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Identification of time-varying neural dynamics from spike train data using multiwavelet basis functions

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HIGHLIGHTS

- The proposed multiwavelet-based time-varying generalized Laguerre-Volterra (TVGLV) method is a novel and intuitive way of modeling time-varying neural dynamics from spike train data.
- The proposed method gave excellent results of revealing time-varying system properties for synthetic spike train data and real datasets from spontaneous retinal spike train recordings.
- The proposed method provides a more powerful performance of tracking time-varying parameter changes comparisons than existing time-varying parametric estimation methods.

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ABSTRACT

Background: Tracking the changes of neural dynamics based on neuronal spiking activities is a critical step to understand the neurobiological basis of learning from behaving animals. These dynamical neurobiological processes associated with learning are also time-varying, which makes the modeling problem challenging.
New method: We developed a novel multiwavelet-based time-varying generalized Laguerre–Volterra (TVGLV) modeling framework to study the time-varying neural dynamical systems using natural spike train data. By projecting the time-varying parameters in the TVGLV model onto a finite sequence of multiwavelet basis functions, the time-varying identification problem is converted into a time invariant linear-in-the-parameters one. An effective forward orthogonal regression (FOR) algorithm aided by mutual information (MI) criterion is then applied for the selection of significant model regressors or terms and the refinement of model structure. A generalized linear model fit approach is finally employed for parameter estimation from spike train data.
Results: The proposed multiwavelet-based TVGLV approach is used to identify both synthetic input-output spike trains and spontaneous retinal spike train recordings. The proposed method gives excellent the performance of tracking either sharply or slowly changing parameters with high sensitivity and accuracy regardless of the *a priori* knowledge of spike trains, which these results indicate that the proposed method is shown to deal well with spike train data.
Comparison with existing methods: The proposed multiwavelet-based TVGLV approach was compared with several state-of-art parametric estimation methods like the steepest descent point process filter (SDPPF) or Chebyshev polynomial expansion method. The conventional SDPPF algorithm, or SDPPF with B-splines wavelet expansion method was shown to have the poor performance of tracking the time-varying system changes with the synthetic spike train data due to the slow convergence of the adaptive filter methods. Although the Chebyshev polynomial basis function method gave the good parametric estimation results, it requires prior parameter estimation. It was shown that the proposed multiwavelet-based TVGLV method can track the time-varying parameter changes rapidly and accurately.

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Conclusions: The multiwavelet-based TVGLV modeling framework developed in this paper can not only provide a computational modeling scheme for investigating such nonstationary properties, track more general forms of changes in time-varying neural dynamics, and but also may potentially be applied to investigate the spatial-temporal information underlying biomedical spiking signals.

1. Introduction

Neurobiological processes underlying spiking activities including dendritic integration, synaptic transmission and spike generation across brain regions are challenging tasks to study during behavioral experiments. Certain forms of plasticity can be regarded as a time-varying change in the input-output function between neuronal ensembles (Yger and Gilson, 2015; Feldman, 2012). To better understand the mechanisms underlying these time-varying processes, two major classes of model identification approaches for time-varying (TV) systems using spike train signals have been proposed which are briefly described as follows.

The first class time-varying parametric estimation approach is adaptive filtering. For example, the adaptive point process filters iteratively updates the model parameters based on the difference between the occurrence of a real spike and the estimated probability (Eden et al., 2004). This method has been adopted in establishing dynamical modeling framework to track time-varying neural systems, and successfully applied to reconstruct monkey hand movement trajectories from a dynamic ensemble of spiking motor cortical neurons (Chan et al., 2011; Song et al., 2015; Eden et al., 2004). However, if the model coefficients changed sharply, adaptive filters might not be capable of capturing the transient properties of the time-varying systems due to the potential deficiency in slow convergence of adaptive filters method (Li et al., 2016).

