LABORATORY HARDWARE IMPLEMENTATION OF NON-UNIFORM SAMPLING ECG RECORDER

Piotr Augustyniak[+]

[+]University of Mining and Metallurgy, Institute of Automatics,
al. Mickiewicza 30, 30-059 Kraków, Poland,
august@biocyb.ia.agh.edu.pl, http://galaxy.uci.agh.edu.pl/~august

Abstract: *This paper concerns the prototype of ECG recording system using variable sampling rate. The signal-dependent non-uniform sampling is currently an interesting alternative for the effective discrete signal representation. Author is reporting the implementation of main concepts of non-uniform space sampling in a microcontroller-based recording system that uses the fixed-point data representation. The experiences gathered during this implementation are particularly useful for future development of real-world devices based on micropower circuitry. Main result, however, is the proof of feasibility for implementation of advanced mathematical concepts in the energy-saving hardware of today.*

1 Introduction

Electrocardiogram is the most frequently performed electrophysiological test. Its accessibility, however, is often limited by the cost of data transfer or storage. An emerging solution, developed currently in our laboratory, makes use of variable density of diagnostic information in the cardiac signal that is obvious to the expert but difficult to express in a mathematical way. Our proposal is an alternative to the compression of electrocardiogram data that has great practical significance and is widely used in clinical practice despite the disscussion about the reliability of the restored signal [1].

In many discussions the topic of the adequate sampling frequency for the ECG data was concerned. In the stand-alone 12-lead standard recorders the rule is very simple but the long-term cardiac recordings (i. e. Holter techniques) always involve a compromise between the amount of the stored data and the precision of signal representation.

Usually, digital recorders comply with the general assumption made on signal analysis saying that the occurrence of any probable signal component is possible at any time, hence full bandwidth of the transmission channel is to be provided continuously [2]. This approach is widely used for its generality and careless use of technical resources, however the output data stream is overestimated. It guarantees that the parameters of the channel throughput are time-invariant and thus the transmission features, such as distortions, are related to the amplitude and frequency characteristics of input signal components and not to their occurrence in time. It is worth a remark here, that when the bandwidth of the digitized signal changes in time, the sampling frequency may be locally adapted for satisfy the Shannon theorem. This remark is the foundation of sampling signals at the variable rate and is developed further in this chapter.

Certainly, for the ECG recorder sampling at the variable rate, the most important issue is the definition of the local sampling interval based on the signal features. Fortunately, the ECG has several properties of high relevance when considering the local optimization of sampling frequency:

- The full bandwidth is used for short time intervals only representing the ventricles' contraction (i. e. the QRS complex) - these intervals are identified with high reliability by commercially available software and by hardware detectors.
- For a large amount of time the local bandwidth is significantly (to four times) lower [3], [4].
- The medical point of view that the diagnostic information is distributed irregularly in the signal converges with the technical notion of information throughput expressed by the local bandwidth.
- Some extend of regularity may be anticipated, and the variety of possible co-occurrences of signal components is limited by the physiology.

The prototyped recorder uses the memory resources in more efficient way, but preserves the signal diagnostability typical for devices sampling continuously at the high rate. Another advantage resulted from the irregular sampling is the immunity to the interference in the frequency band between the current signal bandwidth and the maximum signal bandwidth. For the lack of this interference, the signal sampled at the variable rate differs from the identical signal sampled continuously at the maximum rate, what is sometimes confused with distortions.

The non-uniformly sampled ECG was already verified as appropriate discrete representation of the cardiac electrical activity. These algorithms [5, 6], however, were tested on signal processing software platforms without the limitations of portable device's circuitry. This justifies the work described in the present paper that aimed at proving the feasibility for implementation of non-uniform sampling of the ECG directly in the hardware. As the energetic aspect is the crucial issue in design of long-term portable ECG recorders, micropower IC are considered in our prototype whenever available.

