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## **OPTIMAL PATTERN-TO-SIGNAL SYNCHRONIZATION FOR TIME-FREQUENCY TEMPLATE MATCHING ECG COMPRESSION TECHNIQUE**

### Abstract

Time-frequency template matching ECG compression algorithm has an outstanding compression effectiveness and very low distortion of medical data content. Its main disadvantage is the presence of spare patterns as a consequence of poor pattern-to-signal synchronization. This issue is investigated in detail in this paper, and possible solutions are derived: P-onset, QRS-onset and R-max synchronization points are used. Finally these three methods are compared with use of the same data set in order to minimize the number of templates created.

Results may be interesting to a wide range of scientist working on a time-frequency representation of a heart's beat, since it gives several considerations on the representation stability.

### 1. INTRODUCTION

Time-frequency template matching ECG compression concept is recently one of the most promising method for effective signal reduction and maintaining all its diagnostic features untouched. The compression algorithm has been described in [1] in detail, so the principle is only repeated here. The discrete ECG signal can be split into two components: a continuous low bit rate coarse approximation (CA) signal and a numerous separate details (SD) signals being a completion (in the sense of addition) of the signal for its more important sections. These SD signals are valid only if significantly greater than the baseline noise level, and thus usually not continuous: one high frequency pattern (HFP) stands for a heart beat. The compression can be even more effective with use of HFP classification [2]. The storage of all time-frequency coefficients for a pattern is no longer necessary, only a pattern number, being an index in HFP dictionary, is enough to correctly reconstruct the ECG content from the archive. From the signal theory's point of view the compression is lossy, because of not identical sample values of original and reconstructed signal. Nevertheless main distortion concentrates at the signal sections of slight medical significance, while the most important part (namely P-QRS-T section) is reconstructed perfectly.

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The algorithm was implemented in Matlab experimental environment (except for a pre-processor procedure that was available from a commercial manufacturer as a "black box" executable file) and widely tested on different data types. The compression ratio achieves a value of 7, and the distortion reach 5% rarely. Even so, the quantitative diagnostic parameters computed on reconstructed signal are much closer to the original, thanks to high fidelity of signal in P-QRS-T section.

High number of patterns created even for relatively short signals are reported as a main disadvantage of the method. The spare patterns lower the compression ratio and lengthen the computation time, because of additional entries in pattern dictionary. In addition, for longer signals (i.e. Holter 24-hours recordings) the maximum available number of patterns may easily be reached, and any new HFP is stored directly as a full set of t-f coefficients.

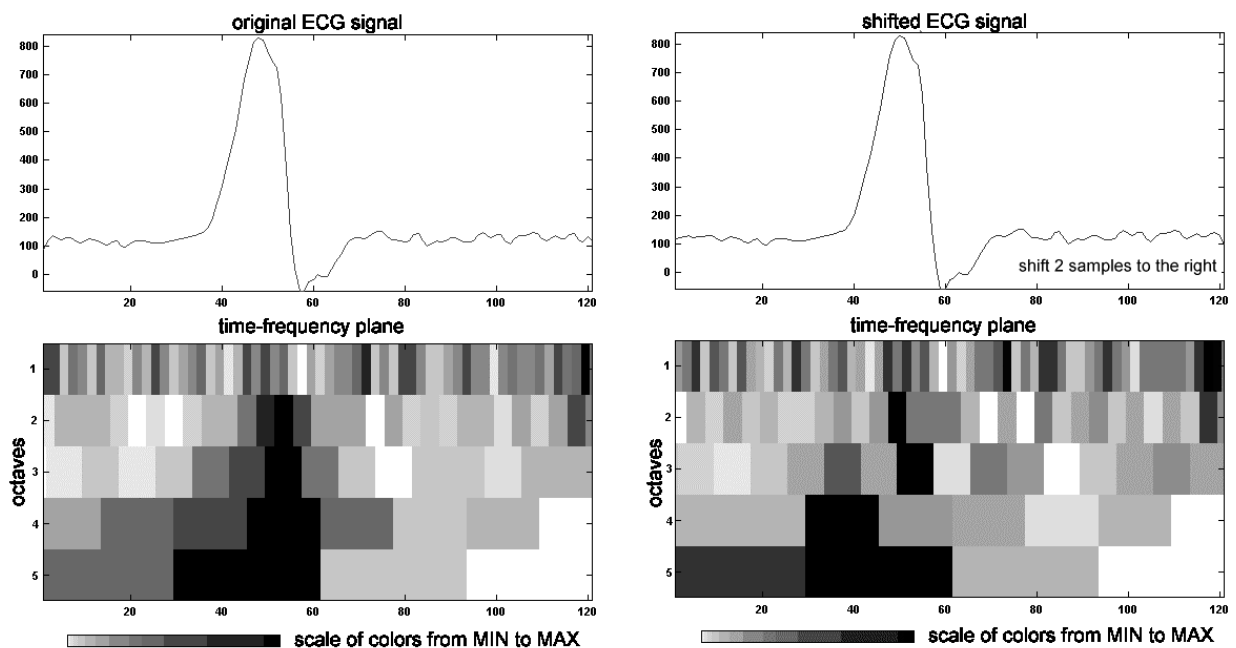
The investigation of this problem and possible solutions are main issues of this paper. The research being described hereby aimed to answer the following questions:

