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PVC ARRHYTHMIA IDENTIFICATION USING NONLINEAR SYNCHRONIZATION

BY

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Abstract. In the present paper we propose to identify cardiac PVC arrhythmia using a discrete-time additive model that can exhibit complex dynamics, including chaos. The proposed signal processing is performed on a single derivation ECG by means of an adaptive synchronizing additive nonlinear system. Monitoring the parameter variation of the nonlinear adaptive system, PVC arrhythmia can be identified and reliable alarm signals can be automatically generated, as the simulations confirm.

Key words: chaotic dynamics; adaptive synchronization; ECG signal processing.

1. Introduction

Cardiac chaos is mostly related, in medical literature, with HRV analysis, based on the presumption that the fluctuations of heartbeats during normal sinus rhythm could be partially attributed to deterministic chaos and that a decrease in this type of nonlinear variability could be observed in different

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cardiovascular diseases and before ventricular fibrillation (Tsipouras & Fotiadis, 2004). Different approaches have been used to attest the chaotic nature of the resulted time series, such as quantitative methods like fractal analysis, largest Lyapunov exponent evaluation, or qualitative methods by determining self similarity properties (Krstacic *et al*., 2007).

In contrast with these approaches, our test signals are one-lead ECG recordings, a modified limb lead II (ML II), obtained by placing the electrodes on the chest. We approach the discrimination of premature ventricular contraction (PVC) arrhythmia using an inverse parametric identification method based on discrete-time adaptive nonlinear additive systems, by monitoring the time variant system parameters. As previously emphasized, our system is able to detect the chaotic behavior of the heart, reflected in the electrical recordings excerpts, which prove the chaotic nature of certain transients from normal behavior to PVC's. Based on this, it discriminates multiform PVC's from other waveforms, being able to alarm in real-time about emerging unwanted dynamics, such as those mentioned above, VT or VF, or any other behavior related to the presence of PVC waveform in an electrogram.

The theoretical background and parametric identification method are presented in the following section. Simulation results of the developed algorithm are detailed based on test signals from annotated reference ECG database. Discussion and conclusions are the final chapters of this paper.

2. PVC Arrhythmia Identification Method

The proposed identification method is based on a recursive, time variant, Additive Nonlinear Discrete-Time System (ANDS) (Grigoraş & Grigoraş, 2000, 2001), which was chosen for its rich dynamics, including periodic, quasi-periodic and chaotic behavior, depending on the system parameters. The model is designed using linear elements and an additive residue function

$$r(x) = x - \mathrm{round}(x)\,, \tag{1}$$

graphically represented in Fig. 1.

The recursive nonlinear difference eq. for the ANDS model is given by

$$y[k] = \bigoplus_{n=1}^{N} h[n,k]\,y[k-n]\,. \tag{2}$$

In eq. (2), the additive summation, $\oplus$, is defined using the additive residue nonlinear algebraic function as

$$x \oplus y = r(x+y)\,. \tag{3}$$

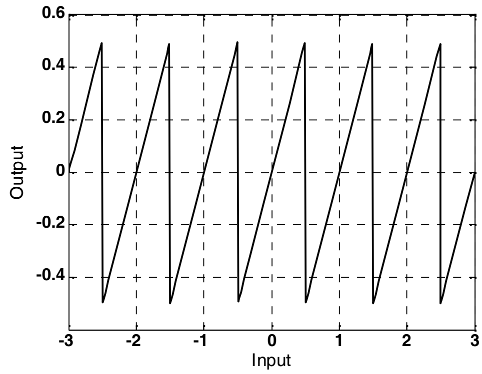

Fig. 1 – The additive algebraic nonlinear function.

In order to achieve parameter identification in a reliable way, we used an inverse system approach to design our receiver, synchronizing with the proposed model. The resulting non-recursive ANDS receiver was demonstrated by Leuciuc and Grigoraş (1997) to synchronize to the proposed model. The N-th order difference eq. of the synchronizing system is the inverse of one described by eq. (3), *i.e.*

$$\varepsilon[k] = y[k] \oplus \bigoplus_{n=1}^{N} h[n,k] y[k-n] . \quad (4)$$

Considering the model to be time variant, the synchronizing receiver must be an adaptive one, its cost function minimizing the synchronization error. The instantaneous error is given by

$$\varepsilon[k] = d[k] - \mathbf{h}^T[k] \otimes \mathbf{y}[k] . \quad (5)$$

The cost function to be minimized is the weighted average of L successive instantaneous errors

$$E\left(\mathbf{h}[k]\right) = \sum_{l=0}^{L} \rho^l \varepsilon^2[k-l], \quad \rho \in \left(0,..,1\right) . \quad (6)$$

If the synchronizing system parameters vary with time, after a short enough settling time, the resulting values can be considered as approximations of the emitter system corresponding ones, within the limits of the synchronization error.

