Human Movement Science 51 (2017) 27–40

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Full Length Article

Wavelet-frequency analysis for the detection of discontinuities in switched system models of human balance

Salam Nema [a,*], Piotr Kowalczyk [a], Ian Loram [b]

[a] School of Computing, Mathematics and Digital Technology, Manchester Metropolitan University, Manchester, UK
[b] School of Healthcare Science, Manchester Metropolitan University, Manchester, UK

ARTICLE INFO

Article history:
Received 17 March 2015
Revised 3 August 2016
Accepted 4 August 2016
Available online 10 November 2016

Keywords:
Switched systems
Wavelets
Normalized Hilbert transform
Discontinuities
Instantaneous frequency

ABSTRACT

This paper is concerned with detecting the presence of switching behavior in experimentally obtained posturographic data sets by means of a novel algorithm that is based on a combination of wavelet analysis and Hilbert transform. As a test-bed for the algorithm, we first use a switched model of human balance control during quiet standing with known switching behavior in four distinct configurations. We obtain a time–frequency representation of a signal generated by our model system. We are then able to detect manifestations of discontinuities (switchings) in the signal as spiking behavior. The frequency of switchings, measured by means of our algorithm and detected in our models systems, agrees with the frequency of spiking behavior found in the experimentally obtained posturographic data.

1. Introduction

Many engineering and biological systems are characterized by the presence of switchings and/or dynamics evolving over multiple time scales. For instance, brain activity, which is measured by means of Electroencephalography (EEG), is characterised by natural time scales related to spiking and bursting behaviour, with the dynamics evolving over time scales ranging from milliseconds to minutes. Feedback control mechanisms used, for instance, in power engineering contain switching elements which, on the macroscopic scale, may be considered as acting instantaneously. In robotics, the control problem of biped robots has several characteristics such as the inherent instability of two-legged motion, high-dimensional dynamics, and the existence of different phases of the walking cycle, which require a fuzzy switching control system to represent the continuous-time dynamics and discrete event dynamics of a walking biped (Liu, Zhang, & Wang, 2007).

In recent years, much of research effort has been spent on understanding the character of control strategy which ensures human balance control during quiet standing. Human balance control during quiet standing is often modelled using linear, continuous time systems (Jeka, Kiemel, Creath, Horak, & Peterka, 2004; Kiemel, Oie, & Jeka, 2002). These models exclude thresholds, instantaneous switchings and time variant processes such as open loops. However, impulsive like muscle movements have been detected during quiet standing (Bottaro, Yasutake, Nomura, Casadio, & Morasso, 2008), and so it should come as no surprise that among the biomechanics community switched and intermittent control models have been used to account for sway dynamics during quiet standing (Gawthorp, Loram, Lakie, & Gollee, 2011). There is currently a controversy whether human quiet standing can be better captured by a linear time invariant process, or whether it is an intermit-

* Corresponding author.
E-mail address: s.nema@mmu.ac.uk (S. Nema).

http://dx.doi.org/10.1016/j.humov.2016.08.002
0167-9457/

tent or switched control that can better capture the balance control mechanism. The aim of the current work is to find in experimental posturographic data sets the possible existence of switching transitions (discontinuities). To this aim we propose an algorithm which would allow one to detect time instances of the occurrences of discontinuities in signals generated by switched systems with noise. In particular, we are interested in determining time instances when a PD (proportional-derivative) control is switched on/off when a state variable crosses some threshold value.

