electrocardiogram compression,
wavelet transformation,
QRS complex detection

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IMPLEMENTATION OF WAVELET COMPRESSION OF THE ELECTROCARDIOGRAM IN SIGNAL PROCESSOR

The paper presents the study of the algorithm of wavelet compressor dedicated to electrocardiographic signals and results of its implementation in the signal processor SHARC ADSP-21364. The designed compressor is characterized by a work in the real time and with possibility of the separate compression of the signal about the higher diagnostic worth determined as the QRS complex.

1. INTRODUCTION

The electrocardiographic signal represents the electrical activity of the heart action. With regard on the presence of different phases of the heart action, the recorded signal has not uniform frequency band in the whole time domain. The notion of local bandwidth in context of electrocardiogram contents was defined in [1]. Sampling the electrocardiographic signals with the fixed frequency causes the acquisition of large amounts of the excessive information. The elimination of excessive data not associated directly with the information about the action of heart is the object of considerations in the presented work. Leaving from the side of notion of local band to compression of electrocardiographic signal it's possible to apply one of the following approaches. First approach relies on sampling the signal with variable frequency, fitted adaptively to the local band of the recorded signal. Second approach is based on adaptive modification of time-frequency representation of uniformly sampled ECG signal.

In the presented work the second approach was used and involves the application of floating point wavelet transformation as mediator between time and time-frequency domains.

The designed device of compressor should fulfil following requirements

- Compression of eight electrocardiographic signals (analog signals).
- Real-time work.
- Possibility of independent settings of compression levels within and beyond area specified as having higher diagnostic value.

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- Automatically detection of area having higher diagnostic value (defined here as equivalent to QRS complex).

2. REALIZATION

The initial development of compressor algorithm was carried out in the Matlab environment, making benefit of the possibility of fast alterations in the algorithm. The final version of compressor was implemented using C++ language.

The proposed device consists of the three principle parts:

- Compressor – built in hardware with use of signal processor SHARC ADSP-21364 [2]
- Decompressor – built as a PC computer-designed software,
- Communication bridge interfacing the signal processor and the computer. This device is also responsible for feeding the compressor with ECG signals converted from analog inputs connected to high-voltage ECG source.

2.1. QRS DETECTOR – FINDING A PART OF SIGNAL WITH HIGHER DIAGNOSTIC VALUE

The proposed solution of the compressor is based on the division of the ECG signal to two parts differing by their diagnostic significance. For the reason of implementation simplicity, we set the time zone of higher diagnostic value as equal to the QRS complex. In aim of finding the position of QRS complex the Tompkins algorithm was used. With respect to the original version developed by Pan and Tompkins [3], a new digital filters were designed. In purpose to reduce the sensibility of the QRS detector on local artifacts in recorded signal, gradual decrease of thresholds was applied if no new beat has been detected in a time period corresponding to average of eight precedent R-R intervals.

To the assessment of the effectiveness of the algorithm, the arrhythmia base from MIT-BIH base was used. The Arrhythmia base contain 48 two lead signals including the annotations about the position of the QRS complex. The results of tested algorithm are presented in table 1.

Table 1. Results of effectiveness of the QRS complex detection algorithm using the MIT-BIH arrhythmia database.

	All 48 signals	**Excluding signals: 102, 104, 207**
PPV	99.16[%]	99.85[%]
SE	98.55[%]	99.60[%]

Applying the modification of thresholds results in reduction of missing QRS complex but also caused slight growth of the number of false positive QRS detection. These detections have only marginal impact on the compression process, resulting in higher significance assignment and therefore more accurate reconstruction of each signal part erroneously recognized as a QRS complex.

2.2. WAVELET TRANSFORM, QUANTIZATION AND CODING

Applying the floating-point signal processor ADSP-21364 allowed for implementations of the floating-point wavelet transform. However, due to the limited amount of available memory in the processor, the discrete wavelet transform was applied. Instead of calculation of all wavelet coefficients of details and approximation and later removing the every second sample, only indispensable coefficient are being calculated. The decimation process is thus realized in parallel with filtration and result in exit vector containing only relevant coefficients at given decomposition level. The transformation is performed for signal sections of 4096 samples in every of 8 signals. In order to maintain the continuity between neighboring sections of signal, it was necessary to eliminate the edge effect by applying widening the signals at both endings.

To modify the time-frequency surface accordingly to the ECG local bandwidth, small wavelet coefficients are eliminated. Since the algorithm has to be insensitive to the ECG signal voltage, we applied adaptive calculation of main threshold independently for every signal and for every scale of time-frequency representation. For calculation of main threshold we used the method proposed by Donoho [4]. The user has the opportunity to indirectly control the level of signal distortion by setting the percentage value of main threshold applied within and beyond the area of QRS complex.

Because of high memory usage by the time-frequency signal representation, the quantization of wavelet coefficients was necessary. For this purpose, we applied the UTQ (*Uniform Treshold Quantization*) scheme. For every scale of time-frequency representation minimum and maximum values are detected and used as boundaries of a values range. This range is next divided into equal-length quanta defining the resolution in the quandized signal domain. The details coefficients are coded on 8 bits, and approximation coefficients – on 12 bits. Because of significant amount of coefficients equal to zero in statistical point of view, after the quantization all coefficients equal 0.0 have attributed coding symbol 0.

