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Prolonged Wearable ECG Monitoring – a Wavelet Based Approach

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***Abstract*—This paper presents the implementation of an ambulatory electrocardiogram (ECG) monitoring system. The proposed system comprises current trends on ambulatory ECG monitoring like integration of the hardware in clothing, the use of low power components, wireless data transmission via Bluetooth and the use of a PDA. Differing from other approaches the signal processing was located close to the sensor. Thus, more variability in further data handling and therefore a more efficient operation is possible. Employing adequate hardware components on the one hand and adapting a wavelet based signal processing method to the applied components on the other hand, we realized a system optimized in terms of suitability for daily use, energy efficiency and reliability.**

I. INTRODUCTION

Analysis of the electrocardiogram (ECG) is used for diagnosis of a wide range of cardiac diseases. Anomalous changes may indicate arising coronary diseases in an early stage of development. For instance, rhythm disturbances like ventricular premature beats (PVC) in certain circumstances point to an elevated risk of ventricular tachycardias. Further on, acute life-threatening situations can be observed in the ECG immediately after their incidence. Acute myocardial infarcts, for instance, cause detectable elevations of the ST-segment. Increasingly powerful hardware today allows ambulatory long-time monitoring of the ECG. Such recordings are especially useful to detect sporadically occurring events, which are not perceptible in short-time readings. Also, the online observation of patients with increased risk of cardiac breakdowns, due to preliminarily diseases or due to special physiological stress, is feasible. The possibility of early diagnosis of arising diseases and furthermore the ability of an instantaneous intervention in acute threats make the long-time ECG a very powerful tool for improved medical care. Recently, a large number of papers have been dealing with topics related to ambulatory electrocardiography. Many of those publications contain promising results indicating trends for further developments. Most of them focus on particular problems existing in the field of ambulatory ECG monitoring. Covered topics are for example the integration of hardware in clothing [1], the use of a PDA in ambulatory systems [2] and a wide range of advanced signal processing methods. As the performance of an applicable ambulatory monitoring system depends on all components as well as on their interaction the examination of detached parts constitutes a structural weakness of such studies. To overcome this limitation our efforts aim at developing a complete system to best meet the demands of ambulatory monitoring. To our understanding the most striking problems to be considered are suitability for daily use, reliability and low energy consumption during operation. To achieve the best performance concerning these items, we incorporated some of the trends mentioned above, combined optimized hardware components and developed a software concept capable of dealing with typical problems occurring during ambulatory monitoring. Those problems include a reduced Signal-to-Noise Ratio (SNR) as well as strong artifacts mainly introduced by patient motion. In Fig. 1 a schematic view of the system architecture and its components is given. Differing from other approaches the

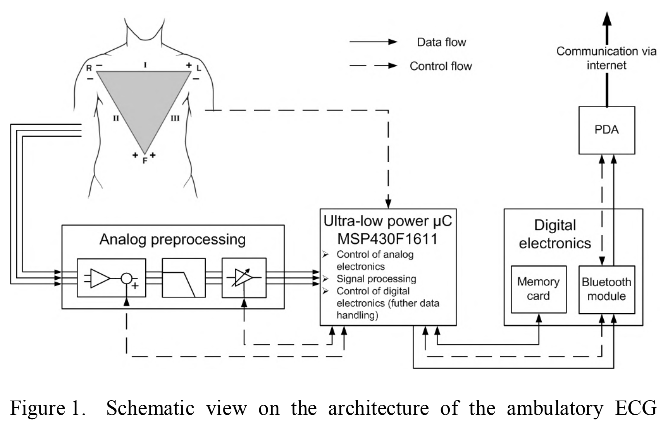

Figure 1. Schematic view on the architecture of the ambulatory ECG monitoring system. The analog subsystem (used for preprocessing of the ECG) as well as the digital subsystem (storage on a memory card and/or wireless transmission via Bluetooth of the ECG) are managed by an ultra-low power µC. The employment of a PDA allows to communicate with medical personnel via internet.

signal processing was located in close proximity to the sensor. This approach provided optimal control of subsequent steps such as storage of data on a memory card and optionally its wireless transmission over Bluetooth to a PDA. In this way, the actual data handling (storage and/or transmission) depends upon the outcome of the just-performed signal processing, thus rendering the overall system more flexible and improving its efficiency.

The paper is organized as follows: Section II describes the components of the system and software-controlled functions in detail. First experimental results are reported in Section III and discussed in Section IV. Finally, Section V contains conclusions and some considerations concerning the future development of the system.

