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QRS detector approach for on-line purposes

***Abstract**. The problem of real time restrictions and effectiveness requirements of the QRS detection algorithm is presented in the paper. Several approaches were taken into account and were tested during the research. CSE ECG databases were used as test signal set. FIR and IIR filters were investigated as well as different filter coefficients floating point data types. The paper summarises Authors' investigations in the field of QRS detector application to the contemporary market platform.*

***Streszczenie.** W artykule przedstawione zostały zagadnienia dotyczące wymagań stawianych algorytmom do detekcji zespołów QRS, przeznaczonych do pracy w czasie rzeczywistym. Szczególnie ważne są przeciwstawne problemy, które dotyczą skuteczności pracy algorytmu i szybkości jego działania. W trakcie testów wykorzystano wiele rozwiązań bazujących na filtrach SOI oraz NOI oraz różnych formatach współczynników filtrów. (**Zagadnienia pracy w czasie rzeczywistym algorytmu do detekcji zespołów QRS**)*

Keywords: ECG signal automated analysis, QRS complex detection, QRS detection testing and evaluation stage, Real time algorithms
Słowa kluczowe: Automatyczna analiza sygnału EKG, Detekcja zespołów QRS, Testy detektorów QRS, Algorytmy czasu rzeczywistego

Introduction

The article concerns the development results of real time ECG analysis algorithm. Proposed solution is dedicated for QRS complex detection and is characterised by two opposing properties. The first one is the ability of stable and uninterrupted functioning on a dedicated low cost platform, in a real time at desired sampling frequency and with the complete set of the ECG signals (leads). The second one is the requirement of the satisfactory level of the detection error rate. The recent parameter should not be lower than 90 % (initial assumption) - if tested on the Measurement and Diagnostics CSE ECG databases. The paper summarises Authors' investigations in the field, together with achieved results and deduced proposals.

Background

ECG signal automated analysis is a very popular and even mandatory feature implemented into contemporary diagnostic instrumentation. There are many different solutions and approaches to the problem and many different signal processing tools are involved in. The most popular are: different applications of digital filters and the wavelet transform. The detection problem is widely described in the literature [1,3], but there are still new possibilities brought by the new, coming into the market computer aided platforms. They all allow for the mobile, user friendly and effective medical, diagnostics applications.

The essential stage of the ECG analysis is the QRS complex detection step as it is the dominant element of the ECG signal.

Reference ECG database

It is obvious that the QRS complex detection algorithm development research as all other investigations must be verified. For that purpose Authors took advantage of the CSE ECG recordings reference database. Two of three main subsets with the complete 12 lead recordings were used during evaluation procedure. These databases have been especially developed for the testing, assessment and development of diagnostic ECG computer programs (Fig.1) [6,7]. Sampling frequency of the CSE reference signals is 500 Hz. This is the value declared as recommended minimum in the normative publications [2]. All signals were upsampled to 1000 Hz as nowadays available ECG recorders utilises commonly sampling frequency starting from 1 kHz.

Databases consist of 125 (multilead measurement dataset) and 1220 (multilead diagnostic dataset) 10s long recordings, respectively. The multilead measurement dataset is released in two forms original and artificial which in turn contains the cardiologists analysis with regard to onset and offset of P QRS and T waves. Both databases were tapped into the research and development. Additionally, according to the normative requirements [2] selected signals were distorted with respect to the given, normative prescription and used again in the test procedure.

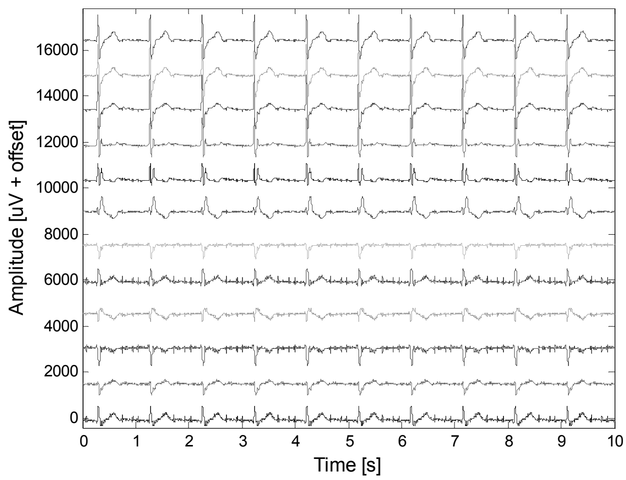

Fig.1. Sample CSE multilead (12-lead) measurement database recording.

Proposed approach

Due to the speed criterion and requirement, which was the essential property of the algorithm being developed, Authors decided to use digital bandpass filter followed by the nonlinear squaring and linear smoothing operation (Fig. 2). Target platform was to be equipped with a FPU unit, so floating point data format was available. The only limitation was a single precision of that format. Computations performed in that way were acceptable in terms of time consumption.