Today's offer of electronic devices includes digitally controlled anti-alias filters and converters triggered by countdown timers at any rate are widely available. The ECG signal is converted at the constant rate for the purpose of heartbeat detection due to the lack of methods accepting as input the variable sampling rate signal. Since the detection information is always delayed with respect to the original signal, the analog delay line is necessary to restore the synchronisation.

2 Materials and Methods

Sampling the signal at variable rate involves two independent processes controlled by the bandwidth function: adaptation of anti-alias filters cut-off frequency and calculation of local sampling intervals. Both of them return quantization-free values in the continuous range from the minimum to maximum.

Following the general guidelines for the prototype recorder the signal should be as much as possible processed by the hardware. This approach justified the separate design of the functional blocks rather than the integrated design. The principal module performs the non-uniform sampling and two auxiliary modules are used 1st as on-line signal interpreter providing the expected bandwidth value and 2nd as an analog delay line. The auxiliary modules should be optimised and integrated within the main microcontroller in the future, but here, for the reason of clarity are considered separately. The following issues had to be concerned in the signal-dependent non-uniform sampling application:

- how to extract the appropriate features from the signal in real time,
- how to synchronise the information on expected bandwidth with the signal itself,
- how to control the anti-aliasing filter of variable cut-off frequency.

2.1 Estimating the local ECG bandwidth

In order to detect a presence of heartbeat in the ECG signal, the detector is built on a '51 microcontroller platform. It runs simple detector software that detects the QRS complexes on a basis of frequency and 2nd derivative slope [7]. The schematic diagram of the algorithm providing the detection function is displayed in the figure 1.

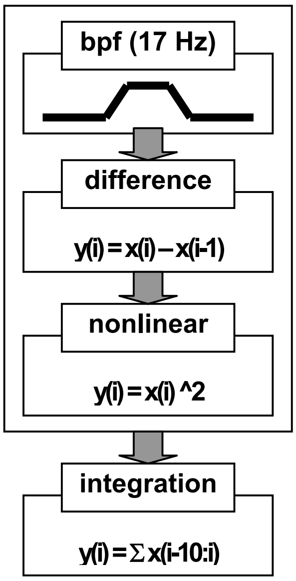

Fig. 1 The algorithm of heart beats detection function

The detection function value is fed to the decision-making subroutine that detects local maxima and compares their values with a given threshold. The threshold value is adapted by the past over-threshold values to follow the local amplitude changes of the ECG.

Apart of marking the presence of the QRS complex, the detector was expected to detect other waves (P and T - figure 2), to compute their borderlines and to calculate the necessary instantaneous signal bandwidth.

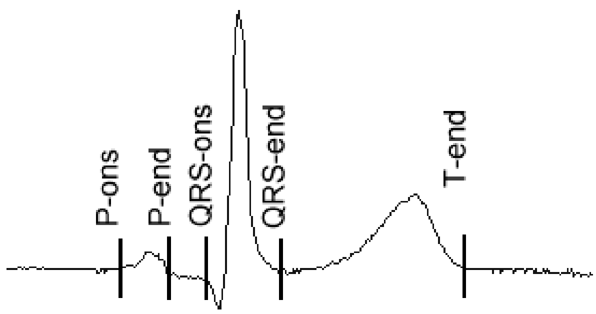

Fig. 2 The segmented ECG for one heart beat

In practice, this task was too complicated to be completed by a microcontroller in real time [8]. Additionally, the standard bandwidth function (fig. 3) had to be piecewise projected to the current wave's positions in order to estimate the expected signal bandwidth. The bandwidth estimation background has to be limited to the QRS complex detection and the current time interval between the adjacent beats. These two data was used to roughly estimate the expected bandwidth of the signal.

