Heart Rate Detection from Ballistocardiogram

Jakub PARAK

[1] Dept. of Circuit Theory, Czech Technical University, Technicka 2, 166 27 Praha, Czech Republic

parakjak@fel.cvut.cz

Abstract. *The heart rate detection from the ballistocardiography signal is described in this article. The ballistocardiography is a technique for recoding of repetitive motions of the human body in form of the ballistocardiogram (BCG). Caused by the sudden ejection of blood into the great vessels with each heart beat, the body motions are in turn causing movements in a suspended supporting structure equipped with piezoelectric sensors. The signal is amplified and filtered by simple electronic measurement circuit. The pre-processed analog signal is sampled on the measuring card. The second lead of electrocardiography (ECG) signal is sampled synchronously with BCG and is used as a reference. The sampled BCG signal is processed by digital filters. Three heart rate detection methods were proposed and tested on BCG signal. Similarity of processed signal allowed us to use methods based on heart rate detection from ECG signal. Proposed methods were tested on the BCG measurements from several persons. According to the results the optimal methods for the heart rate detection are the algorithms based on the autocorrelation and on the thresholding of the signal energy. Due to their simplicity, proposed algorithms are suitable for the real-time BCG signal processing and heart rate calculation.*

Keywords

Ballistocardiogram, piezoelectric sensor, signals processing, heart rate detection.

1. Introduction

The ballistocardiography is one of the noninvasive methods for monitoring heart activity. The main research methods began in 50th of the 20th century [1].

The ballistocardiography is a measure of ballistic forces on the heart. The BCG curve is a graphical representation of repetitive motions of the human body arising from the sudden ejection of blood into the great vessels with each heart beat [2].

Robust BCG acquisition is suitable for home vital sign monitoring. Long-term monitoring during sleep can help in detecting hidden heart defects. One of the biggest advantage of this measurement is that monitored person has no wires around his body [3] [4].

The measurement is done mainly by electromechanical film (EMFi) sensors which transfer mechanical energy to electrical signal and vice versa. These sensors can be integrated in bed or chair [5] [6]. The next possibility is to use optical fibers. If an optical fiber is inserted in the bed's mattresses, its length is changed by heart and breathing activity. By using optical interferometer, it is possible to measure the length of the fiber and to obtain signal that includes information about the heart activity [7]. The BCG signal can be measured by radar system waves on very high frequencies as well. It is truly non-contact measurement of vital signs [8].

The heart rate from the BSG signal can be detected by various methods. The first method is signal segmentation with template beat wave model matching [9]. The next possible method is to use adaptive beat to beat estimation based on component analyses [10]. The neural networks algorithms on FPGA are the next possibility how to detect heart beats from BCG [11].

A disadvantage of the algorithms mentioned above is relatively high computing demand. It means it is difficult to implement those methods in real-time systems. It is also difficult to use the radar system or optical fiber sensors for common measurement tasks.

The piezoelectric sensor pad which was used for described measurement is very similar to EMFi sensor. The heart rate detection methods described in this article are robust, but still enough simple, ideal for implementation into the real-time systems.

2. Measurement system

The hardware of the ballistocardiography measurement system consists of following main parts: a piezoelectric sensor pad and an analog signal processing circuit. A reference ECG signal is measured on the special unit. The BCG and ECG signals are synchronously sampled on measuring card which is connected to the PC.

2.1 Piezoelectric sensor pad

The piezoelectric sensor measures ballistic forces from the heart and converts them to electric impulses. The sensor pad which is used for measurement is taken from a baby monitor. The baby monitor was originally designed for monitoring infant breathing during sleeping. The sensor pad has very high sensitivity and therefore can be used for measurement of the BCG. During the measurement a person lies with his back on the pad. The pad equipped with piezoelectric sensor is displayed on the Fig 1.

