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The investigation of physiological data using the theory of complex systems*

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Abstract. This paper presents a complex dynamic system assessment method based on Hankel matrix rank and inter-relationships between elements of the system evalution method. The possibilities of methods application for various physiological data measure and evaluation are introduced. The international project CareWare for portable sensors and systems development is briefly presented.

Keywords: complex systems, ECG, matrix analysis, wearable sensors.

Introduction

Over the last years there has been growing interest in problems of complexity analysis. There are research fields of a huge scientific interest including the wide spectrum of tackled problems – from software development to analysis of medical information. The complexity can be described as a strength connection between different parts of a complex system. It is obvious that human organism is a complex system. There are many sophisticated methods describing the complexity measure of various physiologic signals and also possibilities to get theses signals in different ways. The complexity of a signal, in a particular case of electrocardiogram (ECG) signal may reflect the physiological function and status of healthiness of the heart. For the purpose to characterize the nonlinear complexity of signals the power spectrum, fractal dimensions, wavelet transformation, phase portrait, correlation dimension, the largest Lyapunov exponent, time-dependent divergence exponent, mass exponent spectrum and complexity measure can be used [6]. The methods verifies the fact that ECG dynamics are dominated by an underlying multi dimensional non-linear chaotic system, whose complexity measure is about 0.7 (in scale from 0 to 1).

Usually in a system identification problem Hankel matrices are formed when there is a sequence of output data and realization of an underlying state-space given or hidden Markov model is desired. But in this paper the ranks of the Hankel matrix will be used as features for the system identification purposes.

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The past few years have witnessed an increase in the development of wearable sensors for health monitoring system. Various data mining and analysis methods are used for real time analysis of biomedical data to estimate and predict patient's or sportsmen's current health state [2]. With the increase of healthcare services in non-clinical environments using vital signs provided by wearable sensors, the need to process and analyze the physiological measurements is growing significantly.

1 Complexity measure using Hankel matrices

In this section the mathematical characterization of complexity will be presented.

Let the dynamical system S is given. This system can be characterized in this way: it consists of m components $K_1, K_2, \ldots, K_m$ and these components K_r, $r = 1, 2, \ldots, m$ are governed by algebraic relations. Usually these relationships are composed of an ordinary sum and product operations, i.e. $S = a_1K_1 + a_1K_2 + \cdots + a_mK_m$. In this case the measure of complexity of the dynamical system S is denoted as $cmplS$. Having proposed interpretation of complexity it is possible to compose the mathematical algorithm of complexity estimation. Suppose that time series $(y_0, y_1, y_2, \ldots)$ describes dynamical system S. Here $(y_k,\ k = 0, 1, 2, \ldots)$ measures are describing the state of dynamical system S in time moment n. It can be scalar, function, matrix etc.

Then the concept of Hankel rank for these series can be defined. Let the series $(y_0, y_1, y_2, \ldots)$ be a sequence of real or complex numbers. Then the sequence $(H_1, H_2, H_3, \ldots)$ of Hankel matrices $(H_k,\ k = 1, 2, 3, \ldots)$ can be formed

$$H_1 = \begin{bmatrix} y_0 \end{bmatrix}, \quad H_2 = \begin{bmatrix} y_0 & y_1 \\ y_1 & y_2 \end{bmatrix}, \quad H_3 = \begin{bmatrix} y_0 & y_1 & y_2 \\ y_1 & y_2 & y_3 \\ y_2 & y_3 & y_4 \end{bmatrix}, \quad \ldots$$

and from values of its determinants $\det H_1 = d_1$, $\det H_2 = d_2, \ldots$ the sequence of determinants $(d_1, d_2, d_3, \ldots)$ can be formed.