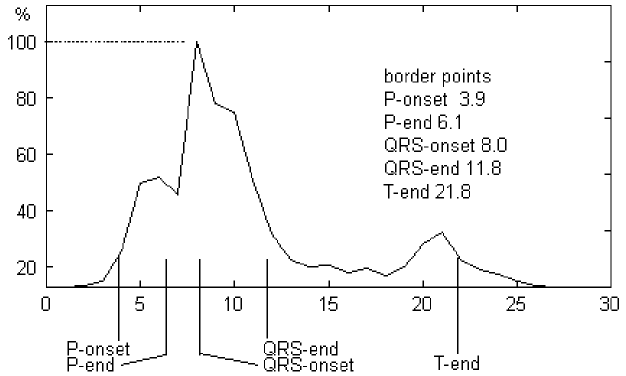

Fig. 3 The standard bandwidth function for ECG

The standard bandwidth function [9] defining the typical ECG properties over one heartbeat interval was coded into the memory. Once the QRS detection was positive, the bandwidth shape was recalculated for the current beat.

2.2 Synchronisation of the ECG and the bandwidth estimate

The instantaneous bandwidth estimate appears on the detector's output with a delay caused by two facts:

- detector uses signal buffering and averaging that leads to a roll-off delay proportional to buffer's length,
- the bandwidth shape is calculated after the QRS detection, however bandwidth modification starts with the P wave which typically anticipates the QRS by 210 ms.

In particular the second of these issues causes methodological problems, because the delay between the QRS detection and the P-wave bandwidth modification is not constant. In consequence, for fast cardiac rhythms the bandwidth needs to be extended closer to the QRS detection point than for the slow rhythms.

This problem has not been successfully solved until now. The adaptive delay line was considered for resynchronise the ECG and the bandwidth information, but it practical implementation is problematic.

In our prototype we used a halfway temporary solution that simplifies the bandwidth shape adaptation. It assumes, that the bandwidth shape is rhythm-dependant only in its second half, and all what precedes the QRS detection point is time-invariant. Thanks to this assumption, the delay of bandwidth modification is constant and the synchronisation to the signal may be achieved with use of constant delay of the ECG. The side effect is that the bandwidth is extended earlier than necessary for fast rhythms, that are much more probable than slow rhythms, and the resulting ECG representation is in some aspect sub-optimal.

The analog delay line was implemented with use of a digital FIFO buffer and a pair of complementary converters. The use of digital buffer facilitates the delay control. The single value limiting the buffer length is used for precise adjustment of performed delay. The signal is sampled with the frequency 2 times greater than the Nyquist value for the ECG (1kHz). That guarantees the assumed signal reproducibility as well as appropriate precision of delay control (up to 1 ms). The analog delay line was supported by a '51 family microcontroller equipped with high quality a/d and d/a converters and an external memory (fig. 4).

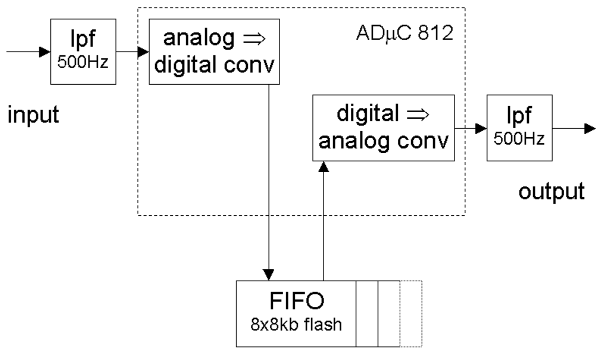

Fig.4 ADuC812 Microconverter-based analog delay line

2.3 Adaptive anti-alias filtering of the ECG

The anti-aliasing filter of variable cut-off frequency was designed with use of Maxim MAX295 8-th order switched capacity low-pass filter (fig 5) [10]. The corner frequency of this device may be precisely tuned with the clock pulse in a wide range including all the variants of ECG bandwidth. The timer in the main microcontroller structure is programmed to provide the clock pulse of variable frequency for the filter device.

