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# Content-Based Adaptivity of Telemedical Recorders

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*Abstract:* The paper presents a novel approach to the remote control of a wearable biosignal-based health monitor. The autonomy of wearable devices is usually an opposite requisite to the interpretation intelligence requiring computation power. The remote programmability idea is applied to continuous optimization of the resources use aimed at the best diagnosis quality. The proposed concept of programmable recorder assumes high flexibility of the patient-side recording device. The application field of programmable monitors extends beyond the traditional long term ECG recording and covers the area of sports, endurance, stress, pregnancy and elderly people surveillance.

*Keywords:* Remote control, Signal analysis, Ambient intelligence, Ubiquitous computing, Telemedicine, Home care

## 1 Introduction

The remote monitoring of physiological signals is currently one of the hottest topics [3], [9], with the application area extending beyond specialized clinical monitors and including also widely accessible home care devices [4], [8]. Several networks offering the continuous monitoring of cardiac risk people are already matured in US and Europe. Those approaches assume the capturing device to interpret the electrocardiogram and to issue an alert message in case of abnormalities. Although the spread interpretation intelligence limits the communication costs, due to resources limitation typical to a wearable computer, the percentage of false alarms is rather high. An alternative approach uses triggered acquisition method typical for the ECG event recorders. In such cases unfortunately, a manually operated independent device risks to miss an electrocardiogram when the patient in pain is unable to start the capture session.

The advantage of remotely controlled device is thus twofold. The signal is interpreted in real time and conditionally transmitted without delay, so the

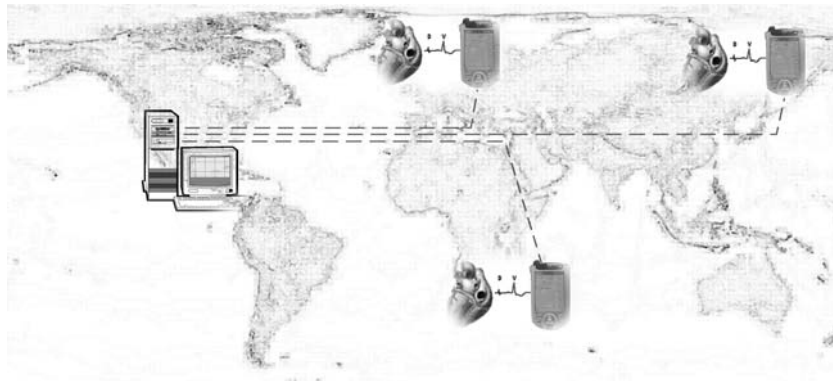
reanimation may start immediately if necessary. Additionally, the acquisition is controlled by the experienced staff with support of technically unlimited knowledge base and with consideration of previous results.

Considering further advantages of remote programmability, two dimensions: the levels and the aspects of adaptation are highlighted in this paper. They are discussed in details throughout chapters 2 considering the processing and chapter 3 considering the transmission. Chapter 4 presents an experimental biosignal recording device and the result of the in-field tests. Conclusions, perspectives and final remarks are summarized in chapter 5.

## 2 Adaptivity of the Hardware and the Software

In a typical topology of distributed surveillance network (fig. 1) patient-side wearable recorders are supervised and controlled by a central node archiving the captured information. Assuming both device types are equipped with signal interpretation software, the analysis of other constraints leads to the following remarks:

- higher interpretation performance of a wearable device results in higher power consumption and in shorter autonomy time,
- lower interpretation performance of the wearable device augments the data stream and increases the costs of digital communication,
- the interpretation needs and priorities vary with time and patient depending on many factors known before the examination starts, but also on directly preceding diagnostic results,
- the central node has not to be mobile, it benefits from a world wide knowledge resources and can be supported by human experts.



**Fig. 1.** Typical topology of surveillance network using wireless digital communication

Following the remarks above, a new concept of adaptive wearable vital signs monitor was worked out in our laboratory. This concept joins the artificial intelligence approach to both device types in the network and the generalized division of tasks practiced by human medics. Our concept assumes that the automatic interpretation task is performed partially in the remote device and partially by a complementary software thread running on the node host computer. The results are prioritized following the changes of diagnostic goals and current patient state. The data format used for communication is also adaptive, so the actual data contents are negotiated between the node and the remote monitor. The automatic negotiation process is driven by distributed optimization of diagnosis quality, transmission channel use and power consumption.

## 2.1 Adaptation Levels

High flexibility of the vital signs monitor may be achieved remotely in real time on various levels of adaptation:

- modification of the hardware structure and functionality with use of analog and digital reprogrammable circuitry
- modification of the software structure and functionality by means of dynamically linked libraries,
- modification of interpretation parameters.