- why the spare patterns are created ?
- what is the possible remedy for the spare patterns ?
- what is the optimal solution ?

## 2. THE ORIGIN OF SPARE PATTERNS

### 2.1. EXPERIMENTAL RESULTS

A numerical experiment has been designed and carried out in order to find whether the high frequency patterns (three highest octaves i. e. 32-250 Hz) suspected to be redundant really are. We used an artificial signal of a supraventricular heart's beat sampled at 500 Hz containing 512 samples. The signal has been shifted along the time axe by an interval of one sample and the successive time-frequency representations were compared (fig. 1).



Main result of the experiment was the confirmation that one particular beat can generate significantly different high frequency patterns. Consequently, without a doubt some high frequency patterns are spare. An additional factor influencing the content of time-frequency plane was the temporal position of a particular frequency component related to the signal beginning.

## 2.2. THEORETICAL BACKGROUND

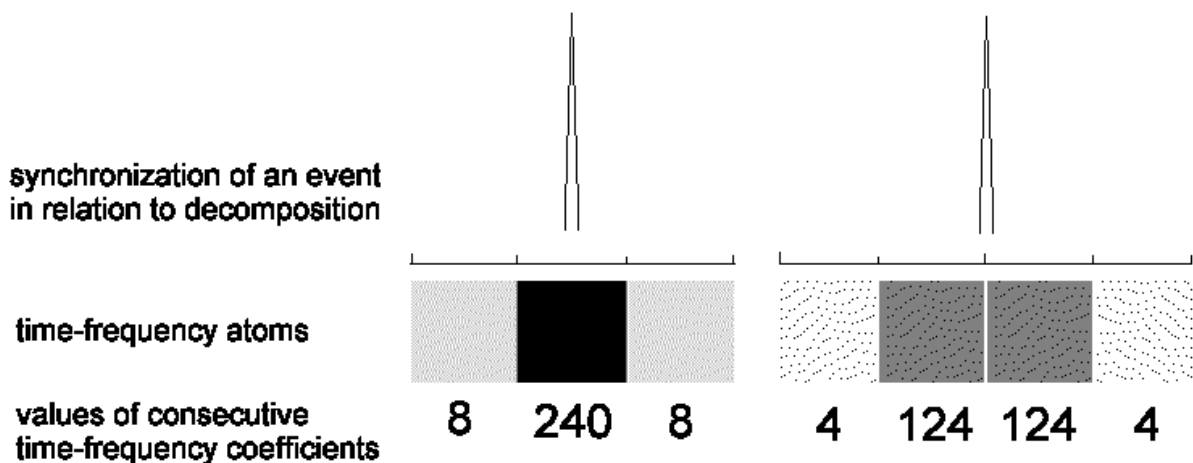
When comparing the reversible wavelet transform, that was used to obtain a time-frequency plane, to the Fourier transform, one can easily remark that wavelet transform maps real-to-real values, while Fourier transform maps complex-to-complex values [3].

In consequence, in Fourier spectrum, the temporal position of a particular frequency component is represented in the phase component, that guarantees the reversibility of the transform. On the contrary, all time-frequency coefficients are real number and the only way to represent the temporal position of a signal component is the coefficient's position referred to time axe. However, taking into consideration that the time precision of time-frequency atoms is variable and that neighbouring frequency bands overlap makes evident that a particular signal component influences several time-frequency coefficients.

For example, a short signal component containing a frequency  $f$  may occur in such a moment, that all energy in a bandwidth containing  $f$  is represented by one atom in time-frequency plane. Now lets suppose a slight time shifting, by an interval  $t$  of half of temporal resolution for a bandwidth containing  $f$ .

$$t = \frac{1}{2} \cdot \frac{1}{f}$$

The component  $f$  falls now to the boundary of two neighbouring time-frequency atoms thus the energy of a component is now split for two coefficients. Even if the signal remains the same, no identical (or even similar) coefficients may be found at the corresponding coordinates at both time-frequency planes (fig 2).