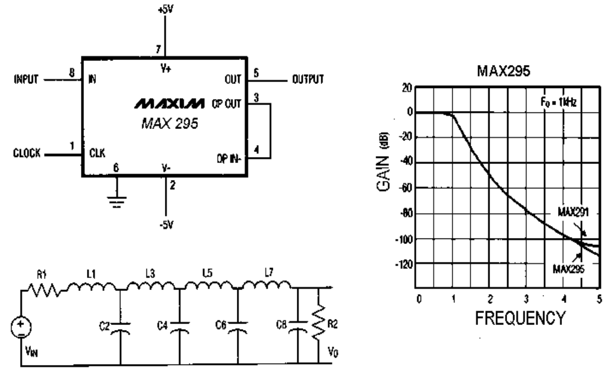

Fig. 5 Application, electrical equivalent and transfer function of the adjustable switched capacity lowpass filter MAX295

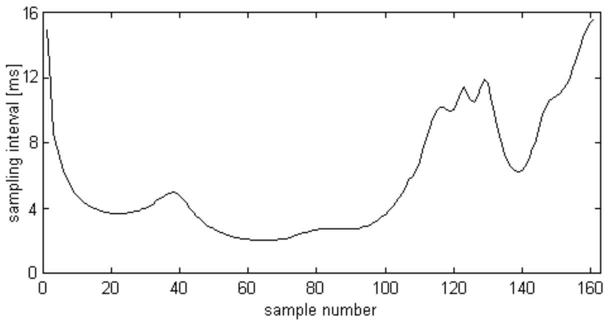

Fig. 6 Sampling interval controlled by the values of bandwidth function (one heart beat)

2.4 Sampling of the ECG at the variable rate

The main module performs two fundamental tasks:

- receives the bandwidth modification data and computes each sampling interval length and the filter clock pulse interval, that are fed to on-board timers (fig. 6),
- receives the delayed and low-pass filtered analog ECG signal and builds its discrete representation with use of non-uniform sampling

Certainly, the main microcontroller performs also several auxiliary tasks: interleaves the ECG data and the sampling interval data and sends them to the recipient system via asynchronous transmission port.

2.5 Laboratory recorder circuitry

The laboratory hardware implementation of the ECG irregular sampling concept was developed in four modules described before (p. 2.1 - p. 2.4). Three of them will be integrated into one microcontroller in the target application, but here are separated for the reason of clarity.

The block diagram of non-uniform sampling ECG recorder is displayed in the figure 7. In order to simplify the designing task and the future integration the ADμC 812 chip is used whenever a microcontroller is necessary. Another limitation comes from the implementation of one channel only, while the usual ECG is a multichannel recording (typically 8 or 12).

