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Sparse representation of ECG signals for automated recognition of cardiac arrhythmias

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ABSTRACT

As per the report of the World Health Organization (WHO), the mortalities due to cardiovascular diseases (CVDs) have increased to 50 million worldwide. Therefore, it is essential to have an efficient diagnosis of CVDs to enhance the healthcare in the clinical cardiovascular domain. The ECG signal analysis of a patient is a very popular tool to perform diagnosis of CVDs. However, due to the non-stationary nature of ECG signal and higher computational burden of the existing signal processing methods, the automated and efficient diagnosis remains a challenge.

This paper presents a new feature extraction method using the sparse representation technique to efficiently represent the different ECG signals for efficient analysis. The sparse method decomposes an ECG signal into elementary waves using an overcomplete gabor dictionary. Four features such as time delay, frequency, width parameter, and square of expansion coefficient are extracted from each of the significant atoms of the dictionary. These features are concatenated and analyzed to determine the optimal length of discriminative feature vector representing each of the ECG signal. These extracted features representing the ECG signals are further classified using machine learning techniques such as least-square twin SVM, k-NN, PNN, and RBFNN. Further, the learning parameters of the classifiers are optimized using ABC and PSO techniques. The experiments are carried out for the proposed methods (i.e. feature extraction along with all classifiers) using benchmark MIT-BIH data and evaluated under category and personalized analysis schemes.

Experimental results show that the proposed ECG signal representation using sparse decomposition technique with PSO optimized least-square twin SVM (best classifier model among k-NN, PNN and RBFNN) reported higher classification accuracy of 99.11% in category and 89.93% in personalized schemes respectively than the existing methods to the state-of-art diagnosis.

1. Introduction

The report of WHO places the cardiac diseases as the leading cause of deaths in the world and will remain till 2030 (WHO, 2013). These cardiovascular diseases (CVDs) are caused due to the long-term effect of cardiac arrhythmias. These arrhythmias are abnormalities possessing a long-term threat and can sometimes lead to cardiac death. For decades, electrocardiography (ECG) has been a significant non-invasive diagnostic tool often used for monitoring the heart electrical activities. These heart activities result in the generation of P-QRS-T waves featuring specific characteristics in terms of amplitude and duration. Any change in either of these factors results in the generation of heart abnormalities, i.e. commonly known as cardiac arrhythmias. The ECG is non-stationary in nature (i.e. due to inter and intra variability); hence, it is often tedious to perform an artificial examination of long-term cardiac signal recordings and therefore is time consuming for the cardiologists. The holter records the ECG data for 24 h or longer containing thousands of heartbeats which is primarily used in the detection of various CVDs caused due to several cardiac arrhythmias. Thus, automated analysis of long-term heartbeat recordings is significant for timely diagnosis of cardiac diseases.

In recent years, with the advancement of classical signal processing approaches, several works have been performed on the automatic ECG detection methodologies to enhance the effectiveness of arrhythmia detection (Chang, Lin, Tao, Kao, & Chang, 1998; Kurka et al., 2015; Luz, Schwartz, Chavez, & Menotti, 2016; Zhu, Ding, & Hao, 2013). As such, several methodologies have been reported in literature by various researchers for an efficient detection and classification of cardiac arrhythmias. Cardiac arrhythmia

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detection is at the core of the automatic ECG signal diagnosis. Automatic cardiac arrhythmia detection includes the integration of feature extraction, and classification methodologies (Luz et al., 2016). In the feature extraction stage, the characteristic features from the corresponding input ECG signals are extracted containing crucial information regarding status of the heart. Among the techniques include time (Chazal, O'Dwyer, & Reilly, 2004; Raj, Maurya, & Ray, 2015; Tsipouras & Fotiadis, 2004), spectral (Minami, Nakajima, & Toyoshima, 1999), time-frequency (Elhaj, Salim, Harris, Swee, & Ahmed, 2016; Ince, Kiranyaz, & Gabbouj, 2009; Raj, Chand, & Ray, 2015; Tsipouras & Fotiadis, 2004), higher order cumulants (Martis et al., 2013) and statistical (Kutlua & Kuntalp, 2012; Martis, Acharya, Mandana, Ray, & Chakraborty, 2012; Melgani & Bazi, 2008; Osowski, Hoai, & Markiewicz, 2004; Raj & Ray, 2015), higher order spectra (Martis et al., 2013) domain analysis tools widely used for capturing the characteristics of the ECG signals. These feature extraction methods are combined with the existing classifiers such as linear discriminants (LDs) (Chazal & Reilly, 2006; Chazal et al., 2004; Llamedo & Martinez, 2011), neural networks (Ince et al., 2009; Moavenian & Khorrami, 2010; Plawiak, 2018; Raj, Luthra, & Ray, 2015b), convolutional network (Acharya & Fujita et al., 2017; Acharya & Oh et al., 2017), neuro-fuzzy approach (Ceylan, Ozbay, & Karlik, 2009; Linh, L. Osowski, & Stodoloski, 2003; Luz, Nunes, Albuquerque, Papa, & Menotti, 2013), support vector machines (Luz et al., 2013; Moavenian & Khorrami, 2010; Plawiak, 2018; Raj & Ray, 2017a; 2017b; Raj, Ray, & Shankar, 2016) and ensemble learning of classifiers (Plawiak, 2017) to provide an automatic and efficient classification of cardiac abnormalities, which may not be detected with ease. Despite of huge research undergone, the efficient analysis of long-term ECG for cardiac arrhythmia classification remains a challenge.