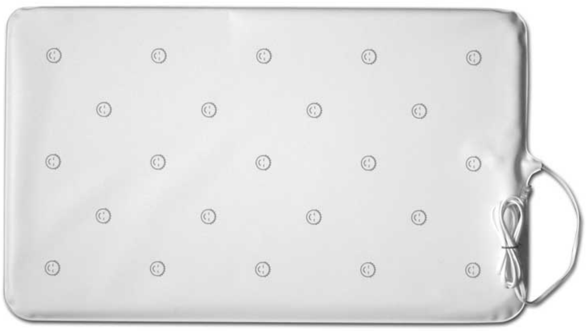

Fig. 1. Piezoelectric sensor pad

2.2 Analog signal preprocessing circuit

The analog BCG from piezoelectric pad has to be preprocessed on the analog circuit before it is sampled on measuring card. The analog circuit consists of three parts: an impedance separation, a low pass filter and a signal amplifier.

At the beginning there is important to determine the input resistance of the sensor pad by resistors. The voltage follower is used as an impedance separation. Next part is the low pass passive filter with the cut-off frequency 30 Hz. At the end of the circuit there is a non-inverting amplifier with adjustable gain. The amplifier gain was empirically set on the value 6.

The electric circuit schema is shown on the Fig. 2.

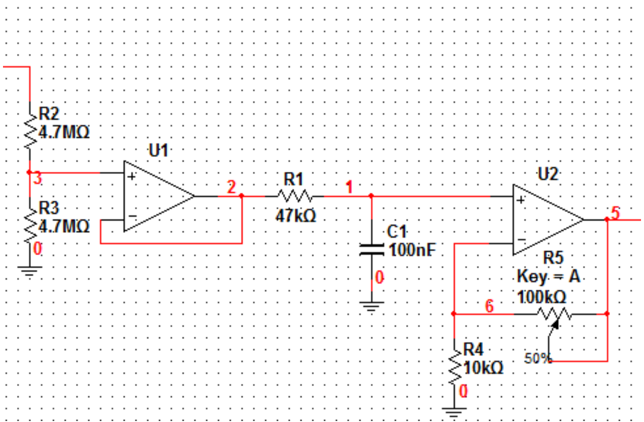

Fig. 2. Analog signal preprocessing circuit schema

2.3 ECG signal measurement unit

The reference ECG signal is measured on the unit which is based on professional electrocardiography device [12]. This unit is described in detail in the [13]. As the reference signal the second lead of the ECG is used. The signal is used for computing the reference heart rate. The ECG signal measurement unit is displayed on the Fig. 3.

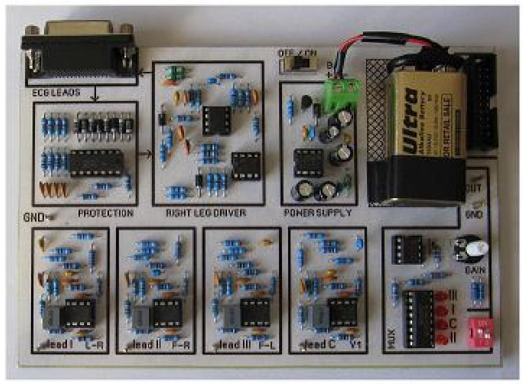

Fig. 3. The ECG signal measurement unit

3. Digital signal processing

Digital signal processing for BCG has been designed in Matlab. The raw BSG is displayed on the Fig 4. The signal is measured using measuring card with the analog preprocessing circuit which was described above.

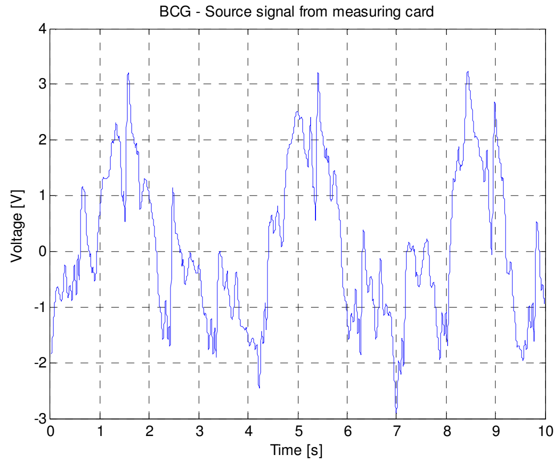

Fig. 4. RAW BCG from measuring card

Block schema of digital signal processing and filtering is displayed on the Fig. 5.