When the temporal shifting is continued and reaches an interval equal to temporal resolution for a bandwidth containing  $f$ , all energy of the control component falls again to one time-frequency atom that value is identical to those derived from an unshifted signal. That was also observed during the numerical experiment: the values of the 1-st (highest) octave (125-250 Hz) repeated identical for every two-sample shift (4 ms), and for 3-rd octave (32-64 Hz) – for every eight-sample shift (16 ms). This remark explains the source of spare patterns: three-octaves high frequency pattern may consist of 8 different templates representing the same piece of signal.

### 3. POSSIBLE SOLUTIONS FOR THE SPARE PATTERNS PROBLEM

All the theoretical and experimental statements above explaining the necessity of some kind of synchronization between the time-domain ECG signal and the decomposition start point or the beginning of decomposed segment of signal. The synchronization point is not necessarily the beginning, but falls always at the same time coordinate of the time-frequency plane. In our application, the synchronization point is expected to be a two neighbouring time-frequency atoms border point for at least three upper octaves. The opportunity for that point repeats thus every eight samples.

Several literature references were investigated [4], [6] and many authorities were asked for a possible manner of synchronization of a P-QRS-T section of an electrocardiogram to a given time frame. The particular difficulty of the problem consist in variable duration of the waves and inter-wave sections. In general, no relationship between the lengths can be observed. Several proposals were considered for further investigation:

- a) separate synchronization of three P, QRS and T waves,
- b) variable-time re-scaling for each wave
- c) synchronization of the whole pattern to a given fiducial point
- d) multiple patterns per beat covering all different shift versions

All those proposals were carefully investigated to give general concept of their applicability. The theoretical considerations were followed by an implementation in Matlab experimental environment, but at this stage the quantitative comparison of the synchronization methods were not expected.

The separate synchronization of P, QRS and T waves is based on one fiducial point per wave. The wave time-frequency representation is invariant for inter-wave sections' changes, but the variable duration of wave (especially observed in case of T-wave) generates different templates. Another drawback is the comparing and coding of three different patterns instead of one that complicates the classification algorithm and dissimilarity measure. The source of additional problems is the length of waves. In most cases it is comparable with the length of octave filters that usually generates distortions called "border effect".

The variable-time re-scaling for each wave makes possible for any wave length to fit to a given time frame (for example of 128 ms). The time axe is locally stretched or tightened depending on the normalization ratio. However the method has several drawbacks. Local changes of time unit for each sub-section of the signal may influence the frequency properties. Applying the continuous function time unit involves the storage of that function

for each heart's beat that significantly lowers the achieved compression ratio. Additionally, if the original set of signal samples is given in integer format (as usually in case of analog-to-digital converters), the variable-time re-scaling will map them to the real what is the cause of further significant increase of data volume.

The synchronization of the whole pattern to a given fiducial point is at the first glance the most straightforward method and generates time-frequency patterns sensible to any interval changes in a heart's beat. Nevertheless its advantage is low computation cost that makes hope even for a real time integer format implementation. Another question to answer is the optimal choice of the fiducial point that minimizes the number of spare patterns.

Another good solution is probably to generate multiple patterns per beat covering all different shift versions. In case of three octaves template size, the maximum number of patterns is 8. The patterns created are sensible to any interval changes in a heart's beat, but the doubtful choice of the fiducial point and its detection in the signal is no more necessary. The drawback is here the huge number of templates to store and compare. Assigning eight patterns per beat complicates and lengthens the classification procedure, and may not be acceptable in real time applications.

## 4. THE OPTIMAL CHOICE OF FIDUCIAL POINT

### 4.1. FIDUCIAL POINTS SET UP

The right choice of the fiducial point is believed to play an important role in synchronization of the whole high frequency pattern to an ECG signal. Three options seem to be reasonable, each of them having its advantages:

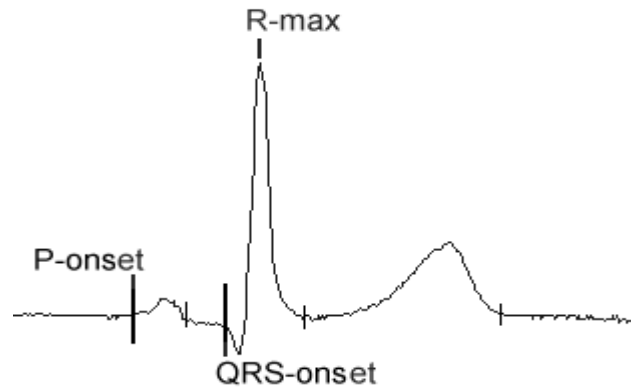
- a) the beginning of P-wave, representing the initial onset of high frequency components,
- b) the beginning of QRS-complex, the most precisely detected point in ECG signal,
- c) the maximum of R-wave, as possible to be detected at a lowest computational cost.

