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Communication

Detection of the electrocardiogram fiducial points in the phase space using the euclidian distance measure

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ABSTRACT

The paper proposes a phase-space based algorithm applying the Euclidian distance measure enabling detection of heartbeats and characteristic (fiducial) points from a single-lead electrocardiogram (ECG) signal. It extends the QRS detection in the phase space by detecting the P and T fiducial points. The algorithm is derived by reconstructing the ECG signals in a two-dimensional (2D) phase space according to the delay method and utilizes geometrical properties of the reconstructed phase portrait of the signal in the phase space for the heartbeat and fiducial-point detection. It uses adaptive thresholding and the Euclidian distance measure between the signal points in the phase portrait as an alternative to the phase-portrait area calculation (Lee et al., 2002 [1]). It was verified with the QT Database (2011; [2]) and its performance was assessed using sensitivity (Se) and the positive predictive value (PPV). Results for the proposed algorithm are 99.06%, 99.75% and 99.66% for Se and 94.87%, 99.75% and 99.66% for PPV for the P points, heartbeats and T points, respectively.

1. Introduction

The paper presents a method enabling detection of all fiducial points of the ECG signal from a single lead and. Its goal is to detect all the fiducial points of the ECG signal from its phase portrait by applying the Euclidian distance measure. It is based on phase-portrait reconstruction in the phase space in which an alternative approach to fiducial-point detection to the already introduced area calculation [1] is proposed: the use of adaptive thresholding and the Euclidian distance measure between data points in the phase portrait.

ECG analysis is crucial in determination of the cardiac function. The paper focuses on processing a single-lead ECG signal from which information about the heart function can be extracted [3–11]. The single-lead ECG signal is reconstructed in a 2D phase space (Fig. 1). The R point of the ECG signal is determined with adaptive thresholding from a phase-space reconstructed ECG signal. The remaining characteristic (fiducial) points are detected among the neighboring data points of the detected R points using the Euclidian distance measure between the detected R points and the neighboring data points.

Single-lead ECG-signal reconstruction in a 2D phase space is also known as the phase portrait. A phase portrait is a graphic presentation of the dynamic-system oscillations in the phase space. Each point in the phase portrait represents a specific state of the system in time. The Takens method of delays [12] is used to reconstruct phase portraits from the ECG-scalar time series. Phase-space reconstruction by delaying the time–series signal is also called the delay coordinate mapping [1]. It is used for visualization of attractors of dynamical systems, such as the cardiovascular (CVS) system with the ECG signal and phase portrait is the term for the visualized attractor (Fig. 1) [1]. One of the main advantages of such visualization is simultaneous presentation of several ECG-signal characteristics of the complete ECG record, such as the P-Q-R-S-T waves.

The method of processing the ECG-signal phase portraits was reported in [1,3,4,13–16]. In [13] the phase portrait of an ECG signal was used to indicate that the heart rhythm resembles a nonlinear dynamic oscillator, in [1,14] a QRS detector using area calculation of the phase portrait was presented, in [3] phase portraits of ECG signals were used to distinguish between healthy and diseased persons, in [4] a technique for detecting acute coronary occlusion from the ECG phase portrait was introduced, in [15] the phase portrait was applied to indicate time–series irregularities in QRS complexes and in [16] the phase portrait was used for detection of the ECG fiducial points. In [1,3,13–16] the delaying of signals was used and in [4] the derivation of signals was used for phase-space reconstruction. Different processing methods of phase portraits were used: in [1,14,16] phase-space area calculation was used, in [4] visual inspection of the phase portraits was used and in [3,13,15] dynamical and statistical analysis (Lyapunov exponents, Poincare maps, complexity measure etc.) were used.

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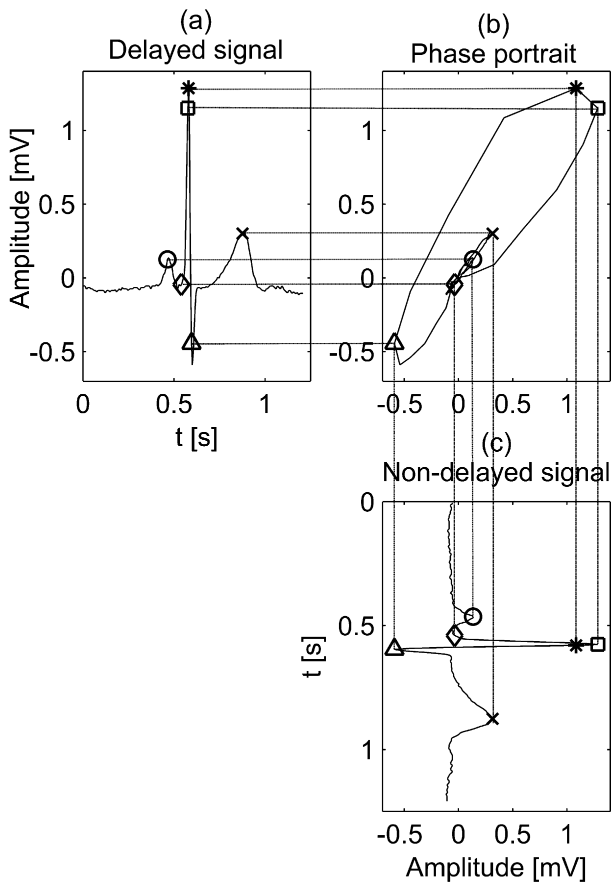

Fig. 1. Normal ECG cycle and the corresponding phase portrait from the recording sel16272 of the QT database [2] (b). The P, Q, R, S and T fiducial points of the non-delayed ECG cycle are marked with a circle, diamond, square, triangle and cross, respectively (c). The asterisk marks the R point of the delayed ECG cycle (a). The non-delayed (c) and delayed (a) signals are positioned respectively to the axes they represent in (c) and the correlated marked points are connected with lines to point out the phase-portrait reconstruction.