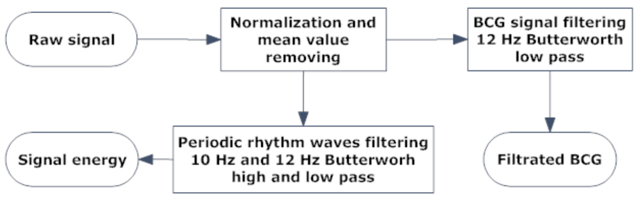

Fig. 5. BCG Digital signal processing block schema

At the beginning the mean value is removed and signal is normalized for the maximum amplitude of the unit. The network interference at 50 Hz is not filtered because the analog low pass filter is set to 30 Hz. The first filter wanders the baseline. The filter is fourth order

Butterworth high pass filter with cut off frequency 1 Hz. The next filter filters BCG. This filter is fourth order Butterworth low pass filter with cut off frequency 12 Hz. The filtrated signal is displayed on the graph on the Fig. 6.

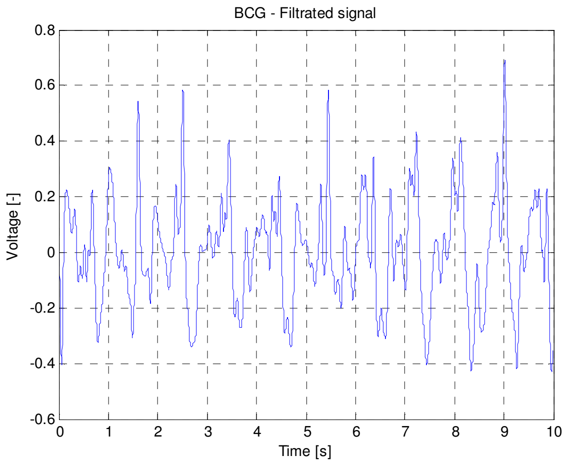

Fig. 6. Filtrated BCG signal

For the heart rate detection purposes it is appropriate to use a filter of periodic heart rhythm waves that are between 10 Hz and 12 Hz in BCG. Highest peaks of these waves correspond to periodic R-peaks in the ECG signal. These waves are filtered by fourth order Butterworth high and low pass filters with cut off frequencies 10 Hz and 12 Hz. These filters were selected because they gave better results than one band pass filter. The filtered signal is display on the graph on the Fig. 7.

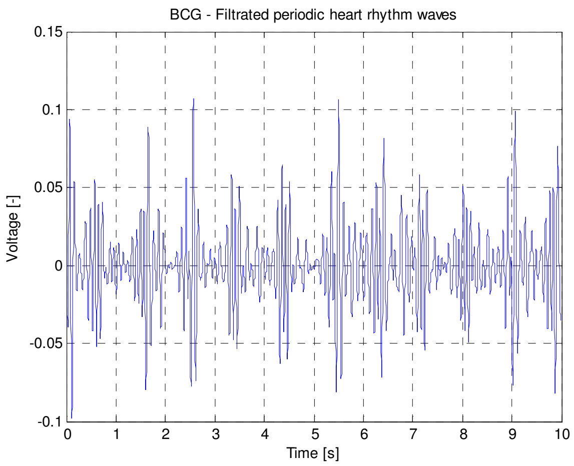

Fig. 7. Filtrated periodic heart rhythm waves of BCG

In the next step, the energy of the signal is calculated (1). The signal energy is shown on the Fig. 8.

