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REDUCING THE SPATIAL SIGNAL CORRELATION FOR THE COMPRESSION OF MULTILEAD ELECTROCARDIOGRAPHIC RECORDINGS

This paper is devoted to the tranform-based methods for decorrelation of simultaneously recorded ECG channels. The conventional 12-lead ECG recordings, due to the non-optimal lead positioning, contain highly redundant data. Eliminating this redundancy yields new possibilities for lossless coding of the ECG, meeting the most severe expectations about the quality of stored signal. The statistical properties featured by uncorrelated signals in the transform domain are more appropriate for the data distribution-based coding techniques. In our work four linear transforms are studied and numerically verified with use of the real ECG data. Additionally, the combination of spatial and temporal decorrelation is proposed and discussed as the practical and lossless method for a real implementation. The compression efficiency significantly exceeds the values obtained with use of general-purpose lossless algorithms.

1. INTRODUCTION

1.1. MOTIVATION

Electrocardiogram (ECG) becomes currently one of the most frequently performed diagnostic test, because of high mortality risk from the cardiovascular diseases. For the high accessibility of the ECG, the compression of electrocardiogram signal is of great practical significance and is widely used in clinical practice. Various ECG applications usually need the data compression, but at least three of them should not be neglected: management of database for reference purpose, transmission of the ECG over telecommunication networks and ambulatory long term recording (Holter systems).

The issue of ECG data compression receives high attention in scientific world and several papers were devoted to reviewing and classifying the compression methods [8]. Our research is focussed on the transform-based methods where after a linear transformation data reduction is performed in the new domain. The main goal was to explore the efficiency and applicability of the perfect reconstructing compression, also called "lossless". For this purpose, the coding algorithm and all the applied transforms have to be reversible in the sense of identity of the original and reconstructed discrete signal representations.

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1.2. LOSSLESS VERSUS LOSSY COMPRESSION

The achieved compression efficiency usually favorizes the lossy compression methods over the lossless coding. Some diagnostic applications of the ECG, however, assume no data loss and in many countries the lossy techniques may not be legally applied to the medical data storage. In the lossless methods, each symbol representing the original data is assigned the unique corresponding output token. The lossless reduction of the data volume is achieved due to the unequal probability of symbols occurrence, when the frequent symbols are represented by shorter tokens. This method is a foundation of histogram-based coding techniques, among of which the most popular is the Huffman Coding and its successors. The compression efficiency increases for the narrow-histogram signals where many datapoints are represented with use of few symbols.

Although the lossless coding may be applied to the raw ECG data making use of the natural distribution of quantized ECG values, aiming at better compression efficiency needs the improvement of the input sequence's statistical parameters. This justifies the pursuit for a reversible transform yielding the distribution of symbols optimized for effective coding. The prediction technique is the simplest example of such transform.

The short- and long-time prediction methods were found very efficient for the single channel ECG compression [2], [10]. For multichannel signals the additional improvement of efficiency is expected because of high information redundancy in the simultaneously recorded signals. The alternative, physiological approach to the channel decorrelation is foundation of the ECG-VCG transform that translates the eight-channel ECG to three-channel VCG orthogonal representation [9] or vice-versa [6]. During the reported research we focussed mainly on transform-based channel decorrelation, but certainly this technique may be a part of a complex coding method [3], [5]. In the end of the paper the results for the superposition of decorrelation in two dimensions are presented.

2. METHODOLOGY

As far as the perfect reconstruction is considered, all transforms applied have to be reversible. The reversibility is here understood in technical sense as the identity of the reconstructed and original discrete signal representations that usually are fixed-point valued. Since the decorrelated signals dynamic range is very low, the round-off error issued when the floating-point representation is used yields an unacceptable distortion level in the reconstructed signal.

The limb channels III, aVR, aVL and aVF repeates information provided already by the channels I and II in the circuit of the Einthoven triangle and are not considered in the data set. The remaining channels are re-ordered as so to put the chest channels V1 ... V6, where high correlation is expected, before the limb channels I and II in the data set [3].