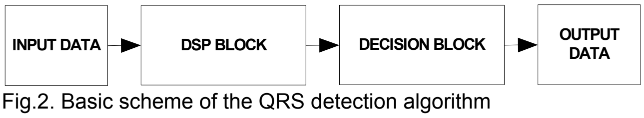

Fig.2. Basic scheme of the QRS detection algorithm

The diagram presented in the figure 2 consists of two main stages. The first one, the DSP block is formed from bandpass filter, squaring and smoothing functions. The second one is the decision block which aims at the optimal thresholding of the DSP block output - that way the QRS localisation is reliable, repeatable and precise.

More details are presented both in the figures 3a and 3b. All operations are performed to emphasise QRS complex occurrences. The input, original signal is first processed by developed, bandpass filter. The filter output signal contains high amplitude episodes representing QRS complex presence. All other ECG components are effectively attenuated. The following stage is a simple squaring function (nonlinear transformation in the Fig. 3a and 3b) which is responsible for nonlinear dynamic boost and unipolar signal generation. Main disadvantage of that processing stage is that the signal contains many local maxima at the presence of the QRS complex. QRS detection based on this form of signal would be quite difficult and burden with potentially considerable position error. Removal of this fault is performed by means of dedicated lowpass smoothing filter. With a use of the filter local “QRS ripples” are eliminated and averaged forming at the output a single, QRS associated, relatively high in amplitude maximum. The output signal of the smoothing filter satisfies the requirements for the detection function. It is to reach possibly high values at the input presence of QRS complex, and zero values for all other cases. Parameters of a single local maximum that correspond to the statistical QRS complex preserve the key factors in the final QRS localisation procedure. These parameters are local maximum amplitude of detection function, duration of local maximum and its slope.

The final realisation of the detection algorithm is designed to work with a single channel as well as the set of channels. The standard ECG examination consists of 12 leads (signals) but it is possible to record only a subset of leads. The simplest recorder could realise a single channel acquisition, but this case is rather not very popular. Commonly used recorders use at least 3 channels (classic leads). Often additional 3 channels (augmented leads) can be calculated programmatically or alternatively in the input analogue circuit.

In all cases where the ECG signal is not polluted significantly by noise and the QRS complexes are clearly visible in a lead it is sufficient to analyse that single lead. Otherwise processing of a set of channels guarantees more reliable final results.

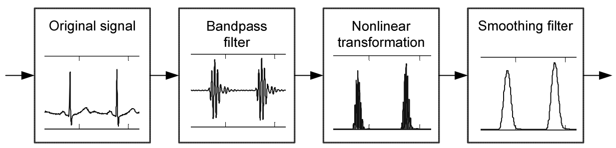

Fig.3a. Basic scheme of the QRS detection DSP processing

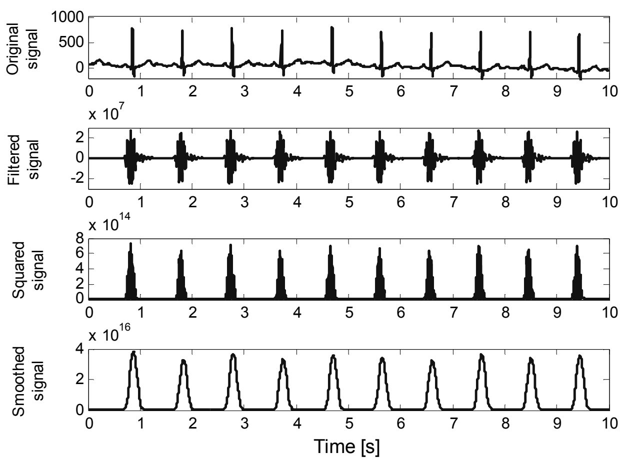

Fig.3b. Digital signal processing performed at consecutive stages

The bandpass filter cut-off frequencies were selected based on the research carried out with a reference MIT-BIH and CSE ECG databases [6,7]. The QRS complex spectrum components are concentrated between 10 and 25 Hz. There are two main solutions of the pass band selection discussed in the literature [3,4,5]. The first one is based on the maximum of the QRS frequency spectrum that is located in the neighbourhood of 10 Hz on the frequency axis (Fig. 4) and the second one relies on the maximum distance between the QRS spectrum and P-wave or T-wave spectrum in the neighbourhood of the maximum of the QRS frequency spectrum. That criterion is satisfied for the neighbourhood of frequency equal to 17 Hz (Fig. 4).

