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Cross-correlation of bio-signals using continuous wavelet transform and genetic algorithm

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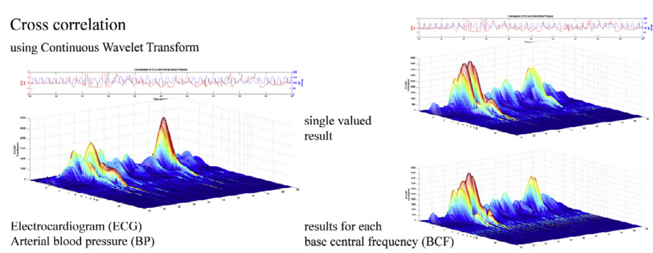
HIGHLIGHTS

- Extension of wavelet transform correlation analysis of the biophysical signals.
- Cross-correlation performed using continuous wavelet transform and genetic algorithm.
- Solving time delay vector for each of the base center frequencies of two signals.
- Examination on correlation of electrocardiography and blood pressure signals.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: Continuous wavelet transform allows to obtain time-frequency representation of a signal and analyze short-lived temporal interaction of concurrent processes. That offers good localization in both time and frequency domain. Scalogram and coscalogram analysis of two signal interaction dynamics gives an indication of the cross-correlation of analyzed signals in both domains.
New methods: We have used genetic algorithm with a fitness function based on signals convolution to find time delay between investigated signals. Two methods of cross-correlation are proposed: one that finds single delay for analyzed signals, and one returns a vector of delay values for each of wavelet transform sub-band center frequencies. Algorithms were implemented using MATLAB.
Results: We have extracted the data of simultaneously recorded encephalogram and arterial blood pressure and have investigated their interaction dynamics. We found time delay whose value cannot be precisely determined by scalograms and coscalogram inspection. The biomedical signals used come from MIMIC database.
Comparison with existing method(s): Cross-correlation of two complex signals is commonly performed using fast Fourier transform. It works well for signals with invariant frequency content. We have determined the time delay between analyzed signals using wavelet scalograms and we have accordingly shifted one of them, aligning associated events. Their coscalogram indicates the cross-correlation of the associated events.
Conclusion: Introducing new methods of wavelet transform in cross-correlation analysis has proven to be beneficial to the gain of the information about process interaction. Introduced solutions could be used to reason about causality between processes and gain bigger insight regarding analyzed systems.

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1. Introduction

Wavelet analysis is a useful tool to extract information regarding signal frequency components that may vary with time. In other words, using this tool, we obtain signal representation in the time-frequency domain. Using wavelet transforms of signals it is also possible to detect their temporal interactions or temporal interactions of their frequency components. As an output, concurrent processes evaluation tools can provide graphical interpretation of signals' events – meta-information obtained using signal analysis. That information can be used to reason about causality and co-occurrence between processes, identify events and take appropriate actions in a given situation.

It may occur that interaction analysis of two processes (performed in time-frequency domain) fails to provide any meaningful information, or may even mislead about causality in the processes when one of the processes is delayed. Then, even if an event represented in the signal has a corresponding event in the other (simultaneously recorded) analyzed signal but a delay occurs, the correlation analysis may be incorrect. On the other hand, the information about delay between two processes gives insight about the way in which the two processes interact with each other.

The correlation analysis has numerous applications that span across many fields like, e.g. computer graphics, medicine, financial markets, geology and engineering. In their paper, (Kenett et al., 2010) mention several examples of such research on stock prices interaction analysis in a financial market. In medical applications, process correlation is used in physiological signals analysis, e.g., (Penishev et al., 2013) use cross-correlation of EEG signals in diagnosing schizophrenia. In Addison et al. (2002), the Morlet wavelet scalogram is used to detect a previously unknown coordinated contractility behavior of the atrium during ventricular fibrillation, a phenomenon which is not captured in a normal electrocardiogram. Kelley et al. (2001, 2005), used Morlet wavelet scalogram and coscalogram to examine the initial stiffness degradation of the wind turbine rotor that was found to be primarily due to early presence of high frequency energy that causes excitation of higher structural modes leading to response coupling and energy exchange between modes. Similar applications of the Morlet Wavelet Transform (MWT) can also be found in González et al. (2008), and Białasiewicz et al. (2013). There are many other examples of such recent research in multiple fields which show that signal interaction analysis is an important process of many applications.

