ECG SIGNAL PROCESSING AND HEART RATE FREQUENCY DETECTION METHODS

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Abstract

Digital signal processing and data analysis are very often used methods in a biomedical engineering research. This paper describes utilization of digital signal filtering on electrocardiogram (ECG). Designed filters are focused on removing supply network 50 Hz frequency and breathing muscle artefacts. Moreover, this paper contains description of three heart rate frequency detection algorithms from ECG. Algorithms are based on statistical and differential mathematical methods. All of the methods are compared on stress test measurements. All described methods are suitable for next simple implementation to a microprocessor for real-time signal processing and analysing.

1 Introduction

Electrocardiogram (ECG) represents electrical activity of human heart. ECG is composite from 5 waves - P, Q, R, S and T. This signal could be measured by electrodes from human body in typical engagement. Signals from these electrodes are brought to simple electrical circuits with amplifiers and analogue – digital converters.

The main problem of digitalized signal is interference with other noisy signals like power supply network 50 Hz frequency and breathing muscle artefacts. These noisy elements have to be removed before the signal is used for next data processing like heart rate frequency detection. Digital filters and signal processing should be designed very effective for next real-time applications in embedded devices.

Heart rate frequency is very important health status information. The frequency measurement is used in many medical or sport applications like stress tests or life treating situation prediction. One of possible ways how to get heart rate frequency is compute it from the ECG signal. Heart rate frequency can be detected d from ECG signal by many methods and algorithms.

Many algorithms for heart rate detection are based on QRS complex detection and hear rate is computed like distance between QRS complexes. QRS complex can be detected using for example algorithms from the field of artificial neural networks, genetic algorithms, wavelet transforms or filter banks [1]. Moreover the next way how to detect QRS complex is to use adaptive threshold [2]. The direct methods for heart rate detection are ECG signal spectral analyse [3] and Short-Term Autocorrelation method [4].

Disadvantage of all these methods is their complicated implementation to microprocessor unit for real time heart rate frequency detection. Real time QRS detector and heart rate computing algorithm from resting 24 hours ECG signal for 8-bit microcontroller is described in [5]. This algorithm is not designed for physical stress test with artefacts.

The designed digital filters and heart rate frequency detection algorithms are very simple but robust. They can be used for ECG signal processing during physical stress test with muscle artefacts. They are suitable for easy implementation in C language to microprocessor unit in embedded device. Design of these methods has been very easy with Matlab tools and functions.

2 Signal acquisition

ECG signal for digital signal processing and heart rate calculation was acquired by measurement card with sampling frequency f_s = 500 Hz. The first ECG lead was measured. Analogue signal pre-processing was done on simple amplifier circuit designated for ECG signal measurement. The circuit with ECG amplifier is fully described in [6]. In Figure 1 there is shown raw ECG signal sampled by measuring card. This signal was used as input signal for the digital filters and the heart rate detection algorithms designing and testing.

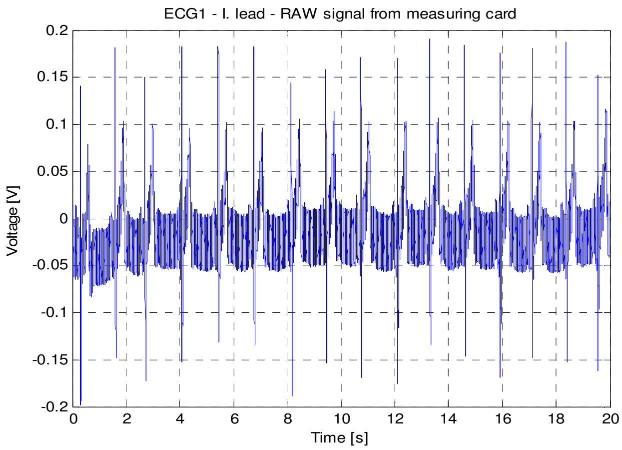

Figure 1: Raw signal acquired by measuring card with simple ECG amplifier circuit.