Frequently the elements of the sequence $(d_k,\ k = 1, 2, 3, \ldots)$ with fixed accuracy $\varepsilon > 0$ satisfy special estimation constructed. There exists fixed natural number m and such number satisfies inequalities

$$|d_m| > \varepsilon, \qquad |d_{m+n}| \leq \varepsilon, \quad n = 1, 2, 3 \ldots$$

If the system of inequalities holds true for the sequence of determinants then the series has Hankel rank equal to natural number m. Besides, this is noted as follows:

$$H_\varepsilon(y_0, y_1, y_2, \ldots) = m.$$

The primary concepts for Hankel matrices analysis in finding exact, periodic and chaotic solutions of ordinary differential equations were presented in [3]. If the dynamical system S is described by time series which has $\varepsilon - H$ rank, then the components K_r can be the functions $Q_r(x)e^{\lambda_r x}$, $r = 1, 2, \ldots, m$, what means that complexity of a dynamical system S is outlined this way:

$$cmplS = \bigl(Q_1(x)e^{\lambda_1 x}, Q_2(x)e^{\lambda_2 x}, \ldots, Q_m(x)e^{\lambda_m x}\bigr).$$

The accuracy of the expression depends on the chosen level of ε.

Analysis of a time series using Hankel matrices is an alternative method for Fourier analysis which is widely developed. But in the proposed method the expression for dynamical systems are finite functions and in most cases it needs less parameters to describe the evaluation of dynamical systems than Fourier methods. For fast classification of dynamical systems by its complexity measure different methods can be used. Among the most popular are Suport Vector Machines. Analysis of ECG complexity is carried out by the scientific group which consists of employees of Kaunas University of Technology, Lithuanian Health University and Lithuanian Sport University. The physiological state of persons with cardiovascular diseases, elite sportsmens, elderly people (project GUARANTEE) were investigated during various physical tasks and internal conditions. Describing cardiac signals with Hankel matrices could be useful for diagnostic purposes because averaged ranks separate the healthy and sick persons' groups and also averaged complexity measure m shows functional level and it varies among persons investigated.

2 Investigation of internal links of system

Suppose that dynamical system S can be described by two (or more) synchronous time series $(y_0, y_1, y_2, \ldots)$ and $(z_0, z_1, z_2, \ldots)$. Then it is considered that internal links of dynamical system S are relations between two synchronous time series described by mathematical expressions. It must be noticed that usually the couple of series are investigated using statistical methods and there are widely developed analysis of correlation of two series which describes tendency of variation of these series (global type features). But statistical methods are not convenient for investigation of instantaneous features of series variation. Experience shows that for the description of instantaneous features of two time series the algebraic matrix analysis is convenient. In this case the elements (y_n) and $(z_n,\ n = 0, 1, 2, \ldots)$ are considered as determined. The basis of algebraic matrix analysis is algebraic arrangement of matrices. The discriminant of matrix A or quadratic difference of eigenvalues is outlined by this formula:

$$\operatorname{dsk} A = |\lambda_1 - \lambda_2|^2$$

and it shows the informative degree of matrix [4].

The smaller value of $\operatorname{dsk} A$ implies simplicity of dynamical system described by matrix A. When two time series describing a dynamical system are given then it is possible to relate one matrix time sequence $(A_1, A_2, A_3, \ldots)$ to these series when

$$A_n = \begin{bmatrix} y_n & y_{n+1} - z_{n+1} \\ y_{n-1} - z_{n-1} & z_n \end{bmatrix}.$$

Then the features of matrix series sufficiently reflect the interdependence of two series. It shows the variation of discriminates series $(\operatorname{dsk} A_1, \operatorname{dsk} A_2, \ldots)$. Nevertheless, these series can be considered as analogue of correlation characteristic [4] if the statistical methods for a couple of initial series would be used.

The primary step of investigation of physiological systems requires the development of appropriate sensors and instrumentation to transduce the phenomenon of interest in a measurable electrical signal. The next step of the signals analysis, however, is not always an easy task for a physician or a specialist of life-sciences. The

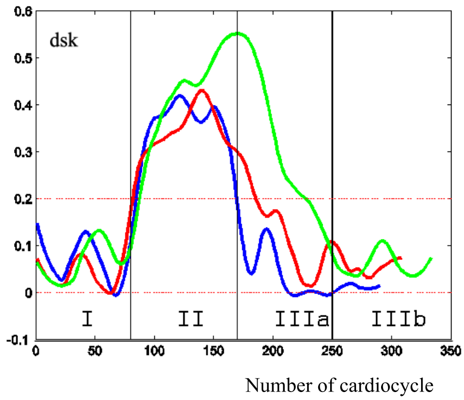

Fig. 1. Example of matrix analysis.

clinically relevant information is often masked in the signal by noise and interference, and the signal features may not be readily comprehensible by visual or auditory systems of a human observer. Processing of biomedical signals is not only directed toward filtering for removal of noise and power-line interference, spectral analysis to understand the frequency characteristics of signals and modelling for feature representation and parametrization. Recent trends are oriented to quantitative or objective analysis of physiological systems and phenomena via the signal analysis [6].