Several methods have been proposed in the literature for different applications to detect change points in the process data. For instance, auto-covariance methods (Killick & Eckley, 2013), time-domain methods (Thornhill & Horch, 2007; Theron & Aldrich, 2004) and spectral methods (Antoniadis & Gijbels, 2002; Babji, Gorai, & Tangirala, 2009) have been considered. In particular, Killick and Eckley (Killick & Eckley, 2013) introduced a method to detect changes in general auto-covariance structure within non-stationary time series data. Their method is based on locally stationary wavelet framework and does not assume a specific structure for the auto-covariance. Thornhill and Horch (Thornhill & Horch, 2007) developed a time-domain approach for detecting and diagnosing plant-wide control system disturbances in chemical processes. Antoniadis and Gijbels (Antoniadis & Gijbels, 2002) have contributed to the methodology available for dealing with the detection and the estimation of the location of discontinuities by implementing a curve fitting estimation method followed by wavelet smoothing to detect and locate discontinuities in a time series data. Babji et al. (Babji et al., 2009) proposed a method based on Hilbert–Huang Transform to detect control valve nonlinearity. The nonlinearity can be captured by Intrinsic Mode Functions obtained from the Empirical Mode Decomposition of the process output. Inoue and Sakaguchi (Inoue & Sakaguchi, 2015) proposed an analysis method for extracting intermittent discontinuities observed in human hand movement using the amplitude and phase information of the complex wavelet transform. It was found that the discontinuous changes in the velocity profile roughly corresponded to specific peak positions in the jerk profile, and confirmed that these peaks could be effectively detected by continuous wavelet transform with a Gaussian derivative kernel.

Each of these methods relies on the recognition of certain characteristics of the process data, and they are dependent on the domain of analysis. The character of discontinuities that we are concerned with here is different from all these cases in so far that we are interested in revealing discontinuities in a deterministic signal buried in noise. Let us suppose that we are concerned with a switched system with additive noise that is switching between two distinct differentiable vector fields when a control variable crosses some threshold value. A system trajectory, ignoring the presence of noise, will contain discontinuity in one of its derivatives. Added noise will have some 'linearising' effect on this 'deterministic' discontinuity (Gammaitoni, 1995). The question now arises how could one detect these types of discontinuities in a signal. That is, to investigate the 'deterministic' part of a stochastic system it is required to separate the 'deterministic' components of a signal 'buried' in additive noise. Thus we need to reconstruct the signal without noise components.

As explained by Boashash in (Boashash, 1992), for non-stationary processes, produced signals do not lend themselves well to decomposition into sinusoidal components, and they cannot be represented in a meaningful way by Fourier expansions. Consequently, a time series data of a switched or time variant stochastic system cannot be represented by a Fourier series due to the apparent presence of non-stationarity. In such cases, the notion of frequency looses its effectiveness, and one needs to use a parameter which accounts for the time-varying nature of the process. Therefore, for non-stationary signals, in which frequency value changes at any moment, it is more useful to characterise the signal in terms of its Instantaneous Frequency (IF), which is a time dependent representation of the frequency of a signal at any moment. It is the instantaneous frequency which will provide us with the information on the presence of discontinuities in a signal at any given time instant.

In this article, we propose a novel Wavelet-Frequency Analysis algorithm for detecting discontinuities in time series data of switched systems with additive white noise by combining the advantages of discrete Wavelet decomposition technique and Normalized Hilbert Transform (NHT). The wavelet analysis can extract important information of switched model systems at different time intervals, and the computed instantaneous frequency can effectively provide us with the information on the presence of discontinuities in the signal at any given time instant. In the designed algorithm, we introduce an energy wavelet decomposition technique to resolve one key obstacle for computing a meaningful instantaneous frequency from a multicomponent signal by reducing it to a collection of monocomponent functions. Once we obtain the monocomponent signals, the instantaneous frequency can be computed using the Normalized Hilbert Transform method. Therefore, a practical wavelet filtering technique has been used to help to decompose the data into monocomponents. It was found that, this decomposition approach has effectively worked as a special band pass filter. One of the advantages of this technique is that it allows us to decompose the data into a set of independent coefficients with a coefficient corresponding to each of the orthogonal basis functions. These monocomponents were then analyzed and recombined into a signal that contained the instantaneous frequency reflections, but not the switched system main response or the noise.

The paper is organized as follows: Section 2.1 discusses the wavelet-based method that we are going to use, whereas Section 2.2 presents an outline of the frequency analysis technique for estimating the instantaneous frequencies. Section 2.3 illustrates the details of the proposed algorithm. Then in Section 3, we present the detection of discontinuous nonlinearities in simulated data sets produced by different model systems. We also consider posturographic data sets in which we identify spiking features resembling those found in our switched model systems. At the end of this section, we evaluate the performance of our algorithm by comparing it against other detection methods available in the literature. Finally, Section 4 concludes the paper and outlines our future work.