II. MATERIALS AND METHODS

A. Hardware

1) System Carrier

As carrier of our system we used the “smart shirt” shown in Fig. 2. A three-channel ECG based on Einthoven is employed. Four electrodes, required for the record, can be integrated within the shirt. In order to allow the long-time deployment of the system, the electrodes do not rely upon any kind of contact supporting gels or liquids. The electronics are arranged on the printed circuit board shown in Fig. 3. In order to guarantee the suitability for daily use we developed a partially flexible board containing all the electronics required for analog preprocessing, data storage, wireless data transmission and energy supply. Four joints allow the adaptation of the board to movements of the carrier. Thus, mechanical stress on the printed circuit board as well as inconveniences for the user are significantly reduced. The dimensions of the board are approximately 10 cm in length and 5 cm in height. In this way, not only the flexibility of the hardware but also its small dimensions provide for a comfortable long-time use of the medical device. The storage of the printed circuit board is realized in the interior of the shirt.

Figure 2. “Smart shirts” used as carrier for the amblatory monitoring system. Four electrodes to record a three-channel ECG and all electronics arranged on a partially flexible printed circuit board are integrated.

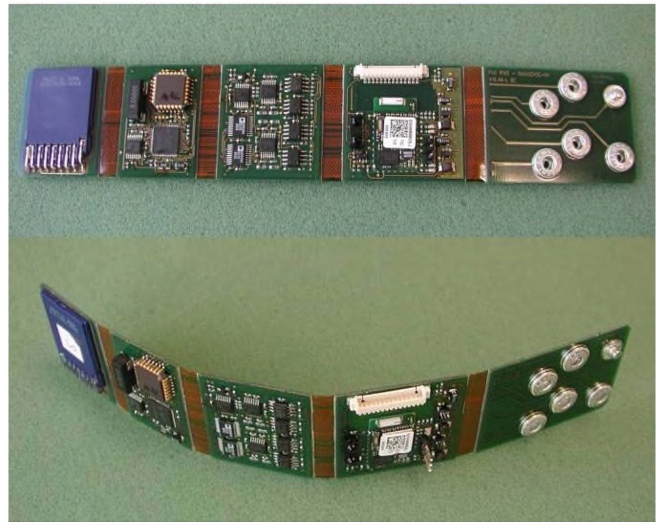

Figure 3. Printed ciruit board. Employing four joints renders the board partially flexible and avoids inconveniences for the user and mechanical stress upon the board.

2) Electronics

The circuit consists of an analog subsystem to preprocess the ECG and a digital subsystem for further data processing. Both parts are managed by the ultra-low power µC MSP430F1611 from Texas Instruments. The desirable low energy consumption of the µC is combined with a relatively low clock frequency of 8 MHz. Analog preprocessing includes an instrumentation amplifier to accomplish an offset-adjustment controlled by the µC and a low-pass filter. An amplifier, also controlled by the µC, completes the analog system. Sampling is done at a frequency of 1000 Hz and 12-Bit resolution. Further data processing is realized in the digital system of our implementation. The processing may include storage of all data on a memory card (conventional SD card). Furthermore, data can be optionally transmitted by Bluetooth to a PDA in situations of eminent risks. The PDA is mainly employed as gateway to communicate with medical personnel via Internet. Besides this major task, it can be equally used for an online visualization of the ECG, to prove the functionality of the system, or to display current values delivered by the signal processing engine.

B. ECG Processing

As the further data handling depends upon the results of the signal processing, the applied algorithm has to assure robust operation even during signal episodes corrupted by strong noise and artifacts. To deal with the strong interferences typical in ambulatory monitoring applications we developed a robust wavelet-based algorithm to detect R-Peaks. Furthermore, we devised an easy method to classify PVC. The implemented method is mainly based on the ideas of the realization proposed in [3].

The wavelet-transform decomposes a signal in scaled and translated versions $\psi_{a,t}(\tau)$ of a basis function called mother wavelet $\psi(\tau)$. The derivates of the mother wavelet are given by

$$\psi_{a,t}(\tau)=\frac{1}{\sqrt{|a|}}\psi\left(\frac{\tau-t}{a}\right) \quad \text{with} \quad a\in\mathbb{R}^+, t\in\mathbb{R} \tag{1}$$

where a is the scale of the wavelet which is a measure of the current width of the applied wavelet and t is the translation parameter which describes the position of the wavelet in the time domain. The wavelet transform $X(a,t)$ results from the inner product of the signal and the scaled and translated wavelets

$$X(a,t)=\langle x,\psi_{a,t}\rangle=\int_{-\infty}^{+\infty}x(\tau)\frac{1}{\sqrt{|a|}}\psi^*\left(\frac{\tau-t}{a}\right)d\tau \tag{2}$$