All three possibilities were subject to the second numerical experiment aimed to minimize the amount of spare patterns created. Figure 3 displays the positioning of proposed fiducial points.

### 4.2. NUMERICAL EXPERIMENT

All three possibilities were subject to the second numerical experiment with use of original ECG signals from the CSE database [7]. This experiment was also implemented in Matlab. P, QRS and T waves start- and endpoints were taken from the database that makes results independent on the pre-processor performance. The position of R-wave maximum was computed by a Matlab procedure, as a time abscise of the absolute maximum cardiac vector  $V$ .

$$V = \sqrt{X^2 + Y^2 + Z^2}$$



Provided every three synchronization methods are invariant to temporal signal shifting, more elaborated processing is required to set up the test signals. From the set of 125 signals given in the database, only 89 beats of supraventricular origin were selected. Ventricular originating beats do not contain P wave, so P wave beginning based fiducial point is not possible to determine on these beats. The selected beats were then scaled to the 95% of their original sample numbers in order to simulate the 5% increase of heart rate. The shortened beats' samples were then rounded to the nearest integer value. The time scaling procedure was repeated 14 times, in consequence the shortest beat was half of the length of the original one. Finally, all scaled beats were multiplied one after another to obtain a continuous ECG signal. The artificial scaling of the consecutive beats led to the signal containing similarly shaped beats (in sense of continuous signal, sample values are different because of approximation) of various heart rate. The waves delimiting points were recalculated for each heart's beat respectively. For each signal, the number of high frequency pattern created is computed with use of every of three proposed fiducial points. The value of tolerance for time-frequency coefficients values for the same pattern was always 5%.

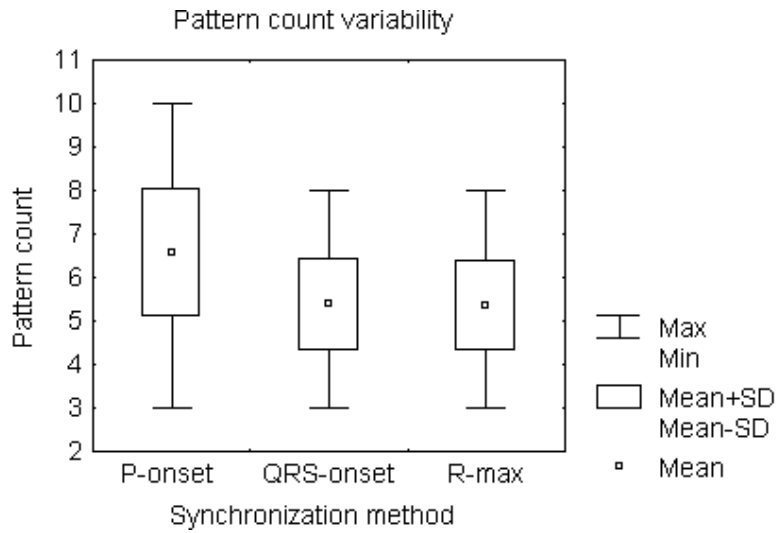
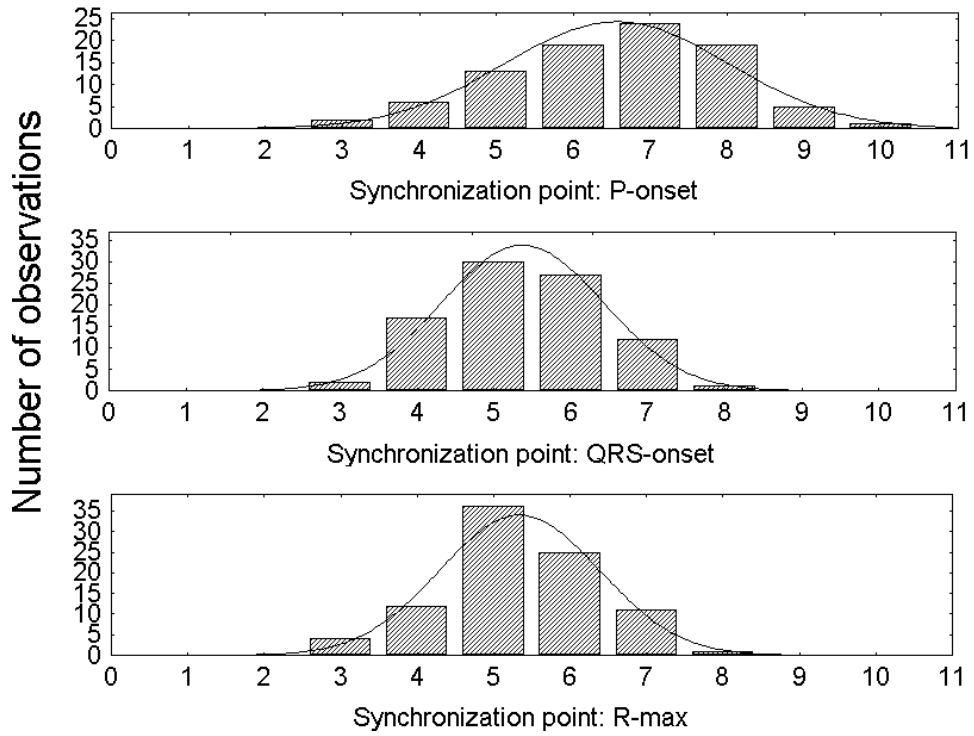
#### 4.3. RESULTS

