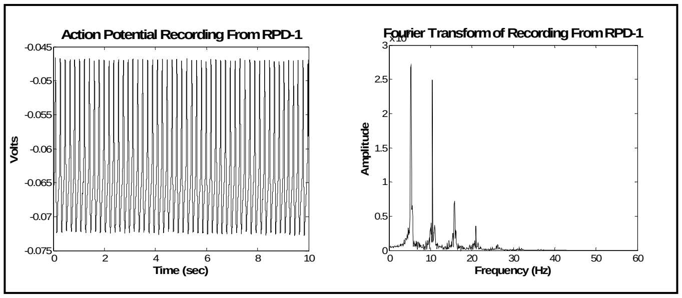
Anna Wagner is a senior biomedical and electrical engineering major at the University of Rhode Island, Kingston, RI 02881 USA

Rachel Bartels is a high school senior at South Kingstown High School, South Kingstown, RI 02881 USA

Dr. Ying Sun is a professor of biomedical and electrical engineering at the University of Rhode Island, Kingston, RI 02881 USA

signal to be represented in the frequency domain according to the following transformation:

$$\Im(x[n]) = X(\omega) = \sum_{n=-\infty}^{\infty} x[n]e^{-j\omega n}$$



Figures 1a and 1b. Figure a (left) shows a 10 second recording from the neuron RPD1. Figure b (right) shows the corresponding frequency components of the signal, with a fundamental at approximately 5 Hz and subsequent harmonics extending to just above 20Hz.

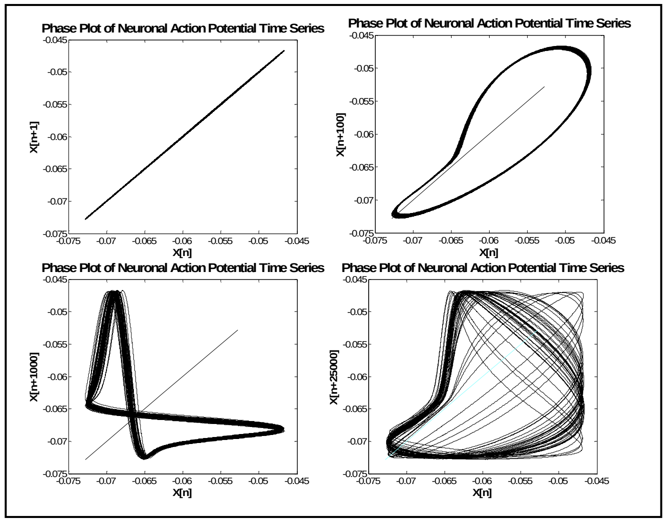
Before establishing the notion of chaos in a signal, it must be shown that the signal is stationary. Given its importance to the underlying nonlinear analysis, a signal will be defined as stationary if it's mean (1) remains constant over the range of the function and its autocorrelation (2) is strictly a function of the time difference between samples [4]. In random processes, these criteria define a signal which is wide sense stationary (WSS), a condition that is less rigid than SSS or strict sense stationary, but is sufficient to allow for the proof of chaos.

(1) $E\left[X(t)\right] = \mu_x$

(2) $E\left[X(t_1)X(t_2)\right] = E\left[X(t_1)X(t_1+\tau)\right]$

Although stationarity is necessary for the proof of chaos, it by no means insures chaos. A further criteria for proving chaos is the existence of at least one positive Lyapunov exponent, where the sum of all Lyapunov exponents is less than or equal to zero [5]. For clarification, a Lyapunov exponent describes the rate at which a trajectory deviates from its previous trajectory in phase space. For instance, a periodic signal, which by definition cannot be chaotic, has a two dimensional phase space with no deviation from its trajectory; it stays on its phase trace.

Figures 2a-2d illustrate the concept of phase space while employing another useful technique in nonlinear analysis. Time delay or embedded phase space analysis allows one to view the progression of a signal versus a delayed, or advanced, version of the signal. If the signal were periodic, its phase plot would not be affected by a delay or advance. The figures clearly show a waveform that is becoming more irregular as the time delay is increased. This irregularity is caused by the highly nonlinear components of the signal and is quantized by the degree to which the [x+1] trajectory deviates from the [x] trajectory.



Figures 2a-2d. . From top left, a signal mapped versus the same signal delayed by an increasing number of samples. Notice the progression, from left to right, top to bottom, as the signal begins to leave its previously well defined orbit. The x=y line is provided for spatial

III. DISCUSSION

The concepts of linear time invariant (LTI) systems are ubiquitous in modern electrical devices, whether they are used in synthesizers, transmitters, receivers or filters. However, biological signals are not linear and are therefore only partially elucidated by the analytical techniques used to address linear signals. To get a more accurate portrait of a nonlinear signal, it must be analyzed with nonlinear methodology.

ACKNOWLEDGEMENTS

The authors would like to thank neurobiology Pr. Kiyoaki Kuwasawa of the Okayama University of Science in Japan for his impeccable dissection technique and ability, and research Pr. Bob Hill of the University of Rhode Island Department of Biological Sciences for his vast knowledge of physiological processes.

This study was supported in part by NIH Grant No. 1 R43NS048682-01A1 and the URI Partnership in Physiological Measurements and Computing.

REFERENCES

[1] Betolaccini, Bussolati and Padovini. IEEE Trans. on Bio. Engin.. *A nonlinear filtering technique for the identification of biological signals*. 1978 Mar 25(2):159-65.

[2] Borradaile, L.A. and Potts, F.A. The Invertebrata: A manual for the use of students. Cambridge University Press, 1958.

[3] MATLAB is a registered trademark of The MathWorks, Inc, Natick, MA. http://www.mathworks.com.

[4] Leon-Garcia, Alberto. *Probability and Random Processes for the Electrical Engineer*. Addison-Wesley Publishing, 1994.

[5] Hillborn, Robert C. *Chaos and Nonlinear Dynamics*. Oxford University Press, 2000.