3 Digital signal processing with digital filters

In this part there is described noise elements filtering and baseline wander elimination with digital filters. The main noise elements are power supply network 50 Hz frequency and breathing muscle movements. These artefacts have to be removed before the signal is used for next data processing like heart rate frequency determination. The block schema of digital signal processing with digital filters is shown in Figure 2.

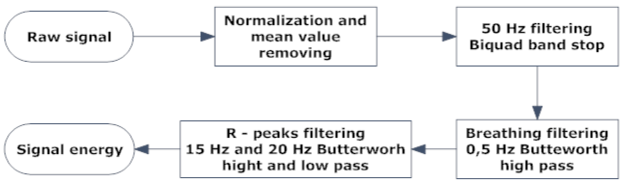

Figure 2: Digital signal processing and digital filters block schema.

At the beginning, the mean value is removed from signal. Then signal is normalized for unit maximum amplitude. Network interference at 50 Hz frequency is removed by first filter. This filter type is biquad band stop. Advantage of this filter is very narrow band stop which is created by poles and zeros location. Baseline wander was provided by means of the next filter. This filter is second order Butterworth filter set to frequency of 0.5 Hz. This filter is usually used in professional ECG filtering applications [7]. The signal filtered by these filters is shown in the Figure 3.

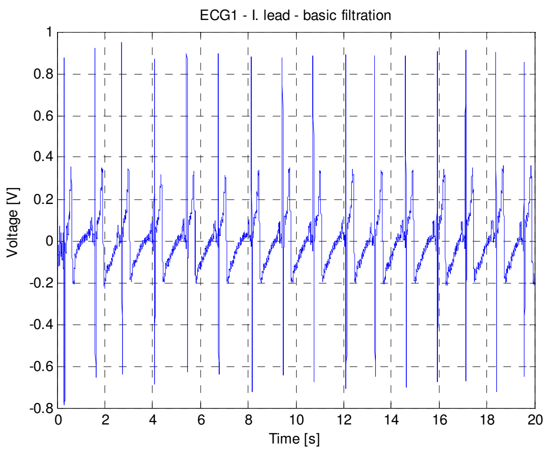

Figure 3: Signal after network 50 Hz and baseline wander filtering..

After the basic filtering, the R-peaks are detected from ECG signal. R-peaks filtering are necessary for next heart rate detection. The signal is filtered by high pass and low pass Butterworth filters with cut-off frequencies 15 Hz and 20 Hz. Both filters are fourth order because of computing difficulty in next implementation in a microprocessor. Using of these two filters has better results than one band pass filters. The signal energy of samples (1) from voltage amplitude is calculated then.

$$E(t) = u(t)^2 \tag{1}$$

This process more highlights R-peaks in signal. In Figure 4 there is displayed energy signal which is ready for heart rate detection.

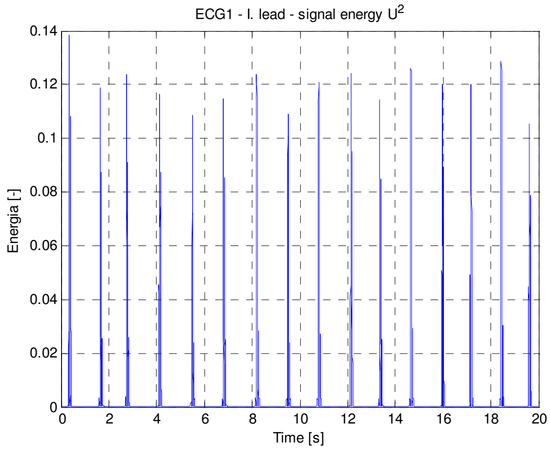

Figure 4: Energy signal after R-peaks filtering.

4 Heart rate detection algorithms

In this part there are described algorithms for heart rate detection which have been designed in Matlab. Algorithms can be divided to algorithms based on statistical and differential mathematical methods.