Capability of real-time processing is one of the most important challenges in the field of ECG-signal applications. Real-time detection of characteristic waves and classification of ECG signals can be successfully achieved by using phase portraits [1,14]. Algorithms based on phase portraits are reported in ECG-signal processing in several important EU research projects, such as [17] and [18].

A normal ECG cycle (Fig. 1(c)) starts with a positive P wave marked with a circle in Fig. 1(c). This is followed by a combination of three waves, called the QRS complex, i.e. a negative Q (diamond in Fig. 1(c)), a positive R (square in Fig. 1(c)) and a negative S (triangle in Fig. 1(c)). The normal ECG cycle is concluded with a positive T wave (cross in Fig. 1(c)). The amplitudes of these five waves along with the time intervals between them are the ECG-signal characteristics and represent important information about the heart function [19]. The term fiducial (reference) points is a common name for characteristic points which are the local maxima or minima of the characteristic waves.

Most of the clinically relevant information in the ECG signal can be derived from processing the P-Q-R-S-T waves of the ECG cycle (Fig. 1) [19,20]. Therefore, detection of these characteristic waves is one of the essential tasks in ECG-signal processing [1], not only in clinical, but also in nonclinical applications, such as biometrics, emotion detection, etc. Prior research efforts were devoted to automated detection of the ECG characteristic waves [16,21–28].

2. Setup

Proposed algorithm using the Euclidian distance measure for the ECG fiducial-point detection was evaluated on signals from the QT Database [2] designed to evaluate algorithms detecting waveform boundaries in ECG. The QT Database [2] contains 105 ECG recordings with signals sampled at 250 Hz. Each signal on the recording is 15 min long and has 225,000 samples. Recordings from the QT Database [2] contain subsets of annotated heartbeats in each signal. These subsets of annotated beats include at least 30 beats in each signal record. In all, 3622 QRS complexes, 3193 P points and 3541 T points were annotated in the database. The algorithm was designed and verified in MATLAB® [29].

3. Method

Algorithm development was motivated by applications using only one ECG lead. It is known that several different leads can be combined into one complex lead according to [30] and processed with the same algorithm. The QT database used in evaluation of the proposed algorithm includes only two ECG leads in each recording. However, the goal of this paper is to show that the P-Q-R-S-T points can be detected by using a single ECG lead.

The proposed algorithm is composed of four steps: preprocessing, phase-space reconstruction, detection of the R points by using adaptive thresholding and detection of the remaining fiducial points by using the Euclidian distance measure between the R points and the neighboring data points.

3.1. Preprocessing

In the preprocessing step, all signals were filtered with a band-pass filter with cut-off frequencies of 0.5 Hz and 100 Hz thus eliminating the low- (baseline wandering) and high-frequency (muscle contractions) interferences. The band-pass filter is composed of a 4th-order Butterworth high-pass filter and a 4th-order Butterworth low-pass filter which have the flattest pass-band magnitude response. The Butterworth filters for ECG filtering were used also in [31–36].

3.2. Phase-space reconstruction – the delay method

In the second step, the signals were reconstructed in the phase space and the phase portraits were obtained. In general, as defined by Packard [37] and Takens [22], a phase portrait of a dynamic system – described-by a one-dimensional time series of measured scalar values $y(t)$ – can be reconstructed in a k-dimensional state space. From the time–series signal we can construct an n-dimensional signal $\mathbf{Y}(t)$.

$$\mathbf{Y}(t) = [y(t),\ y(t+\tau), \ldots, y(t+\tau(n-1))]^T \tag{1}$$

where τ is the time delay and n is the mapping dimension of the reconstruction space.

According to [1] two dimensions are satisfactory to reconstruct the attractor. Hence, the phase portrait is reconstructed in a 2D ($n=2$) phase space ($y(t)$, $y(t+\tau)$) (Fig. 2). In Fig. 2, three examples of such reconstruction are illustrated for the sel116, sel117 and sel16265 signals which are normal signals of the MLII lead. The delay value for each of the reconstruction examples is set to 4 ms (one sample). On phase portraits in Fig. 2(a–c), each of the fiducial points of the ECG signal, namely the P, Q, R, S and T points, is marked. They represent the peaks of the corresponding waves of the ECG signal. In Fig. 2(a–c), they are marked with a circle, diamond, square, triangle and cross symbols, respectively.

As seen from distribution of the fiducial P, Q, S and T points in Fig. 2(a–c), the major part of the ECG signal in the phase portrait is