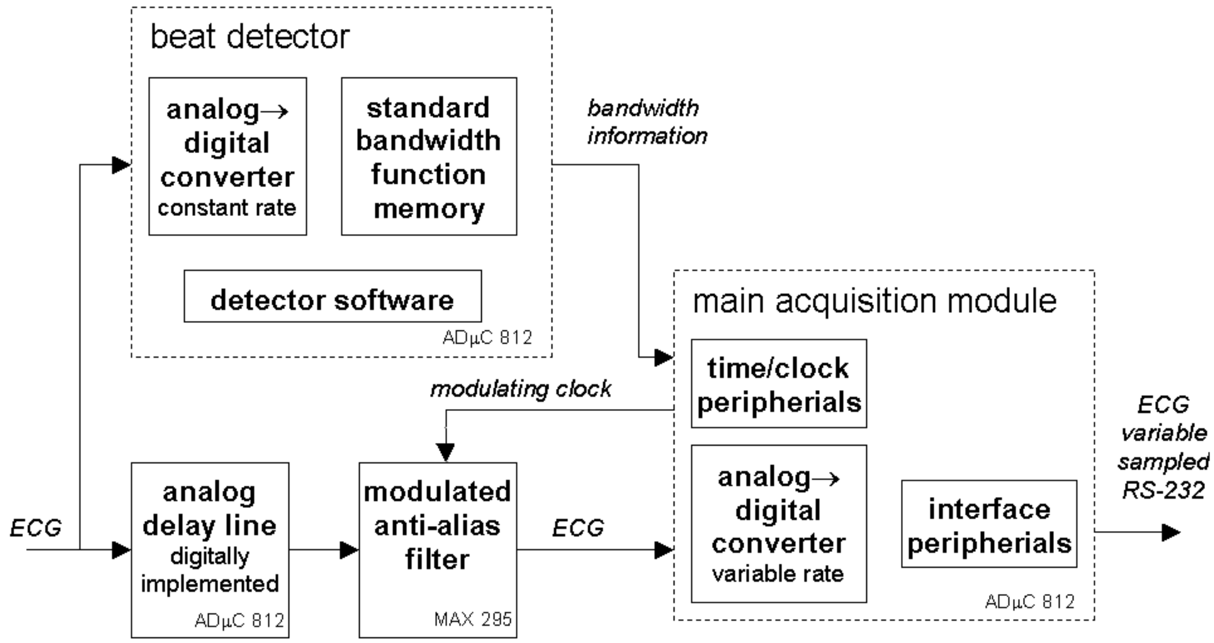

Fig.7 Block diagram of non-uniform sampling ECG recorder

3. Testing the irregularly sampling ECG recorder

The developed recorder was subject to test with use of artificial ECG issued by a test generator and with use of original recordings digitized in the CSE database (500 Hz, 2.44 μV, 12 bit) [11, 12] and issued by the D/A converter plug-in card from the PC.

Another PC featuring the analog input was used to acquire the input ECG signal when a test generator was used for the reference purpose. In case of database-originated recordings the reference signals were the database files.

The irregularly sampled signals were transmitted using a standard asynchronous serial interface to the computer and stored in a disk files. First the amplitude and sampling interval information has to be decoded from these files. Further floating-point processing was necessary to restore the regular sampling representation with the sampling rate identical as for the reference signals. For this purpose, cubic splines interpolation technique was found the most appropriate. Finally, the temporal synchronization between the restored and the reference data was computed with use of maximum correlation method.

All the processing aimed at comparing the restored and the reference electrocardiograms and to evaluate the signal quality loss due to the irregular sampling (fig. 8). Moreover, for the database signals the P, QRS and T-wave border points provided in the annotation file make possible to compute the local signal differences. This measure is more appropriate for express the ECG distortions since it reflects the irregular medical relevance of the signal.

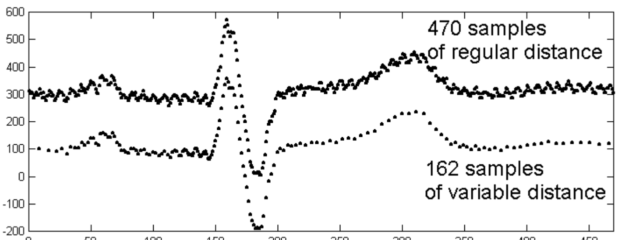

Fig. 8 Comparing the heart beat represented in the regular and in the variable sampling rate signals

4. Results

The laboratory system was built and validated for its electrical correctness before it was subject to the numerical test aiming at assess the method's performance. The initial tuning involved the adjustment of the delay-line's buffer length, that was estimated theoretically, but needed verification in the real system. The correct delay is necessary to synchronize the bandwidth information with the signal itself. The average compression ratio (CR) is displayed in the table 1 together with the global and local differences estimate (PRD) between the original and the reconstructed regularly sampled ECG signals. Table 1. The average compression ratio (CR) and differences (PRD) values.