In the final step of processing, the stream is subjected for encoding with using the static Huffman encoder. As a results of zeroing of small coefficient, we get groups of zeros. We are using this knowledge for building the model of symbols source by applying a context quantization for group of zeros. The optimal calculated length of context is 8.

2.3. REAL MODEL OF COMPRESSOR

The design of the wavelet compressor for electrocardiographic signals working in the real time was a main purpose of this work. The necessary data buffering for the compression causes a delay of over 22 seconds between the sampled signals and the decompressed result displayed on the computer screen. The compressor was built with use of the signal processor SHARC ADSP-21364 Development Kit. In aim to supply the data for compression, the interfacing device was designed based on microcontroller ADuC842. This device collects samples with sampling frequency of 360 Hz and resolution of 12 bits from 8 analog signals previously amplified in external amplifier (for example an electrocardiograph). The interfacing device communicates with the signal processor over an SPI interface.

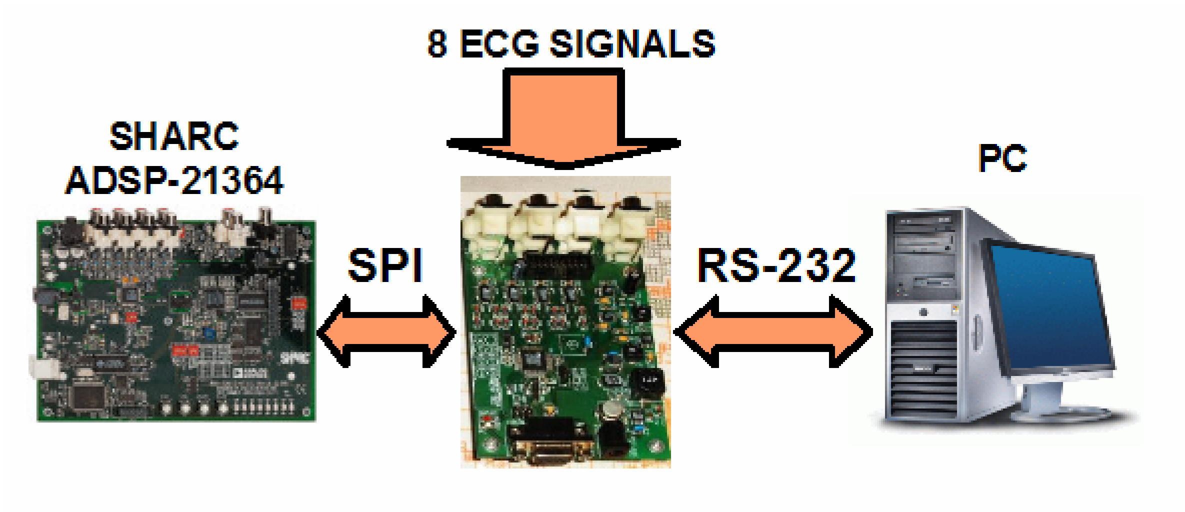

Fig.1. Scheme of proposed compressor architecture.

PC computer was chosen as the target where compressed stream of electrocardiographic signals is directed. This solution was chosen in order to low cost and ease demonstrating of registered signals on the monitor screen in real time. Communication between the PC and microcontroller is through RS-232 interface, however in the future may easily be replaced by wired or wireless TCP/IP-based link.

The software was written in C++ language. Graphical user interface of the decoding and presentation application was made with using free wxWidgets 2.8.2 library.

The features of the software include:

- Individual compression settings for every signals
- Decompression the stream received on RS-232 port in real time
- On-screen presentation of decompressed signals in real time
- Saving received stream/decompressed stream to a file in few available formats
- Read data from file

Fig.2. Screenshot of presentation application running on a standard PC computer.

3. RESULTS

3.1. RESULTS OF WAVELET COMPRESSOR PERFORMANCE

For the purpose of testing the signal s0060lre was used from the PTBD directory of the MIT-BIH database. Before use, the signal was decimated to the sampling frequency of 360 Hz and the resolution was decreased to 12 bits. Because of limited knowledge of compressed signal shape, the wavelet resembling the shape of arterial morphology was chosen, it's mean: daubechies 6, 7, symlet 7.

The chart presented in figure 3 shows dependence between mean square error and compression ratio as function of coefficients describing indirectly compression ratio within and beyond the QRS complex. Dashed lines connect the points of equal coefficients values.