The resulting coefficients can be seen as a measure for the similarity of the examined signal portion, specified by t, and a wavelet of varying width, specified by a. There are three common methods to compute the wavelet transform: the so-called continuous WT (CWT), the dyadic WT (D_YWT) and the discrete WT (DWT). These schemes differ in the needed computational load, the degree of redundancy of the results and in some additional properties like the shift-invariance of the results. We applied the D_YWT which is a shift-invariant version of the WT. Analogous to the discrete WT, the scale parameter a is sampled along a dyadic grid. Differing from the DWT, the translation remains independent from the scale, meaning that no downsampling is performed. So, the property of shift-invariance can be maintained while reducing the degree of redundancy and the computational load (in comparison to the CWT). Considering those modifications, the definition of a family of wavelets changes to

$$\psi_{2^m,t}(\tau)=\frac{1}{\sqrt{2^m}}\psi\left(\frac{\tau-t}{2^m}\right) \quad \text{with} \quad m\in\mathbb{Z}^+, t\in\mathbb{R} \tag{3}$$

By means of the "algorithme a trous" a recursive algorithm is available allowing the fast calculation of the D_YWT. Decomposing a signal with the WT is equivalent to the application of a filterbank. As the width of the pass-band increases with higher center frequencies, a good resolution in the time domain for high frequencies is achieved, whereas for lower frequencies a good resolution in the frequency domain is obtained. This property of the WT makes it very suitable for the analysis of non-stationary signals containing different frequency ranges like the ECG.

In our implementation we use the quadratic spline wavelet introduced in [4]. Considering the specific wavelet and the sampling frequency of 1000 Hz we get the transfer functions displayed in Fig. 4. QRS complexes result in modulus maximum pairs in the coefficients of the WT. To allow the recognition of a wide range of QRS complexes, even despite the occurrence of morphological changes within QRS complexes, minimum-maximum pairs as well as maximum-minimum pairs are considered as possible QRS complexes. To extract possible QRS complexes adaptive thresholds

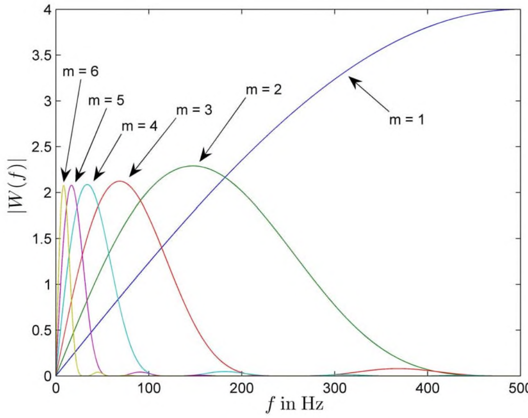

Figure 4. Transfer functions realized by the quadratic spline wavelet. The proposed method uses scales for m=1,m=4,m=5 and m=6

across the different scales are applied. According to the main energy portions of the QRS complexes, the scale m=5 is used for the search of QRS candidates. In m=4 the detection is validated and in m=1 an additional elimination of artifacts is carried out. The classification of PVC is based on the modified ratio of amplitudes within QRS complexes in the scales for m=5 and m=6. A shift of energy portions to lower frequencies (associated with higher scales) is commonly observed for PVC. The scales for m=3 and m=4 are not used and so neither have to be calculated.

III. Results

Tests with own records demonstrate the capability of the developed method to deal with typical artifacts occurring in ambulatory monitoring (Fig. 5).

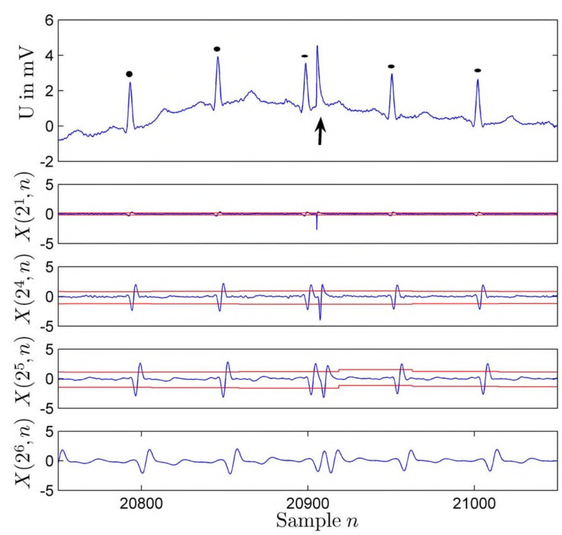

Figure 5. Example of a typical artifact (marked by an arrow) in ambulatory monitoring. In the time domain and higher scales a distinction to normal QRS (marked by points) is hardly possible, but using the scale for m=1 the distinction is easily done by an amplitude criterion.