2.1. THE OPTIMAL TRANSFORM

Decorrelating the multichannel signal involves the use of linear transform (1) [3].

$$Y_n = A \cdot X_n \tag{1}$$

where $X_n = [x_1(n),..., x_C(n)]^T$ is the original domain signal representation, $Y_n = [y_1(n),..., y_C(n)]^T$ is the transform domain signal representation and A is the $C \times C$ transform matrix.

Although the optimum linear transform, the discrete Karhunen-Loeve Transform (KLT), is defined for the stationary random processes, it may be extended for slowly varying non-stationary processes like ECG. The transform matrix is computed for each data section separately from the statistics of the ECG signals. The storage of the individual transform matrix is thus necessary and unfortunately occupies extra space in the output data stream.

First step is the estimation of the covariance matrix V_x from the ECG channels:

$$V_X = \frac{1}{M} \sum_{i=0}^{M-1} \begin{bmatrix} x_1(i) \\ \vdots \\ x_C(i) \end{bmatrix} \begin{bmatrix} x_1(i) & \cdots & x_C(i) \end{bmatrix} \tag{2}$$

where M is the number of ECG samples per channel and $C = 8$ is the channel count.

In next step, the eigenvectors of the covariance matrix V_x (2) are computed and used as rows of the transform matrix A (1).

The KLT performs the optimal channel decorrelation due to the use of eigenvalues decomposition. Unfortunately, the floating-point data representation, the need of optimal signal segmentation and the data overhead are important disadvantages constraining the practical application of the KLT.

2.2. THE SUBOPTIMAL TRANSFORM

The alternative approach uses the Discrete Cosine Transform (DCT) in the role of linear transform. The transform is fed by the sequence of corresponding samples in all considered channels: $X = [x_1(i) \quad \cdots \quad x_C(i)]$. For this sequence, the DCT coefficients are defined as:

$$G(k) = \sqrt{\frac{\alpha_k}{C}} \sum_{s=0}^{C-1} x(s) \cdot \cos \frac{(2 \cdot s + 1) \cdot k \cdot \pi}{2 \cdot C} \tag{3}$$

where $k = 0, 1, 2, ... C$-1, $\alpha_k = 1$ for $k = 0$ and $\alpha_k = 2$ otherwise. Although the DCT is a suboptimal transform and only approximates the theoretical features of KLT, its computation is more efficient thanks to the fast algorithm of order ($N \log N$). Some specialized DSP processors also provide the ability of DCT operation in the hardware. The additional advantage is the absence of transform matrix, because of using the cosine function, which does not require extra storage. The compression efficiency is thus not affected by the overhead.

2.3. THE WAVELET TRANSFORM

Third option is the channel decorrelation by computing residual inter-channels time-frequency representation. The important frequency components occur in the same time in all simultaneously recorded channels that justifies the hope for lower dynamic range of the sequence containing differences of the corresponding time-frequency atoms [1], [7]. Unlike the traditional analytical approach, the t-f representation was obtained with use of the lifted wavelet transform (LWT) that preserves the orthogonality in a fixed-point valued domain [4]. The lifting algorithm generates two subsampled strings: the decimated low-pass coarse signal and the detail high-pass signal, exactly like one decomposition stage of a traditional wavelet transform. Similar steps are repeated at each node of the decomposition pyramid.

Simple Haar lowpass (*s*) and highpass (*d*) filters were used to increase the count of wavelets vanishing moments up to the value of eight. The use of custom-designed filters, better adapted to the shapes typical for the ECG signal, would probably yield the same results at a lower price of computation reducing the order of "wavelets", being in fact the count of lifting steps.

$$\begin{aligned} d_{1,l} &= s_{0,2l+1} - s_{0,2l} \\ s_{1,l} &= \frac{1}{2}(s_{0,2l} + s_{0,2l+1}) \end{aligned} \qquad (4)$$

The lifting scheme is a reversible process, thus the strings $s_{1,l}$ and $d_{1,l}$ contain complete original information. Thanks to perfect reconstruction property, the residual t-f representation contains all the information necessary to restore the original signal.