The first algorithm is focused on statistical signal processing methods like autocorrelation. Autocorrelation method can be used because the ECG signal is quasi-periodical. Matlab provides very simple using of autocorrelation method in signal processing which is very useful for this purpose.

The second and third algorithms are detecting heart rate as difference between R waves in ECG. These waves are filtrated by band pass filters firstly and then the signal energy is computed. The wave's peaks are detected by peak detector or signal thresholding.

These algorithms compute heart rate frequency from the signal energy. The signal energy was pre-processed in preceding part. All three described algorithms were used on same signal. It means it is possible to compare the results and to choose the best one.

4.1 Autocorrelation of energy signal

The first algorithm computes heart rate frequency using mathematical statistic autocorrelation function. Autocorrelation function is applied on signal energy. Integrator filter highlights peaks in autocorrelation function. Peak detector is used for extract peaks from autocorrelation function. In the Figure 5, autocorrelation function, peaks and computed heart rate frequency are displayed.

4.2 Thresholding of energy signal

The second algorithm computes heart rate frequency using the energy signal thresholding [8]. The threshold is computed according the equation (2). This equation was derived empirically.

$$TH = 2 \times \overline{E}(t) \tag{2}$$

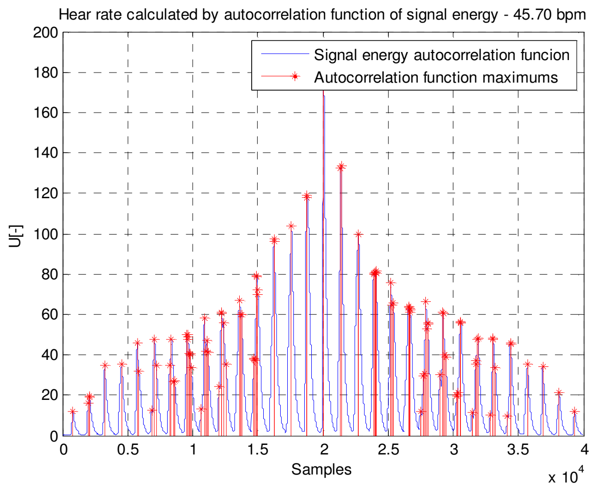

Figure 5: Autocorrelation function of signal energy.

The threshold is used for finding the signal parts where R-peaks are situated. The peak detector in this algorithm is not used. Firstly, time indexes of samples higher than the threshold are found. After that, the algorithm computes differences between time indexes. Only samples with time index differences higher than the minimal physiological heart period are selected as the R-Peaks. In the Figure 6 the signal energy, threshold, R-peaks timestamps and the calculated heart rate are displayed.

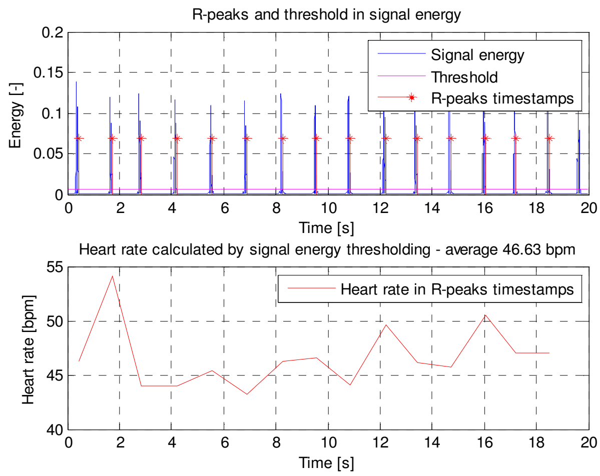

Figure 6: R-peaks timestamps, threshold in signal energy and calculated heart rate frequency.