## 2.2 Adaptation Aspects

The combination of proposed technical methods open the possibility of changing the device functionality and purpose substantially. The list of aspects of adaptation includes, but is not limited to:

- acquisition and interpretation of many different vital signs (ECG, EMG, EOG, blood pressure, phonocardiography, uterine contraction and other signals from the human and his surrounding) up to the number of channels available in the hardware and with their proper sampling characteristics.
- cooperation with a node as a 'transparent' recorder, in partial autonomy with optimized interpretation task share or as an independent remote device with full interpretation of signal.
- operation in a continuous surveillance mode or as an event monitor triggered manually or by given physiological event with an optional pre-trigger,
- continuous adaptation of interpretation depth following the patient state and the diagnosis goals.

### 3 Adaptive Data Formats

The consequence of interpretation programmability is the multitude of output signal formats ranging from raw electrogram to the sparse data (e.g. heart rate). The modifiable transmission protocol is also useful for optimization of wireless channel use aiming at reducing the monitoring costs to the acceptable level. The general rule assumes the transmission of basic interpretation results for all the monitoring time and more detailed reports for short time intervals. Every occurrence or suspicion of any abnormality results in a more detailed report including up to the corresponding strip of raw signal. This approach was proposed as a result of cardiologist's behavior analysis, but it can be remotely programmed upon request. The machine description of electrocardiogram contains all meta-information interfacing the non-assisted signal interpretation routines and the manual or semi-automatic diagnostic decision making. Although the goal is reproducing the expert reasoning as far as possible in a computer algorithm, there are several approaches to establish the final data set included in the optimal ECG description.

#### 3.1 Expert-Machine Learning

The computer algorithm calculates parameters  $d$  being a quantitative description of the waveform in the  $n$ -dimensional diagnostic domain  $\mathbf{D}^n$ . The parameters are well defined on physiological background, but not always easy to derive properly from the unknown signal.

$$d \in \mathbf{D}^n : d \rightarrow w_1 \cdot f_1(s) \otimes w_2 \cdot f_2(s) \otimes \dots \otimes w_n \cdot f_n(s) \quad (1)$$

where  $f_i$  are heuristic signal transforms and  $w_i$  corresponding weighting functions. Usually during the tests of newly developed interpretation software the results are calculated for a limited database (learning set), verified, and used for corrections of computation coefficients.

#### 3.2 Matching Pursuit

The procedure compares the current record with a set of dictionary functions  $g_{\gamma_0} \in \mathbf{S}$  known beforehand. Amplitude and scale normalization are used to suppress basic extracardiac variability sources. The matching coefficients  $R^n$  estimate how far the signal  $f$  could be explained by a given pattern. The decomposition procedure starts with the best fitted pattern

$$f = (f, g_{\gamma_0})g_{\gamma_0} + R^1 f \quad (2)$$

and the residual signal  $R$  is recursively processed up to the desired number of coefficients  $n$ :

$$R^i f = (R^i f, g_{\gamma_i})g_{\gamma_i} + R^{i+1} f. \quad (3)$$

The procedure yields the signal represented by a set of matching coefficients  $R^i$  over the dictionary functions  $g_{\gamma i}$  and the remaining signal  $R^n f$  representing all unexplained signal components:

$$f = \sum_{i=0}^{n-1} (R^i f, g_{\gamma i}) g_{\gamma i} + R^n f. \quad (4)$$

Its energy is the estimate of matching quality (or dictionary adequacy). The construction of appropriate dictionary resulting in explanation of principal diagnostic features with use of minimum number of coefficients is a very challenging, but still unresolved issue.

### 3.3 Extension of Compression Algorithms

ECG data compression techniques do not have a common mathematical expression and are usually classified in three major categories:

- direct data compression (e.g. AZTEC, SAPA, CORTES, delta coding, approximate Ziv-Lempel etc.)
- transform coding (e.g. Karhunen-Loeve Transform, Discrete Cosine Transform, wavelets etc.)
- parameter extraction methods (e.g. linear prediction, vector quantization, neural networks etc.)

Since the expectation of maximum signal fidelity at a minimum data rate is very similar to those of signal compression, specialized data reduction algorithms may be adapted to the computation of machine ECG description. Main assumption of such adaptation is no necessity to accurate data reconstruction. This approach is already commercialized for management of digital multimedia as the MPEG-7 standard. However, in case of medical record the diagnostic meaning of the signal have to be preserved with maximum care. Therefore, the unchanged content is completed by a preceding data fingerprint containing the description of most representative features from the user's viewpoint.