3. RESULTS

3.1. CONDITIONS OF THE NUMERICAL EXPERIMENT

All three compression algorithms was custom-coded in Matlab 5 (MS Windows platform), except for the Huffman coding procedure downloaded via Internet [11]. As a source of multichannel ECG data we used the CSE-Multilead Database (data set 3) providing a set of 125 recordings containing simultaneous 12-lead ECG and the P-QRS-T segmentation points. The amplitude resolution is 12 bits (2.44 μV/LSB) and sampling frequency is 500 Hz. For the re-ordered ECG chanels (V1...V6, I, II) the original bitrate is 500 * 12 * 8 = 48000 bits per second, or 6.0 kbytes/s.

We developed all m-files necessary for the KLT and LWT transforms accordingly to the original authors, while the DCT is supported by the internal Matlab function.

The compression procedures were subject to numerical competition using all the recordings available. Main goal of our research is to eliminate the data redundancy aiming at the effective but lossless signal storage. For this reason the efficiency of decorrelation algorithms was measured as the compression ratio yielded by the Huffman coding performed on decorrelated data. The computation speed was behind of our interest this time and thus the developed code was not optimized.

3.2. RESULTS FOR THE KLT OVERHEAD

For the important size and high computation complexity of the optimal transform matrix *A* (1) needed for each data set, the KLT, although performing the optimal decorrelation, is hardly applicable in the real-world implementation. The chosen fixed-point representation for storage of the floating-point valued matrix *A* implies round-off errors and results in signal distortion. Otherwise, a sub-optimal fixed-point matrix should be found increasing the computation cost.

Taking longer signal sections reduces the data overhead caused by matrix storage, but the stationarity condition is less fulfilled in these cases and the decorrelation is no longer optimal. In the introductory part of the experiment the distortion level and the percentage of the data overhead contribution were studied as dependent on the signal length. Table 1 summarizes the distortion level and the data overhead percentage for various section's length.

Table 1. The distortion level [PRD %] and the percentage of the data overhead for various signal length

CSE-ID (ECG leads)	signal length [ms]		
	500	1000	2000
distortion level mean ± std	0.28 ± 0.07	0.31 ± 0.09	0.34 ± 0.09
data overhead mean ± std	62.3 ± 10.6	38.2 ± 4.51	20.8 ± 2.05

3.3. EFFICIENCY OF SIGNAL DECORRELATION

The principal aim of our work was the performance assessment of the transform-based decorrelation methods. All three procedures use constant-length signal sections of 512 samples (i.e. 1024 ms), that corresponds to the average duration of a heartbeat. Table 2 displays the statistics on decorrelation efficiency. The figures 2 and 3 show an example of decorrelation based on KLT and LWT respectively.

Table 2. Decorrelation efficiency expressed as Huffman coding output bitrate (kbytes/s) original bitrate 6.0 kbytes/s

CSE-ID (ECG leads)	decorrelation method			
	no transform	KLT	DCT	LWT
1	3.66	2.80	3.45	1.51
2	3.85	2.82	3.26	1.66
124	4.12	2.53	2.51	1.16
125	4.11	2.72	2.87	1.40
mean ±std	3.85 ±0.50	2.82 ±0.32	3.10 ±0.40	1.49 ±0.21
CR (to orig. bitrate)	1.56	2.13	1.94	4.03
PRD [%]	0	0.31	0.38	0.071

Low distortion values are reported here because of use of nearly lossless (modified KLT) or truly lossless (LWT) algorithms. Best statistic results are outcome of the LWT-based compression method yielding the lowest average bitrate of the output data stream. Comparing the figure 2 to the figure 3 gives main outlook of the signal representations in the KLT and LWT domains and helps to catch the keypoint of time-frequency domain signal decorrelation.