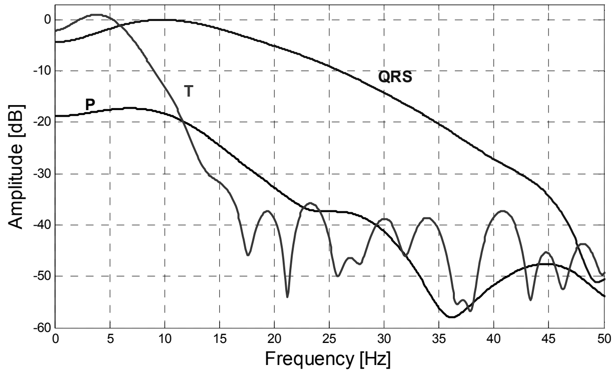

Fig. 4. Frequency spectra of the QRS complex together with P and T waves

These two approaches presented above, were investigated and verified. Based on the empirical research the filter with 14 Hz and 20, Hz low and high cut-off frequency, respectively has been designed (Fig. 5).

Another problem discussed in the paper is the filter realisation. FIR filters guarantee stability and phase linearity but their computational complexity is much more demanding. On the other hand relative narrow pass band of the IIR filter with respect to the sampling frequency often causes filter instability. Different filter structures were tested and finally, due to the real instability threat, the cascaded second order IIR filter set was developed and used.

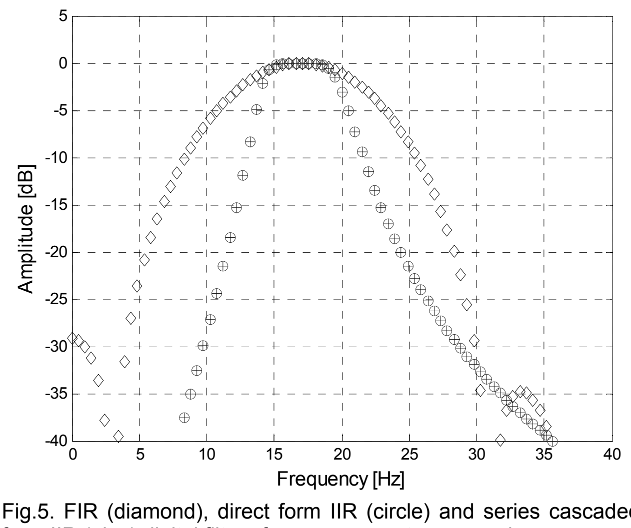

Fig.5. FIR (diamond), direct form IIR (circle) and series cascaded form IIR (plus) digital filters frequency spectra comparison

Results of frequency spectra for different filter structures are presented in the figure 5. The FIR filter spectrum was achieved for FIR filter order equal to 150 (diamonds in the Fig. 5). Though, the FIR filter structure guarantees stability, the total number of required operations were exhausting for the available CPU resources (simple low cost PC compatible platform). That was the main reason for rejection the filter in FIR structure. Authors decided to use an IIR filter. The IIR bandpass filter of developed approach was very promising. Its frequency spectrum is plotted with circles in the figure 5. The order of designed filter was equal to 3 so the total number of necessary software operation was dramatically reduced. The nonlinearity of the filter phase in the pass band was also negligible. There was only one limitation. Coefficients of the filters originally designed in floating point double precision data format were to be converted to the single precision. At this point possibility of IIR filter instability arose due to the coefficients round off. What is more the pass band of the filter was relatively narrow as compared to the sampling frequency. This fact caused this risk very realistic, what was confirmed by several experiments. “Round off” instability was eliminated by means of consecutive coefficient distortion in the least meaning digit range followed by filter parameters and stability verifications. Resulting filter (plotted in pluses in the Fig. 5) of satisfactory parameters was finally converted to the series cascade of second order IIR filter structure. This operation made developed filter better in terms of stability and filter response decay time.

Fig.6. Example results of the QRS detection, presented in the Authors’ dedicated environment

Results

Developed algorithm achieved satisfactory accuracy of the QRS real-time detection. Detailed tests were carried out on the CSE multilead measurement MA1 dataset. Normative publications [2] recommend verification tests based on the defined 100 signals selection of the whole 125 signals set. Authors used 123 signals from this dataset (Fig. 6). Signals no. 67 and 70 contain pacemaker spikes and were excluded from the verification procedure.

According to the recommendations [2], QRS detection algorithm performance parameters were calculated: Sensitivity - 99.59%, Positive predictivity - 99,59% and additionally Error rate - 0.81% (tested on the CSE ECG MA1 database). Reference signals contain many QRS complexes placed in the signal at the early beginning and late end, too. None of them were excluded from the test procedure. Similarly some false positive detections occurring at the beginning of a test signal due to abrupt signal change (technical artefact or incompletely recorded QRS complex) were not removed from the final results. Achieved QRS detection performance allows for direct implementation of the developed algorithm into the medical diagnostic instrumentation real time realisations. Here it is worth to mention that achieved results are almost comparable to the contemporary off-line detection algorithms. These realisations are characterised by Error rate lower than 0.3% [1,3].

Conclusions

The developed algorithm, based on the bandpass IIR filter is characterised by the promising properties in terms of its accuracy and speed requirement for its real time applications. It is also a reliable base for the further off-line modifications.

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