The results are expected to indicate the optimal choice of synchronization point. The minimum average number of patterns distinguishes the method using the optimal synchronization. Before taking into account the average value one should verify if it is representative for the population. In other word, first step is checking whether the values' distribution is normal or not. Figure 4 displays histograms of pattern values per signal obtained in three synchronization methods. Figure 5 and table 1 summarizes the mean values and standard deviations being main results of the experiment.

Table 1. Summary on created pattern statistics

synchronization point	minimum pattern count	maximum pattern count	average pattern count	standard deviation
P-onset	3	10	6.5618	1.4613
QRS-onset	3	8	5.3708	1.0486
R-max	3	8	5.3371	1.0439

## Histogram of pattern count



## 5. CONCLUDING REMARKS

Testing the values distribution with the statistical Shapiro-Wilk [5] test of normality, we got the probability of 0.25%, 0.004% and 0.003% for each synchronization method

respectively for a distribution other than normal. That entitles to use the mean value and standard deviation to represent the whole data set.

It seems reasonable to reduce 14 different (scaled) hearts' beats of the same shape to 5 (in average) high frequency patterns. Smaller reduction arouses suspicion of spare patterns that affect the global compression ratio. Greater reduction is a proof of mistaken similarity between significantly different shapes that lead to distortion of the compressed signal.

As displayed in Table 1, both QRS-onset and R-max based synchronization result in almost the same expected number of patterns. The P-onset based method is significantly worse, probably because of lateral position of synchronization point in the time-frequency beat representation. In addition the P-onset based method is not applicable to other than supraventricular hearts' beats.

It is questionable to prefer either QRS-onset or R-max as better synchronization point. In particular application the true advantage of the maximum of R wave may be simplicity of computation. First of all, this concerns the ECG processing systems that are not designed for precise delimitation of waves. In this case the precise delimitation of QRS-onset is no longer necessary.

#### BIBLIOGRAPHY

- [1] AUGUSTYNIAK P. "Separate Compression of Highest ECG Octaves" (in Polish) in proceedings of the Conference on Biocybernetics and Biomedical Engineering, Warszawa 02-04.12.1999
- [2] AUGUSTYNIAK P, TADEUSIEWICZ R. "The ECG-dedicated compression method using high frequency patterns" in proceedings of First International Conference on Advances in Medical Signal and Information Processing, Bristol, United Kingdom, 4-6.09.2000
- [3] DAUBECHIES I. "Ten lectures on wavelets" CBMS-NSF conference series in applied mathematics. SIAM Ed, 1992
- [4] MORLET D. "Contribution a l'analyse automatique des electrocardiogrammes – algorithmes de localisation, classification et delimitation precise des ondes dans le systeme de Lyon" – (in French) these INSA-Lyon 1986
- [5] STANISZ A. "Accessible Course of Statistics" (in Polish) StatSoft Polska, Kraków, 2000
- [6] TOMPKINS W. J. (ed.) "Biomedical Digital Signal Processing – C-languages Examples nad Laboratory Experiments for the IBM PC" University of Wisconsin-Madison, Prentice Hall, New Jersey 1993.
- [7] WILLEMS J. L. "Common Standards for Quantitative Electrocardiography" 10-th CSE Progress Report, 1990. Leuven: ACCO publ., 1990, 384p.