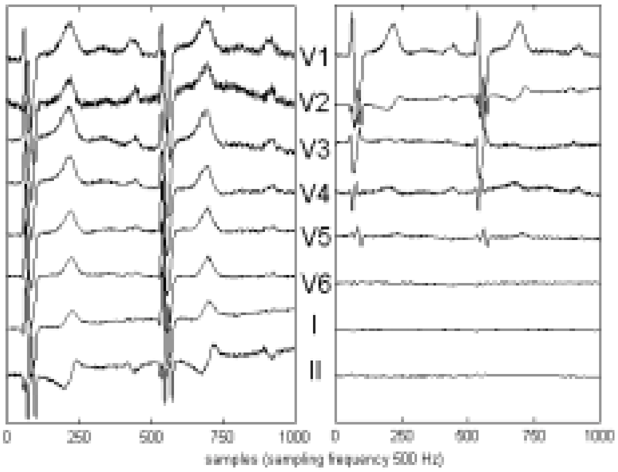

Fig. 1. Example of KLT–based decorrelation (CSE file Mo_00001)

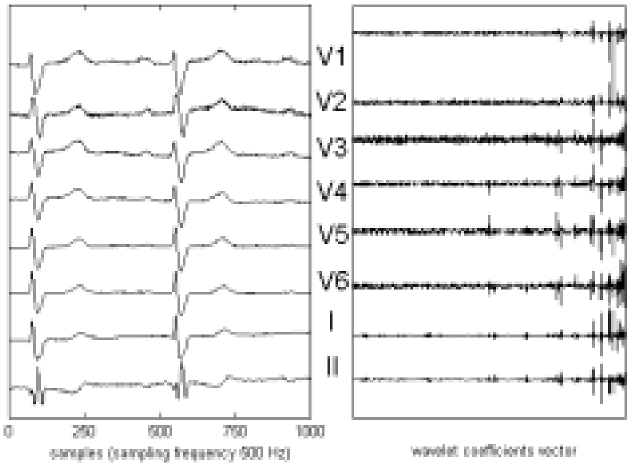

Fig. 2. Example of LWT–based decorrelation (CSE file Mo_00001)

3.4. EXTENDING THE SCOPE OF EXPERIMENT

Encouraged by the surprisingly efficient decorrelation of electrocardiograms in time-frequency domain, we decided to extend the experiment to the following objectives:

- testing the decorrelation of vectocardiograms, where normally no improvement is expected, but in practice the Frank recording system is not orthogonal in mathematical sense and some data redundancy may still be found,
- testing the efficiency of decorrelation-based compression with use of two-dimensional decorrelation (spatio-temporal).

Adapting the appropriate m-file to support the VCG was the only modification needed for the first of these objectives. The original bitrate for the VCG signals is 500 * 12 * 3 = 18000 bits per second, or 2.25 kbytes/s. The resulting output bitrates (tab. 3) confirm that the vectocardiograms in average do not contain redundant data, and thus the decorrelation gives no significant improvement. The only exception is here the LWT yielding the reduction of data stream by a factor of three. Second conclusion on these results is the similarity of the corresponding VCG and ECG data streams. That proves the identity of data amount in both recording methods, in case of VCG the acquired time series are initially "decorrelated" by the quasi-orthogonal positioning of electrodes.

The second modification consists in applying the Huffman Coding technique to the data decorrelated in spatio-temporal domain. The modified procedure applied first the spatial decorrelation, and afterwards the temporal decorrelation. For the spatial domain all three decorrelation transforms (i.e. KLT, DCT and LWT) were subject to test. For the temporal domain the only tested decorrelation method consisted in coding the difference of consecutive samples instead of their absolute values. This simulates best the conditions of the real world DSP application. The resulting bitrates of the output data streams are reported in the table 4.