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

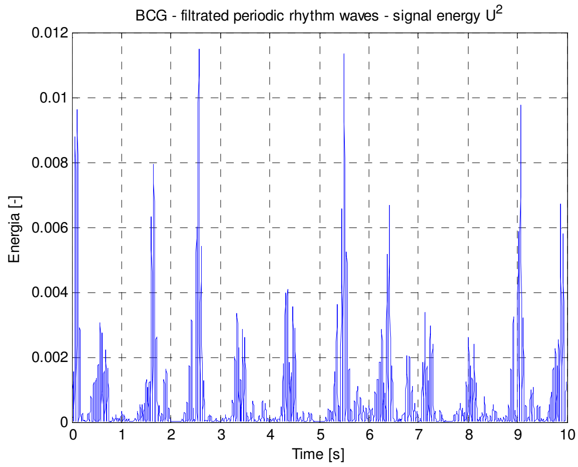

Fig. 8. Signal energy of filtrated periodic heart rhythm waves

The reference ECG signal processing could be divided into following steps:

1. Normalization and mean value removing,
2. 50 Hz power supply noise removing,
3. Base line wandering,
4. R-Peaks filtering,
5. Energy computing.

Digital signal processing and filtering of the reference EGG signal is described in detail in the [14].

4. Heart rate detection algorithms

The BCG and ECG signals are very similar. Therefore heart rate detection from BSG is made on the redesigned algorithms. These algorithms were originally designed for computing heart rate from the ECG signal. The original designs of the algorithms are described in the [14] and [15].

All the algorithms compute heart rate from signal energy. In the algorithms there were changed only the smoothing integrator and the peak detector constants for BCG processing.

All three algorithms were compared during their design with original heart rate detection from ECG.

4.1 Signal energy autocorrelation function

The first algorithm computes heart rate frequency using mathematical statistic autocorrelation function. The algorithm is based on the assumption that BCG is a periodic signal like the ECG. In the Fig. 10 the autocorrelation functions of BSG and ECG signal energy are displayed with computed hear rate value.

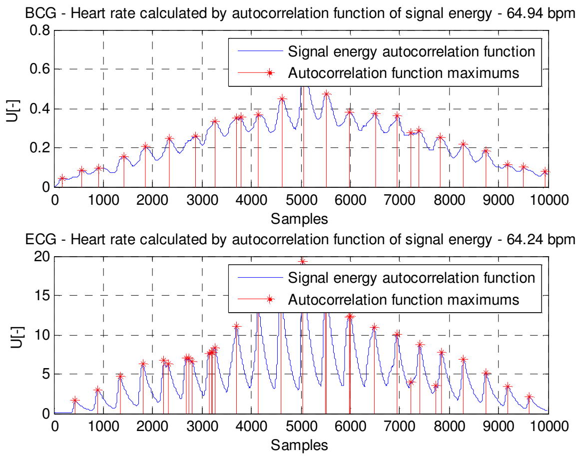

Fig. 10. BSG and ECG signal energy autocorrelation function

4.2 Signal energy thresholding

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

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

In the Fig. 11 the BCG signal energy, threshold, peaks timestamps and the calculated heart rates are displayed.

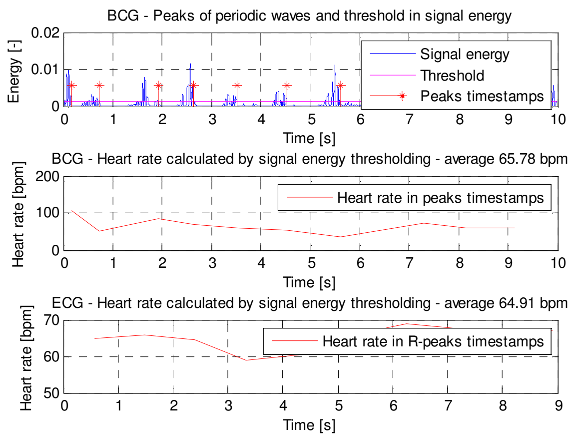

Fig. 11. BSG peaks timestamps, threshold in signal energy and calculated heart rate frequencies.

4.3 Peaks in signal energy envelope

The third algorithm uses the integrator filter. Firstly the energy signal is smoothed by this filter. The peaks from the signal energy are well highlighted. Moreover the energy signal envelope is made. The peak detector is used to find the peaks in the signal envelope. Heart rate frequency is computed from peaks difference. BCG signal energy smoothed by integrator filter, peaks timestamps and calculated heart rates are shown in the Figure 8.