Discriminates for healthy people in normal conditions fluctuate between 0 and 0.2 and grow if physical load is applied. Results for three different sportsmen (wrestle, stage 10–12 years, 11–13 place in Europe championship) are shown in Fig. 1 (I Rest – 1 min; II – physical load, Rouffier test (30 squats in 45 s); IIIa – Recovery (1st minute); IIIb – recovery (2nd minute)). Results show difference of discriminants in various physical conditions and also similarity of physiology (by similar character of graph) of sportmens.

3 ITEA2 project CareWare

With the increase of healthcare services in non-clinical environments using vital signs provided by wearable sensors, the need to process and analyse the physiological measurements is growing significantly. In this section the information about ITEA2 project CareWare – "Electronic Wearable Sport and Health Solutions" will be introduced. The aim of this project (which involves more than 20 partners) is to develop and leverage novel unobtrusive cyber physical systems for monitoring and advancing personal health and wellbeing. Lithuanian partners: KTU, Lithuanian Sport University, Audimas and Optitecha are involved in Health promotion use case and will develop functional state monitoring system, based on the use of new generation sensors integrated for best wearing comfort and best signal quality during the motion (dynamic mode). Integrated solution of different sensors, smart interfaces, modelling and data analysis techniques should warrant that the created system will be comfortable and effective for the assessment of individuality and dynamics of functional state during daily-life activities as well as for exercise dosage control.

During this project KTU researchers will develop data mining methodologies and algorithms (anomaly detection, prediction, decision making, data integration and etc.) for physiological monitoring of vital signs in healthcare service. They will also be involved in analysis of stochastic processes and health characteristics, information from wearable sensors as well as analysis and integration of information in order to provide the algorithms for effective and robust decision making and creation of low-footprint low-power software modules for data processing. Recently, the healthcare services have been focusing on deeper data mining tasks in order to have deeper knowledge representation. Based on the literature analysis, three types of data mining tasks are predominant: Prediction; Anomaly detection; Diagnosis/Decision making [1]. During this project KTU researchers will develop data mining methodologies and algorithms (anomaly detection, prediction, decision making, data integration etc.) for physiological monitoring of vital signs in healthcare service. They will also be involved in the analysis of stochastic processes and health characteristics, information from wearable sensors as well as analysis and integration of information in order to provide the algorithms for effectiveness, robust decision making and creation of low-footprint low-power software modules for data processing.

Researchers have applied several data mining techniques to analyze ECG and accelerometer sensor data. SVM, NN and DT are commonly used data mining methods for wearable sensors. Challenge is to exploit the multiple measurements of vital signs simultaneously.

According to the data mining tasks considered, for anomaly detection task Support Vector Machines, Hidden Markov Models and statistical methods are more commonly applied. For prediction tasks – Decision Trees, for decision making task Neural Networks have often applied [5].

4 Conclusions

The ranks of Hankel matrix and second order coherence matrices for describing complexity of ECG and relationship between parameters of ECG were presented. Such type analysis was applied in evaluation of the physiological state for different persons.

The increasing amount of studies in this area and application of complex system theory in medicine raises hope to have more detailed and motivated interpretation of intra and interpersonal concatenation and complexity itself. This is one of the tasks in international project CareWare.

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REZIUMĖ

Kompleksinių sistemų teorijos taikymas fiziologinių duomenų tyrime
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Straipsnyje pristatomi dinaminės sistemos komplekiškumo vertinimo metodas, pagristas Hankelio matricų rangu, ir vidinių ryšių tarp sistemos elementų dinamikos nustatymo metodas, naudojantis specialiomis matricomis. Pateikiamos šių metodų naudojimo galimybės bei trumpai pristomas projektas CareWare, skirtas nešiojamų jutiklių ir jų sistemų vystymui.

Raktiniai žodžiai: kompleksinė sistema, EKG, matricinė analizė, jutikliai.