CR		2.61
PRD [% (μV)]	global	2.71 (40.5)
	within P-wave borders	0.12 (1.6)
	within QRS-complex borders	0.22 (3.3)
	within T-wave borders	0.42 (6.3)
	out of waves	1.43 (21.4)

The compression ratio mentioned above was calculated without taking into account the sampling intervals data stream. This information is common for all recorded channels in a typical multichannel ECG recorder.

5. Discussion

The idea of variable sampling rate has been implemented in the laboratory single-channel ECG acquisition system. The sampling rate was related to the medical contents of the signal detected on-line. The instantaneous bandwidth of the discrete cardiac electrical representation was controlled by the embedded standard function.

The work described here proves the feasibility of hardware implementation of irregular sampling, although it uses a simplified bandwidth function that requires the revision in the future.

The compression efficiency is similar to the result of best lossless algorithm applied to the ECG [13]. Our method is in fact lossless from medical viewpoint, although it is not bit-accurate. The mean reconstruction error is negligible for the important parts of recording.

The overall performance of the system is slightly worse than results of the software implementation of the irregular sampling using interpolation-based resampling [6]. This is mainly due to the use of simplified adaptation of standard ECG bandwidth function to the local signal properties, that bases on R-wave peak only instead of on the five wave bordering points. In consequence, the P-wave bandwidth is over-estimated in majority of cases. That manifests itself by the lower distortion ratio (PRD) within the P-wave borders comparing to software resampling system.

Since main features of the variable sampling rate algorithm depend on the standard bandwidth function, the proposed relationship may be an initial point for further investigation or adaptation to the needs of particular users. The user-defined sampling profile is the principal advantage of this method.

Acknowledgment

This work was supported by Polish State Committee for Scientific Research grant no: 8 T11E 007 17

REFERENCES

[1] Jalaleddine S. M. S., Hutchens C. G., Strattan R. D., Coberly W. A. *ECG data compression techniques – a unified approach* IEEE Trans. Biomed. Eng. vol. 37 pp 329-343, 1990

[2] Proakis J. *Digital communications* 2-nd ed. New York McGraw-Hill 1989

[3] Augustyniak P., Tadeusiewicz R. *The Bandwidth Variability of a Typical Electrocardiogram* Proc. EMBEC '99, Wien, Austria, pp. 394-395.

[4] Augustyniak P. *Measuring the local bandwidth of the ECG with noise estimation for lower frequencies* (in Polish) in proc. 2-nd Workshop on Measurements and Modelling in Medicine, Krynica Górska 8-12.05.2000 pp. 191 – 196

[5] Augustyniak P., Wrześniowski A. *ECG Recorder Sampling at the Variable Rate* in proc. VI-th International Conference SYMBIOSIS 2001, Szczyrk, Poland 11-13 September 2001, pp. 128-135.

[6] Augustyniak P, *ECG Sampling Rate Controlled By Signal Contents* in Proc. 12NBC of Biomed. Eng. and Med. Physics, Reykjavik, 2002, pp 154-155.

[7] 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.

[8] 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) – PhD these INSA-Lyon 1986

[9] Augustyniak P. *Pursuit of the ECG Information Density by Data Cancelling in Time-Frequency Domain* in Proc. 12NBC of Biomed. Eng. and Med. Physics, Reykjavik, 2002, pp 152-153.

[10] *Datasheet of the Switching Capacity filters MAX 291, MAX 292, MAX 295 and MAX 296* www.maxim.com

[11] Willems J. L., Arnaud P., Van Bemmel J. H. *Assessment of the performance of electrocardiographic computer programs with the use of a reference data base* Circulation, 1985, Vol. 71 No 3, p 523-534.

[12] Willems J. L. *Common Standards for Quantitative Electrocardiography* 10-th CSE Progress Report, 1990. Leuven: ACCO publ., 1990, 384p.

[13] Duda K. *Lossless ECG Compression with Adaptive Lifting Wavelet Transform*, Proc. Intnl TICSP Workshop on SMMSP 2001, Pula, Croatia.