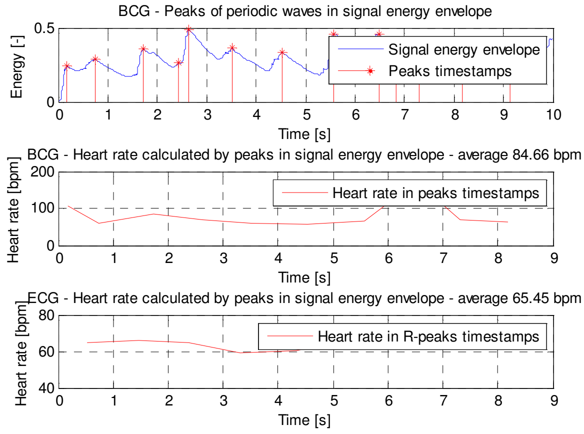

Fig. 12. BSG peaks timestamps in signal energy envelope and calculated heart rate frequencies.

5. Measurements and results

Experimental measurements were made on 4 persons. During the measurement every person lay on the sensor pad which was placed under person's back. All persons didn't move during the measurement. This position simulated sleeping and lying in bed. Every person has been measured three times for 1 minute. The ECG signal for reference heart rate computing was measured synchronously.

Heart rate from BCG was computed with all three algorithms for all 12 measurements. The reference heart rate acquired from ECG signal was calculated using peaks detected in signal energy envelope. This method was used for all 12 measurements. The method was chosen as reference method due to the experiment results which are described in [14]. For every measurement and method absolute deviation from reference heart rate was calculated. The deviation was calculated from average heart rate from whole 1 minute measurement.

In the graph (see the Fig. 13) there are displayed absolute deviation calculated for all measurements and methods.

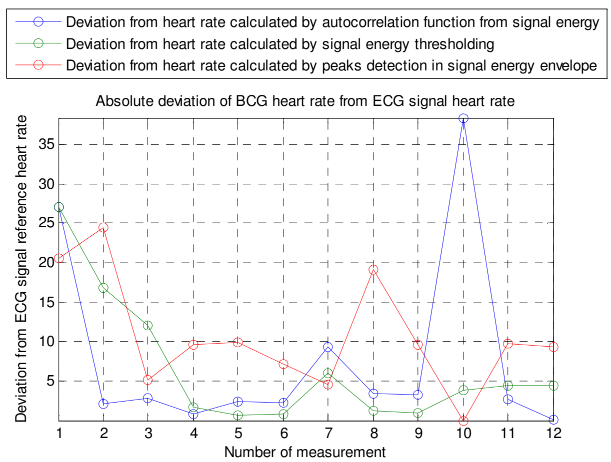

Fig. 13. Absolute deviation of BSG heart rate from ECG signal heart rate

In the Tab. 1 there is written the mean values of the heart rate absolute deviations computed for all measurements and methods.

Mean values of hear rate absolute deviations	
Computing method	**Value**
Autocorrelation function from signal energy	7.8934
Signal energy thresholding	6.6772
Peaks detection in signal energy envelope	10.7647

Tab. 1. Mean values of heart rate absolute deviations

Based on the results it may be argued that the autocorrelation function algorithm and the thresholding algorithm are the most suitable for the heart rate computing from the BCG signal.

6. Conclusion

The heart rate detection algorithms were designed and tested on several persons. Reliability of the algorithms was verified by the heart rate values calculated from the reference ECG signal. The most reliable algorithms were selected.

Based on the simplicity of the digital signal processing and heart rate detection algorithms they can be easily implemented into embedded hardware systems.

In the future, similar measuring systems with piezoelectric pads will be integrated in assistive technology system inside a smart home. Measured BSG signal and computed heart rate value will be used for real-time classification of life threatening situations.

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About Author

Jakub PARAK was born in Bratislava, Slovakia. In 2011 he graduated in biomedical engineering at the FEE CTU in Prague. He is currently a PhD-student at the same university at the Department of Circuit Theory at the FEE. Main topics of his research are classification of life threatening situations and vital function monitoring. He is interested in signal processing and embedded hardware applications.