The classical feature extraction techniques exhibit certain disadvantages that limits the development of an efficient methodology for arrhythmia detection. The statistical methods i.e. principal component analysis (PCA) (Martis et al., 2013) and independent component analysis (ICA) (Martis et al., 2014) are non-linear methods being computationally complex and do not include the symmetry and reflection properties (Raj et al., 2016). In the spectral domain analysis, such as fourier transform (FT) generates the frequency components of an input signal, however it lacks in providing any information regarding the time of occurrence these components. This limitation of FT is overcome by short-time fourier transform (STFT) which provides a window to gather the time information (Raj et al., 2016). Due to the constant length of the window, the STFT is limited to stationary signals only. The wavelet transform (WT) addresses the limitation of constant window size by providing shorter windows at high frequencies and longer windows at low frequencies, making it suitable for non-stationary signal analysis yielding time-frequency features. But, the choice of mother wavelet and sampling frequency remains a challenge in WT. The limitation of WT is addressed by stockwell transform (S-transform) (Raj et al., 2016) which uniquely combines a frequency dependent resolution of time-frequency space and absolutely referenced phase information, however the method is highly redundant. In case of hilbert huang transform (HHT), the output is very much affected by the noise associated with the signal. The aforementioned existing feature extraction methods limit the efficient representation of ECG signals in their domain of analysis due to the variability of these features among various subjects and its non-linear, rhythmic and non-stationary nature. Further, these methods involves high computational complexity. Thus, an efficient feature extraction technique is required to efficiently represent different classes of ECG signals. In recent years, the method based on sparse representation has reported better results in data analysis and modelling (Zhang, Xu, Yang, Li, & Zhang, 2015). The sparse representation deals with the models of data having large numbers of parameters or variables, of which only a few are relevant. Recently, the sparse method is used to remove the noises associated with the ECG signals (Satija & Manikandan, 2017). In this study, the sparse method is used to extract the subtle changes in the ECG signals using few coefficients for an efficient representation. The representation of ECG signals using few coefficients involves less training, optimization and classification time for early diagnosis of cardiac arrhythmias.

In Melgani and Bazi (2008), the morphological features are extracted and brought down in lower-dimensional space by using PCA. The features extracted are classified using support vector machines (SVMs) into 6 categories of ECG signals with an accuracy of 91.67%. In Raj and Ray (2017b), the DCT based DOST approach is applied to extract the time-frequency features, that are classified using the PSO optimized SVM classifier achieving an accuracy of 98.91% for classifying 16 categories of ECG signals. In Osowski et al. (2004), higher order statistics and hermite features are computed for classification of 13 categories of ECG signals using SVM to achieve an accuracy of 95.91%. In Raj and Chand et al. (2015), wavelet based features are extracted for classification of 8 categories of ECG signals using back propagation neural network (BPNN) which reported an accuracy of 97.4%. In Qiao, Rajagopalan, and Clifford (2014), the time domain features are extracted that are categorized using SVM into 5 categories of ECG signals yielding an accuracy of 98.60%. In Rodriguez, Goni, and Illarramendi (2005), morphological features are extracted that are classified using a decision based technique yielding an accuracy of 96.13%. In Martis et al. (2013), the PCA based features are extracted from the corresponding ECG signals that are classified using least-square support vector machines achieving an accuracy of 93.48%. In Chazal et al. (2004), the feature set comprised of ECG morphology, heartbeat intervals, and RR-intervals. This feature set representing each of the ECG signal is classified using linear discriminants (LD) classifier into one of five categories as per AAMI standard achieving an accuracy of 81.9%. In Ye, Kumar, and Coimbra (2012), the feature set consists of wavelet features, independent components and RR-intervals. This feature set is classified using support vector machine classifier and reported an accuracy of 86.4% as per AAMI standard.

This study presents a new feature extraction method to address the challenge of non-stationary ECG signal analysis using sparse signal decomposition (SSD) technique. In the signal decomposition, a crucial role is played by the choice of dictionary. In this study, an overcomplete gabor dictionary is explored where an ECG signal is decomposed into elementary waves. The significant atoms from the gabor dictionary are selected for extracting discriminative features. For each of the gabor atom, four features such as time delay (τ_i), frequency (f_i), and the width parameter (σ_i) are extracted to efficiently represent various classes of ECG signals. These captured features are concatenated and employed for their categorization into their subsequent categories using least square twin SVM, k-NN, PNN, and RBFNN classifiers. The learning parameters of these classifier models are optimized using the artificial bee colony (ABC) and particle swarm optimization (PSO) techniques to develop an efficient classifier model. The proposed method with all possible classifier models are evaluated under two analysis schemes, i.e. category and personalized schemes. The assessment under personalized scheme is suitable for practical applications. The experiments are validated on the benchmark MIT-BIH arrhythmia database under both these analysis schemes predicting sixteen classes in category-based and five classes of ECG signals in personalized scheme. The results reported using the proposed method outperform the existing methods mentioned in literature.

This study aims (a) to propose a new feature extraction approach for an efficient representation of ECG signals (b) to develop an optimal classifier model for classifying the feature sets into var-