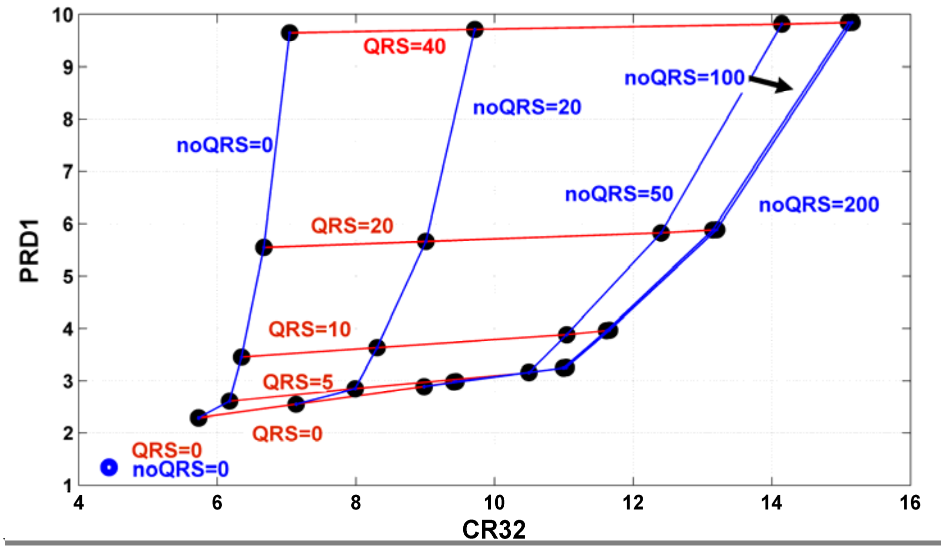

Fig.3. Correlation between achieved mean square error (PRD1) and compression ratio CR_{32} (related to 32 bit floating number) as a functions of percentage value of main threshold within and beyond the QRS complex (marked QRS and noQRS respectively).

Applying the higher threshold for coefficient beyond the QRS complex causes improving the compression ratio and keeping value of mean square error on more or less fixed level. This is an evident example of redundancy of the information which is connected with the representation of the signal outside the QRS complex. However elimination of the coefficients within the QRS complex causes that we get opposite result – as the cost of small growth of compression ratio, the significant growth of distortions follows.

The not bit-accurate compression applied to medical images has been widely discussed in context to preserve diagnostically meaningful details. One of the solutions is defining a zone of interest where the image is reproduced accurately. Our approach is the analogy of the above in the one dimensional signal domain. The particular accuracy zone (or technically writing: full bandwidth zone) is roughly assumed to be equivalent to the QRS complex and delimited automatically by a standard algorithm. Such assumption is simplified by not considering P and T waves as well, but full waves detection procedure was found too complex to be run in real time in our experimental DSP platform. Wavelet technique was used as the instantaneous bandwidth adjustment tool, providing - depending on the wavelet-to-signal similarity - the smoothest possible transient between the zone of interest and the background.

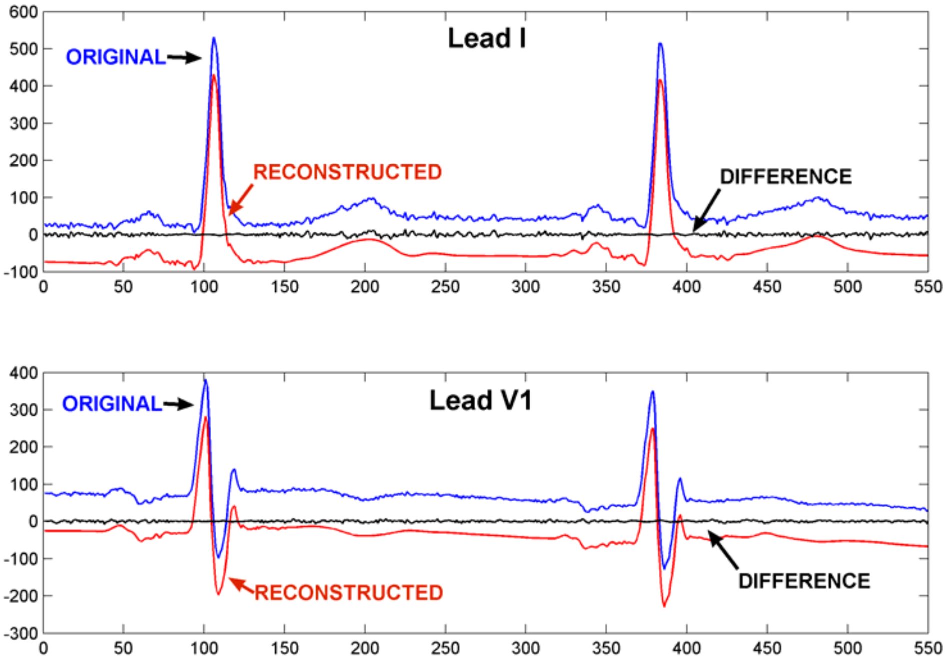

Fig.4. The plot of ECG signals from lead I and lead V1. The reconstructed signals was got for compression parameters: noQRS=100, QRS=5.

4. CONCLUSION

In this document the practical realization of wavelet compressor of electrocardiograms working in real time was presented. The device will be used as component of remote telemonitoring system for cardiology. The effective degree of compression ratio taking over 4, at the acceptable mean square error of about 3.25, support the expectations for significant reduction of monitoring costs, and for including larger number of patients in the monitoring program. The results of our research testify about advisability of applying separate thresholds for essential with point of sight of diagnostic part signal.

5. ACKNOWLEDGMENT

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