### 3.4 Syntactic Description of the Electrogram

The syntactic description of the electrogram consists of words composed of symbols  $x_i$  belonging to the finite alphabet.

$$\mathbf{V} = \{x_1 \dots x_n\} \quad (5)$$

The alphabet includes tokens referring to the waveform shapes expected in the signal as well as the features of signal derived automatically. Tokens are grouped to symbols using a grammar  $G_A = (V_N, V_T, S_{out}, S_{in})$  accordingly to its syntactic and semantic rules.

$$X \rightarrow a, \text{ for } X \in V_N \text{ and } a \in V_N \cup V_T \quad (6)$$

$$\begin{aligned}
Y_1 &= f_1(X_{11}, \dots, X_{1n1}, Y_1, \dots, Y_n) \\
&\vdots \\
Y_n &= f_n(X_{n1}, \dots, X_{nnn}, Y_1, \dots, Y_n)
\end{aligned}
\tag{7}$$

where  $X_{ij}$  are symbol attributes and  $f_i$  represent semantic procedures. Definition of semantic rules is based on the cardiologist's reasoning and thus high adequacy of signal representation can be well combined with algorithms flexibility [10], [11], [2].

## 4 Experimental Recorder for Cardiology - Design and Tests

The portable ECG recorder was developed in our Laboratory on demand from cardiology researchers and comply with the following criteria:

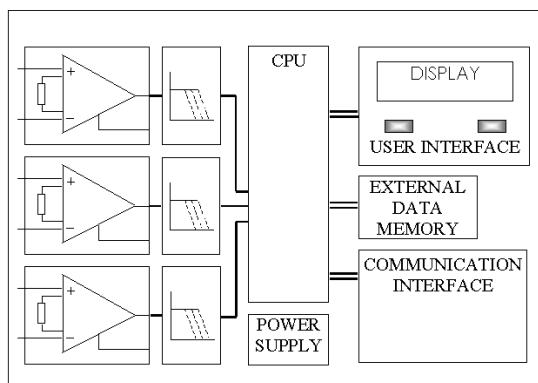
- three simultaneous channels sampled at up to 200 Hz,
- co-operation with a GSM modem for on-line wireless transmission of recorded signal or with the PDA as the source of data for interpretation,
- autonomy for at least 24 hours of operating.

The recorder was designed for medical experiments, the lack of build-in interpretive algorithm was intended making the research on the adaptive software fully independent. The recorder does not contain reprogrammable hardware, but the basic set of remote configuration commands, offers high flexibility of acquisition parameters.

The recorder was developed around the popular circuit from the MicroConverter family integrating analog to digital converters, serial communication interfaces, internal flash memory and a '51-type processing kernel running at 2,7V. The on-chip PLL-adjustable oscillator with the Fast Interrupt Response feature is very useful in a portable device where the power management is critical. The diagram of the recorder's circuitry is displayed in figure 2.

The analog circuitry repeats the same architecture in each recording channel and uses micropower (230  $\mu$ W) instrumental amplifiers with rail-to-rail input and output signal swing. The effective input voltage range can be set by the software from 2mV to 16mV in order to cover all the area of applications. The digitizers provided in the MicroConverter [1] chip guarantee 12-bits resolution.

The external memory lasting for ca. 12 minutes is used for data storage in the recording mode and acts as a data buffer in the interactive mode. Another function of the external memory is the closed loop buffer used for defined length of pre-trigger data. The internal non-volatile memory is used to store the recorder configuration. Therefore, the device status, the data organization and other settings are preserved in case of power failure.



**Fig. 2.** The block diagram of the recorder's circuitry

The communication interface uses the bi-directional UART that could be directly connected to a PDA computer or to a mobile telephone for independent wireless connection. Moreover, the communication channel is used for sending the textual messages to the user and the configuration data to the device.

Although, the recorder size was taken into the consideration, further reduction by up to a half of current dimensions is possible. During all the development process the requirements of international standards for medical devices and electromagnetic compatibility [5], [6], [7] were carefully observed.