One of the important applications concerns the analysis of interaction dynamics of concurrent processes that may take place at distant points of complex dynamic systems. The neuroscience research community is interested in the interaction dynamics between two anatomically distant neuronal populations (Li et al., 2007) as in the interactions between cardiomuscular events (taking place in the ECG) and other events in the human body, such as events that appear in the BP signal (Gross and Białasiewicz, 2014). In these publications some qualitative evaluations of interaction dynamics are investigated. For effective use of these measures, Gross and Białasiewicz (2014), developed in MATLAB (RRID: nlx_153890) a user-friendly Graphical User Interface (GUI) that enables the user to load two processes under investigation, make choice of the required processing parameters and then perform the analysis. However, the time delay between the investigated processes was not considered. This has been the topic of research whose results are reported in the current paper.

Time delay analysis could be done manually by shifting the signal in time domain but it is almost impossible to accurately set delay in such measurements in a non-automatic manner, because whole signal timeframe has to be taken into account. Obviously such approach also involves providing an input from a person analyzing processes, which is accordingly trained to use the software and tools.

Calculation of the coscalogram, based on the time-delay-corrected convolution of continuous wavelet transforms provides a detailed information about the interaction of signals in the time-frequency domain. The purpose of this paper is to present the introduced correlation methods that can be incorporated into the CWT analysis.

2. Materials and methods

The correlation analysis of the electrocardiogram (ECG) and arterial blood pressure (BP) signals shows the way that those processes interact. Such signals, when processed with signal transform methods can provide useful information about the state of the patient, giving insight about state of a physiological system. In interaction evaluation, time delay between ECG and BP has to be taken into account to provide more accurate insight into the way how the two processes influence each other. To obtain better results and thus draw conclusions from the correlation of two processes, BP signal had to be shifted in time domain accordingly to the occurring time delay.

The signals used in this paper come from MIMIC[1] Database (Goldberger et al., 2000) made freely available on PhysioNet website (http://physionet.org/).[2] MIT's PhysioNet is part of the project whose goal is to provide easy to use tools to access physiological data. MIMIC database contains high-resolution recordings of multi-parameter data coming from monitoring critically ill patients in intensive care units. Database has been made publically available to support research community for researchers that do not have access to the medical environment. Furthermore, using known, publically available database makes it possible to objectively compare research results. In the data used, coming from MIMIC database, the delay between ECG and BP processes is visible during the analysis of signal scalograms and coscalogram, as shown in Fig. 1.

The relationship between scale and frequency of the Continuous Wavelet Transform is of fundamental importance to the scalogram/co-scalogram representation of the local energy density of the signals considered. It is important to choose mother wavelet or wavelet at scale $s = 1$ with high frequency resolution or narrow bandwidth. The increase of the scale s improves the frequency resolution at lower frequencies. For a constant scale (or constant center frequency) we can vary the frequency range of analysis using different sampling frequencies. Since the frequency resolution is much better for the higher scales (or lower frequencies), the poor resolution at higher frequencies can be improved by oversampling the analyzed signals at such rate that the constant bandwidth frequency strips, corresponding to low scales, in particular to $s = 1$, will not contain any useful frequencies, i.e., the frequencies of analyzed signals components that would belong to the low scale strips. More detailed analysis of this issue that also includes justification for the choice of Morlet wavelet, can be found in Białasiewicz et al. (2013).

Scripts implemented in MATLAB have been used to obtain figures presented in the paper and therefore visualize the results. The software, whose functionalities and applications are described in (Gross and Białasiewicz, 2014), has been extended to allow cross-correlation of input signals. Developed scripts use MATLAB implementation of CWT analysis (MathWorks, 2014a,b) to obtain corresponding transforms of the signals. Wavelet transform is obtained using Morlet wavelet and 40 scales of continuous analysis linearly spaced between 1 and 400 units. Changes made to the

[1] Multiparameter Intelligent Monitoring in Intensive Care.

[2] As of 14.10.2014.