4.3 Peaks detection in energy signal envelope

The third algorithm uses the integrator filter firstly. Energy signal is smoothed by this filter. R-peaks are highlighted as well. Moreover the energy signal envelope is made [9]. The peak detector is used to find the peaks in the signal envelope [10]. Heart rate frequency is computed from R-R intervals. If the interval between two R-peaks is lower than the maximal physiological heart rate, the next R-peak is taken. It prevents failures caused by artefacts in signal from occurring. The energy signal smoothed by integrator filter, R-peaks timestamps and calculated heart rate are shown in the Figure 7.

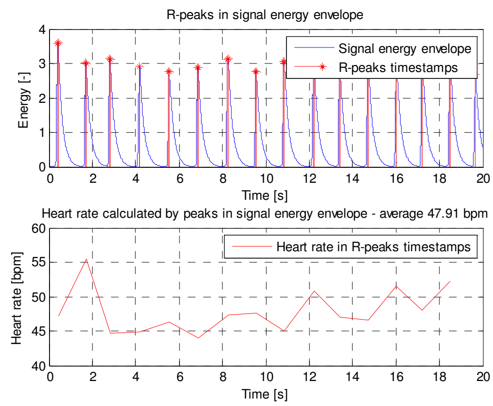

Figure 7: R-peaks timestamps in signal energy envelope and calculated heart rate frequency

5 Applications of designed algorithms

Finally the designed algorithms were applied to compute heart rate frequency from ECG signals which were measured during stress tests. ECG signal was certainly filtered by digital filters described in third part of this paper. The stress test was composite from during pedalling on an exercise bike and exercising with dumbbells.

The signal was sampled continually during stress test. The heart rate frequency was computed in frames of signal with length of 4 s which were 2 s overlapped. The division of signal to frames simulates real-time processing which will be used in microprocessor implementation.

In the Figure 8 there is shown the behaviour of computed heart rate frequency during pedalling on the exercise bike and in the Figure 9 there is shown the behaviour during exercising with dumbbells.

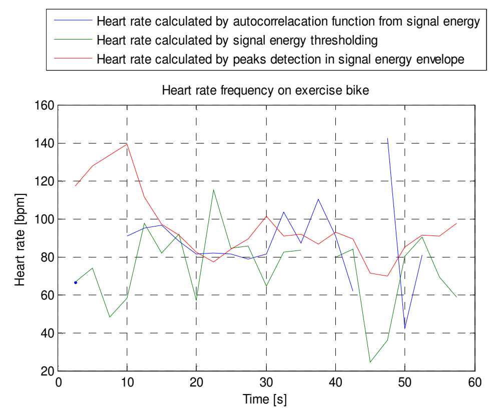

Figure 8: Heart rate frequencies calculated with all three algorithms during pedalling on exercise bike.

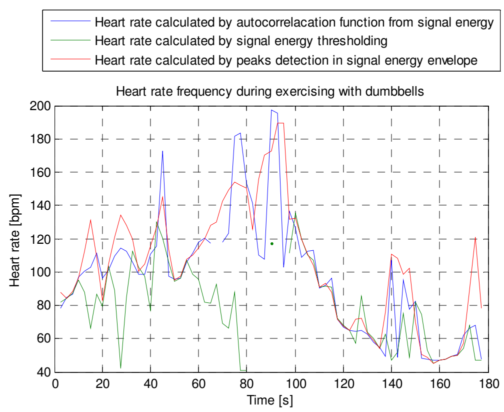

Figure 9: Heart rate frequencies calculated with all algorithms during exercising with dumbbells.

In the Figures we can see that the differential computing methods are better than the statistical computing method in the stress tests measurement application with real-time processing simulation. The main problem of autocorrelation function algorithm is quality of signal periods in fast signal changes. That is the reason why the parts of values are missing in the results of this algorithm.

6 Results

The designed digital filters and the heart rate frequency algorithms are very simple. The filters have small order. It saves the computing time, but it is very effective for processing the ECG signal. It is the reason why these algorithms could be easy implemented to microprocessor unit.

Based on the application of the computing algorithms to digitally filtrated ECG signal which was acquired during the stress test it may be argued that differential computing methods are better for real-time processing implementation.

7 Acknowledgments

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