The second class is the basis function expansion method which estimates the TV parameters by projecting them onto a set of a finite number of predefined basis functions (Zou et al., 2003). This transforms the time-varying identification problem into an expansion-based time-invariant parametric modeling scheme. An obvious advantage of basis function expansion method is that the number of the unknown parameters required to estimate each time-varying parameter will significantly be reduced. Among these, various basis functions are available, such as Fourier series (Niedzwiecki, 2000), Walsh function (Gnoffo, 2014), Legendre series (Mohammadi et al., 2011), Laguerre polynomials (Liu et al., 2012), and wavelets (Li et al., 2016). Indeed, any complete set of basis functions can also be employed to approximate the TV coefficients for identifying the changes in system dynamics with acceptable accuracy if the number of basis functions used is sufficient. However, choosing a proper basis function is essential to capture the form of changes if the number of the basis functions is restricted to minimize the number of parameters to be estimated. In this case, each family of basis functions should be considered based on its own unique fit to the kernel shape. For instance, numerical experiments by Lee and Chon (2011) showed that the Cheybshev or Legendre polynomials are efficient for smoothly or slowly parameter changes over time. Walsh functions, on the other hand, work well for TV parameters that have sharp variations or piecewise stationary changes. In capurting sharp jumps or step changes in the time-varying model, Aziz and ul Islam (2013) demonstrated that Haar basis functions perform better than Legendre basis function. As proof-of-concept of its applicability to systems with spike train inputs and outputs, we have extended the Chebyshev basis expansion technique with Generalized Linear Model and tested its performance in both simulations and experimental data (Xu et al., 2016). However, *a priori* knowledge of the inherent dynamics with a time-varying system is commonly required to select the proper basis functions. For example, a biological system generally involves multitudes of varying dynamics, thus multiple basis functions should be adopted to reveal the potential time-varying properties (Lee and Chon, 2011).

Recently, a series of research studies have been conducted on the use of wavelet-based time-frequency analysis for biomedical signal processing (Fan et al., 2015; Faust et al., 2015). Wavelet is a function localized both in time and frequency domain (Wang et al., 2013), which can be used to represent an abrupt variation or a local function vanishing outside a short time interval (Li et al., 2016, 2011). Several wavelet-based approaches have been proposed under the basis function expansion scheme. For example, Li et al. (2011a, 2011b) combined the cardinal B-splines basis function with a block least mean square algorithm to track both slow and rapid changes of time-varying coefficients effectively in time-varying linear systems. He et al. (2015) extended this method to the identification of nonlinear time-varying systems and obtained promising results of tracking time-varying variations from EEG nonstationary data. However, exploiting the attractive properties of multiwavelets has not been previously applied in time-varying neural dynamics identification based on the binary spike train data that is always rather sparse with low firing rates. A great number of modeling experience shows that the initial full regression model expanded by basis function expansions is usually redundant, indicating that some linearly dependent candidate regressors can be removed from the full regression model. Therefore, the parsimonious model with only some significant model terms can commonly produce reliable results. One of the most popular way for realizing this goal is to implement a penalized regression approach, *i.e.* least absolute shrinkage and selection operator (LASSO) and its related methods (Tibshirani, 1996). However, the LASSO usually cannot guarantee the consistency of the model term selection, and some noisy terms may often be wrongly selected. In addition, the computation for this methods might be challenging (Li and Sillanpää, 2012). An orthogonal least squares (OLS) algorithm with the adoption of error reduction ratio (ERR) criterion is also generally used to select the significant regressors and refine the model (Li et al., 2016). However, the OLS-ERR type algorithms may occasionally select some spurious model terms because the measured data are usually corrupted by certain noise sequences or the inputs are poorly designed, and thus the potential spurious models commonly have bad model generalization properties (Wang et al., 2013).

In this paper, we propose a novel multiwavelet-based time-varying generalized Laguerre–Volterra (TVGLV) model to study the underlying dynamics between multiple neuronal units by observing spiking inputs and outputs only. Specifically, the time-varying parameters of the TVGLV model are first projected onto multiwavelet basis functions with multiple time-varying properties, where both rapid and slow changes of TV parameters can be effectively tracked simultaneously. In addition, instead of the OLS-ERR type algorithms, an effective forward orthogonal regression (FOR) aided by mutual information (MI) criterion (FOR-MI) algorithm is used to determine the model structure selection and model refinement, and thus the redundant or spurious terms or regressors from the initial full regression model can be effectively removed.