TABLE I. COMPARISON BETWEEN THE ELECTRICAL CHARGE NEEDED FOR WIRELESS TRANSMISSION OVER BLUETOOTH AND FOR THE STORAGE OF DATA ON A MEMORY CARD (THE SHOWN DATA RATES ARE THE VALUES REACHED IN OUR IMPLEMENTATION)

Processing Method	**Data rate in kbits/s**	**Charge needed in mAh/MB**
Transmission via Bluetooth*	115	4.78
Storage on memory card*	2000	0.11
*Due to their minor influence additional energy requirements (for instance the energy consumption during standby) are not considered.		

TABLE II. REQUIRED RESOURCES FOR SIGNAL PROCESSING

Processing Step	**Computational load (µC at 8 MHz)**	
	required cycles	***required µs***
Calculation of the WT	1080	135
Feature extraction	<2100	<263
Over all	<3180	<400

The first quantitative evaluation of the performance of the method yielded a sensitivity of 99,85% and a positive predictivity of 99,92% for the detection of QRS complexes. The analysis was carried out offline with own data (8525 normal beats) annotated by a health professional. The high demands on the performance of the algorithm conflict with the limited computational power provided by a low-power µC. Due to the properties of the WT the algorithm can act without any prefiltering of the signal and thus avoid additional computations other than the calculation of the WT and the feature extraction. Because of the advantageous properties of its filter coefficients we selected the quadratic spline wavelet to reduce the computational load. Using the quadratic spline wavelet the transform can be calculated with 16-Bit fix-point values involving only bit-shifts and additions. The whole detection procedure requires less than 400 µs (3180 cycles) (Tab. 1) leaving computing power for other purposes. Based on the results of signal processing, wireless data transmission can be then confined to the transfer of critical passages or registered abnormalities. The advantages of a reduced wireless data transmission can be easily illustrated through inspection of the different energy requirements. In Tab. 2 energy amounts needed for the transmission of data via Bluetooth are compared to the energy demanded to store this same data on the memory card.

First tests furthermore confirm the suitability of the system for long-time recordings: by the integration of the hardware in clothing the user is not disturbed in his activities during operation, thereby preserving a high grade of signal quality.

IV. DISCUSSION

It could be shown that the implementation of a wearable ambulatory monitoring system driven by a ultra-low power µC is possible. Neither the user is considerably limited in his activities nor the operability of the hardware is disturbed by external influences, mainly caused by mechanical stress introduced by movements. Thus, our tests suggest that the long-time application of the system is practicable. The developed signal processing method showed promising results in terms of the required computational load as well as in terms of the results obtained by the implemented method concerning the QRS detection. Essential for the good performance in terms of the pattern recognition is the analysis of different frequency ranges provided by the WT. This feature of the WT makes the method superior to the often employed particular bandpass filters. The advantageous properties of the quadratic spline wavelet render this choice very convenient for real time processing of the ECG. In order to compare the obtained detection rates with other studies, validation with a standard data base will be carried out in near future. Particularly considering the heterogeneous groups of patients we mentioned before, it is usually not necessary to continuously transmit all recorded data to allow an immediate inspection of the ECG by medical personnel. Comparing the energy amounts needed for the different possibilities of further data handling, the advantages that speak for a reduced wireless data transmission are obvious, so that a long-time monitoring up to 7 days becomes possible. Nevertheless, the transmission of data in sections preserves the advantages provided by the use of a PDA and ensures improved medical care.

V. CONCLUSIONS

The proposed system comprises current trends of ambulatory monitoring concerning the employed hardware as well as the signal processing method. By the development of a matched software concept, the required hardware components and their specific advantages can be optimally deployed. In terms of energy efficiency, suitability for daily use and reliability, the presented architecture constitutes an optimized solution for a complete ambulatory ECG monitoring system. In order to enhance the worth of the system, future work will mainly focus on the extension of the signal processing done in proximity of the sensor. A more sophisticated classification of beats, the detection of P and T-waves as well as the detection of additional events like atrial fibrillation will enable the system to cope with a wider range of patients and disease patterns. Further on, extensive testing, including clinical tests, will provide significant information concerning the operating time of the system under real-world conditions.

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