It was demonstrated by Leuciuc and Grigoraş (1997) that the proposed adaptive synchronizing system can be controlled by adaptive algorithms similar to linear systems. The chosen adaptive algorithm is the Recursive Least Squares

(RLS) one, which has the advantages of being faster and less dependent on input signal scaling at the cost of being more complex, thus requiring more computing power for real time implementation. The learning algorithm is described by the discrete state eqs.

$$\begin{aligned}\mathbf{h}[k+1] &= \mathbf{h}[k] + \varepsilon[k]\mathbf{g}[k],\\ \mathbf{P}[k+1] &= \rho^{-1}\left(\mathbf{I} - \mathbf{g}[k]\mathbf{y}^T[k]\right)\mathbf{P}[k],\\ \mathbf{g}[k+1] &= \frac{1}{\rho - \mathbf{y}^T[k]\mathbf{P}[k]\mathbf{y}[k]}\mathbf{P}[k]\mathbf{y}[k].\end{aligned} \tag{7}$$

Thus the synchronizing system parameters follow the model ones, leading to the possibility of inverse identification. As demonstrated by Leuciuc (2000) the convergence of the adaptive algorithm depends on the initial values of the system coefficients, **h**[0], used in the adaptive algorithm. This is why we chose these initial values to give transfer function poles on the unit circle, at the border between stable and chaotic dynamics. By using additive systems we benefit from simple relation between the transfer function poles, z_n , of the linearized system, and the Lyapunov exponents, λ_n, of the recursive, N-th order, nonlinear system

$$\lambda_n = \ln|z_n|, \quad (n = 1, \ldots, N)\,. \tag{8}$$

In order to decide over the normality/abnormality of the analysed ECG trace, with the proposed system, based on the time variant Lyapunov exponents, we tested, at each input sample, k, the position of the polynomial roots of the receiver instantaneous transfer function given by eq.

$$H_k(z) = \bigoplus_{n=1}^{N} h[n,k]z^{-n}\,. \tag{9}$$

If all roots are inside the unit circle in the complex plane, then all Lyapunov exponents are negative leading to stable behavior. If one root is outside the unit circle in the complex plane, the corresponding Lyapunov exponent is positive, highlighting chaotic behavior.

3. Simulation Results

Test signals for our technology validation were taken from MIT-BIH arrhythmia database. Recordings of this database are annotated and verified by practitioners. We used a selection of representative excerpts, in order to evaluate the usefulness of the proposed method to identify different morphological forms of the QRS complexes, especially R-wave, with different occurrence rate in an ECG recording, for the discrimination of the ventricular arrhythmia. The recordings were digitized at 360 samples/s per channel with 11-bit resolution over a 10 mV range. Segments of 60 s time-span were used in separate or 2 to 4 concatenated blocks (120 or 240 s).

A representative example of the simulation results, for an 8th order system, 60 s ECG, signal 124, min. 5, is presented in Fig. 2. On the same time-scale, the top represents the ECG trace and the bottom one the decision signal.

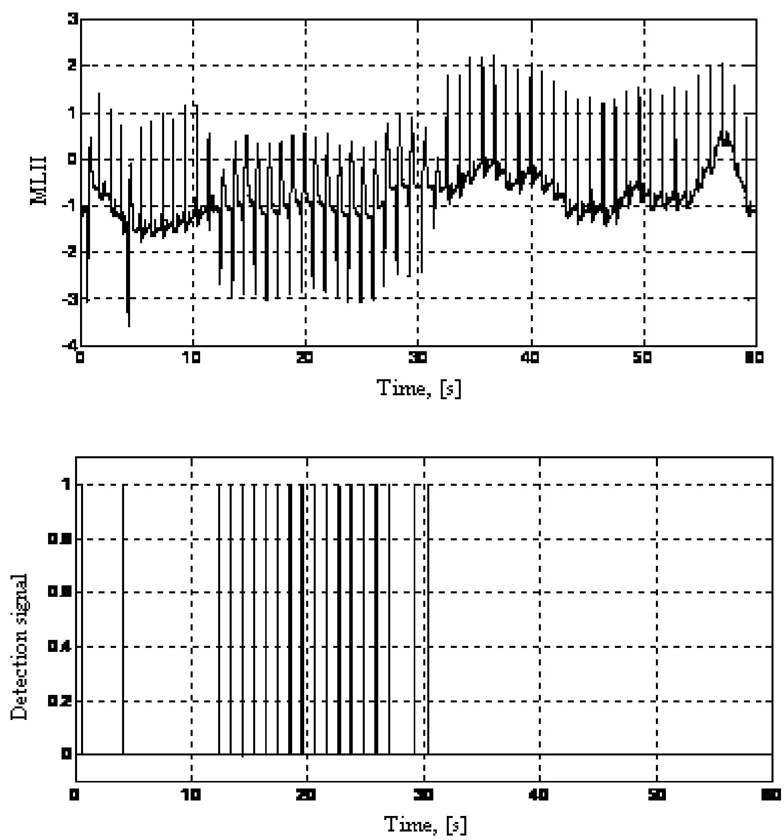

Fig. 2 – Aligned graphical representation of the ECG signal (top), and detection signal (bottom).