Table 3. Decorrelation efficiency expressed as Huffman coding output bitrate (kbytes/s) original bitrate 2.25 kbytes/s

CSE-ID	decorrelation method			
(VCG leads)	no transform	KLT	DCT	LWT
1	3.96	3.91	3.94	2.14
2	4.81	4.60	4.65	2.22
124	3.73	3.13	3.78	1.73
125	4.37	3.76	4.36	1.63
mean ±std	4.03 ±0.58	3.61 ±0.53	3.91 ±0.45	1.88 ±0.3
CR (to orig. bitrate)	0.56	0.62	0.58	1.20

Table 4. Decorrelation efficiency expressed as Huffman coding output bitrate (kbytes/s) original bitrate 6.0 kbytes/s

CSE-ID	spatial decorrelation method			
(ECG leads)	no transform	KLT	DCT	LWT
1	1.97	1.97	2.02	1.74
2	2.21	2.07	2.25	1.93
124	1.43	1.47	1.51	1.39
125	1.81	1.68	1.71	1.71
mean ±std	1.83 ±0.25	1.88 ±0.26	1.98 ±0.31	1.73 ±0.25
CR (to orig. bitrate)	3.28	3.19	3.03	3.46

4. DISCUSSION

Three different signal decorrelation techniques were implemented aiming at reducing the ECG data volume. All of them base on the high inter-channel data redundancy of a conventional 12-leads electrocardiogram (especially for chest leads). The initial experiment showed high data overhead for KLT caused by storage of transform matrix. For this reason, two other suboptimal transforms are more likely applicable in a real world DSP hardware. The DCT-based method, although already supported by some DSP shows inferior efficiency comparing to the LWT-based algorithm. The LWT, at present not directly supported by any available DSP, may be efficiently coded in any microprocessor using only the fixed-point data representation. The resulting average data stream bitrate justifies the estimation of the compression ratio for a value of four. This result outperforms all other lossless compression algorithms and in particular the general-purpose algorithms.

The extension of the experiments provided some interesting remarks concerning the information density in the cardiac signal:

- the resulting data stream bitrate is almost the same (± 12 %) for the ECG and VCG when using the LWT-based method (tab. 2, col. 5 and tab. 3, col. 5), it does not improve for the combined spatio-temporal decorrelation (tab. 4, col. 5)

- applying Huffman coding to the raw VCG signals increases the data volume nearly twice (tab. 3, col. 2) because of the ill-conditioned distribution of signal values and the use of KLT or DCT does not improve the efficiency (tab. 3, col. 3 and 4); the use of LWT-based compression yields a little reduction of the original bitrate (signal values are now replaced by coefficients of the time-frequency domain), but the result is not worth the computational cost (tab. 3, col. 5).
- combining the decorrelation in the spatial and temporal domains yields nearly the same compression efficiency for all the method under test, even without any spatial decorrelating transform (tab. 4, col. 2), the compression ratio was quite important.

The results obtained led us to formulate more general conclusions. The amount of information in spatially decorrelated electrocardiogram is close to those in the vectocardiogram. The VCG may be thus seen as an ECG "decorrelated" by lead positioning.

The interesting features of LWT-based compression need further explanation. As it is displayed in figures 1 and 2, the main difference consists in feeding the Huffman Coding procedure with coefficients of the t-f plane instead of the time series. The cardiac signal contains the prevalence of low frequencies that causes high temporal correlation of the adjacent samples. This correlation remains in the spatially decorrelated signals yielded by KLT or DCT-based methods. In consequence, the medium score of CR (tab. 2, col. 3 and 4) is improved when the temporal correlation is removed, that is, with use of in spatio-temporal decorrelation method (tab. 4, col. 3 and 4). The LWT uses the dyadic tree decomposition and thus the sampling frequency for each frequency band is always 'optimal' resulting in minimum time-domain correlation of the adjacent samples. Therefore, the decorrelation result does not improve from spatial to spatio-temporal method (tab. 2, col. 5 and tab. 4, col. 5). Thanks to the domination of lower part of the spectre, the distribution of t-f representation values is good-conditioned except for few low-frequency coefficients (fig. 2). This feature justifies the outstanding result of LWT-based decorrelaton in spatial domain (tab. 2, col. 5).

For its simplicity, the temporal decorrelation should rather be used in the target application, and the use of spatial methods may be limited to the cases where temporal decorrelation is not applicable.

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