Since the signal quality is of crucial importance, extensive tests were performed in order to confirm the recorder's ability to deliver a medically meaningful signal representation. The electrical tests were made in a specialized laboratory complying with TUV/ISO measurements standards. The parameter set and testing procedure used were typical for ECG long-term recorders. For the transmission channel the electrical tests were limited to the electromagnetic compatibility (EMC) and interference immunity issues. Main results of these measurements are displayed in table 1. The following procedures,

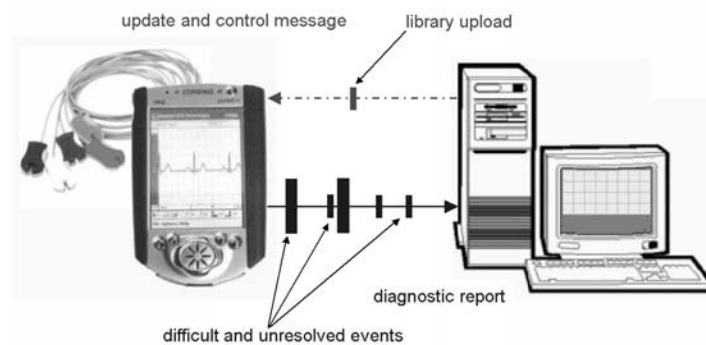
**Table 1.** Selected results of recorders electrical tests

parameter	value	conditions
bandwidth	$0.03 \div 100\text{Hz}$	-3 dB
1 LSB linearity range	$-1.87 \div 1.83 \text{ mV}$	2mV range
voltage noise (ref. to input)	$8.3 \mu\text{V}$	$0.1 \div 10 \text{ Hz}$
CMRR	92 dB	DC $\div$ 100 Hz (worst case)
channel crosstalk	-77 dB	DC $\div$ 100 Hz (worst case)

necessary for independent transmission, were thoroughly tested: scheduled acquisition to the memory; scheduled acquisition and transmission over a GSM

telephone in various conditions; acquisition and transmission initiated remotely over a GSM telephone; displaying of a textual message sent over a GSM telephone; changing of the configuration memory contents over a GSM telephone. The test results confirm the correct support of transmission break, multiple connection retries, data stream redirection etc. The power supply monitoring enables the data-safe shutdown and wake-up with reporting to the supervising remote station, however sudden power failure (battery disconnection) has been found too fast to be serviced correctly.

Supplementary tests were performed in a configuration with the PDA-based interpretation unit. In this configuration the adaptability includes adjustment of processing parameters, on-line modification of communication protocol and processing routines. The PDA uses Pocket Windows operating system that is compatible with Microsoft Windows platform for desktop PCs and provides easy software development and interfacing with standard peripherals. The software architecture consists of a process management and communication control kernel and of a set of basic interpretation routines linked upon request. Each routine is implemented as a dynamic function library and can be adjusted remotely with a vector of interpretation parameters or replaced by an alternative routine from the basic set or by the code provided by the supervising node (fig. 3).



**Fig. 3.** Cooperation of the remote monitor and the supervising node aiming at optimizations of diagnosis quality, transmission channel use and power consumption

## 5 Conclusions and Perspectives

The concept of wireless physiological monitors proposed in this paper may be extended to open networks providing various medical surveillance services and having a considerable impact to the health care in the future. Its princi-



pal advantage is the flexibility of automated interpretation very close to the human medics. It is manifested by:

- adaptive patient description level varying from a general to a detailed report dependent on the result severity,
- adjustability of monitoring and auto-alerting parameters accordingly to the patient-specific signal; during the initial recording phase and anytime thereafter the device may be remotely taught what is correct and what is wrong in the acquired signal,
- possibility of following of any unexpected event and if the remote interpretation is not flexible enough, the uncommon signal is interpreted in the network node with intervention of human supervisors.

The recorder was evaluated in several applications including daily activity and intensive training of sportsmen. The research already completed with use of the recorder include:

- muscle fatigue assessment during training of downhill ski competitors,
- the investigation of environmental stress influence to the physiology of domestic animals.

The concept of wireless physiological monitors proposed in this paper may be extended to various medical surveillance services with a considerable impact to the health care in the future. Its principal advantage is the flexibility of automated interpretation very close to the human medics.

Although main scientific goal was achieved, several problems emerged during the design and testing of the vital signs recorder. At the present stage the compatibility of the interpretive software on the remote device and on the supervising node was problematic. For the reported tests the node is running the same procedures as the remote monitor. Consequently, because of no influence of task sharing to the diagnosis quality, the transmission channel use factor dominated over the battery consumption factor and the task sharing found as optimal favored interpretation done by the PDA. The future extensions should consider:

- deep and medically justified investigation of the interpretation process and reporting format changes implied by the dependency of previous interpretation results.
- development of multi-threaded software for the cardiology centre in order to perform independent supervising of several remote monitors and for the management of patient's data archive.
- audiovisual communication with the patient or his attendee using an interactive channel for instructions necessary in case of technical troubles (e.g. electrode replacement), medical risk (e.g. physical overload), medication intake or modification of wiring up to the monitor's function.

## 6 Acknowledgment

This work was supported by Polish State Committee for Scientific Research grant no: 3T11E 001 27

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