A typical result on the time evolution of the short-term estimates of the Lyapunov exponents is presented in Fig. 3, for the same system and ECG signal. It is worth noting that the largest Lyapunov exponent becomes positive only for short periods of time, and with a very small amount, leading to the necessity of high zoom factor to highlight the presented phenomenon. In order to highlight the connection between the roots based decision and the short-term estimates of the Lyapunov exponents, we presented the variation, in the complex $\underline{Z}$-plane of the polynomial roots of the simulated system, in Fig. 4. Not to clutter the graphical representation, we chose to depict only 4 of the 8 roots, mainly those roots that exhibit short escapes outside of the unit circle.

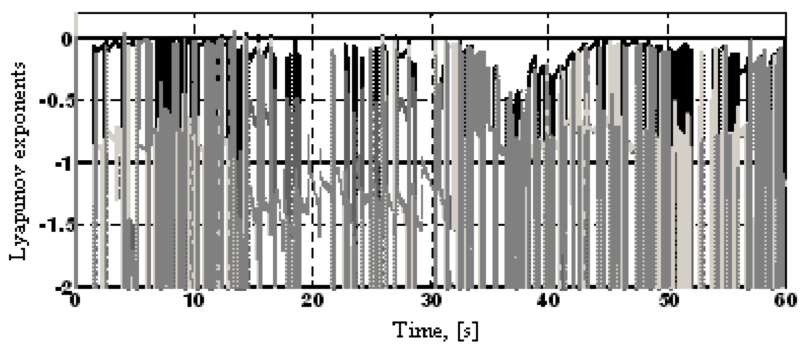

Fig. 3 – Zoom around the null value of the Lyapunov exponents time variation.

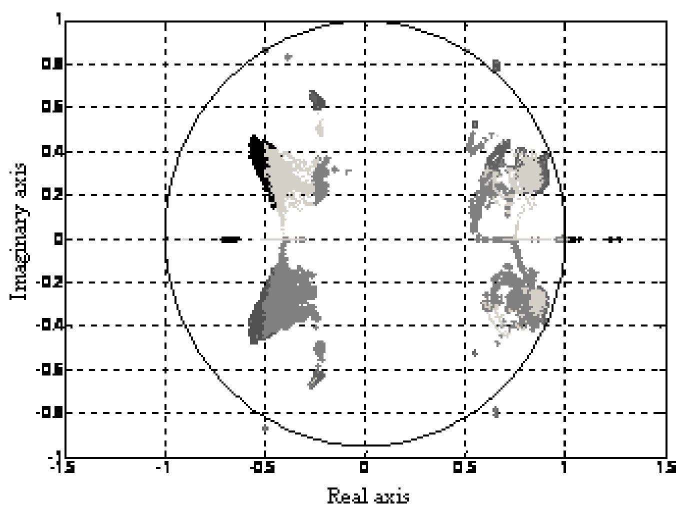

Fig. 4 – Root locus for 4 of the 8th order system poles, in the complex $\underline{Z}$-plane.

4. Conclusions

The method described in this paper provides the means of premature detection of a change in the chaotic dynamics of the heart, reflected in electrical perturbations at myocardial level, which may serve as a screening method, to locate the beginning of a life-threatening behaviour, before clinical evidence. As a monitoring heart method, our method has the advantages of avoiding the eventual errors associated with the scalling of recorded ECG signal and the possibility to be implemented as a minimally wearing device, because the decision is made upon a single ECG lead investigation.

Tests were performed on selected segments of ECG recordings from MIT-BIH Arrhythmia Database. The detection accuracy of the method is 97.98%, average sensitivity is 91.2%, and average specificity is 97.94%.

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IDENTIFICAREA ARITMIEI PVC FOLOSIND SINCRONIZAREA NELINIARĂ

(Rezumat)

Se propune identificarea aritmiei PVC folosind un model aditiv în timp discret, care poate avea o dinamică complexă, inclusiv haotică. Prelucrarea de semnal propusă este realizată pe o singură derivaţie EKG, folosind un sistem neliniar discret aditiv sincronizat. Urmărind variaţia parametrilor sistemului neliniar adaptiv, se poate identifica aritmia PVC şi se pot genera automat semnale de alarmă fiabile, aşa cum confirmă simulările.