
Adaptive Wearable Vital Signs Monitor for Home Care and Sports

Piotr Augustyniak¹

Department of Automatics, Biocybernetic Laboratory AGH University of Science and Technology Krakow, Poland august@agh.edu.pl

Abstract: This paper presents new idea of remote control over a wearable general purpose health monitor based on biosignals. The autonomy of wearable devices is usually an opposite requisite to the interpretation intelligence requiring computation power. The idea of device programmability is applied to continuous optimization of resources use towards the best diagnosis quality. The proposed concept of programmable recorder assumes high flexibility of the remote device, however only certain aspects of adaptation were implemented up to today. The application of such monitors extends beyond the traditional long term ECG recording and covers the area of sports, endurance, stress, pregnancy and elderly surveillance in various combinations.

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 [2], [8] and includes not only specialized monitors for clinical but also home care devices accessible for everyone [3], [7]. Several networks aiming at 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. However, a manually operated independent device risks to miss an electrocardiogram when the patient in pain is unable to start the capture session.

At first glance, the advantage of remotely controlled device is thus twofold:

- the signal is interpreted on-line and if necessary transmitted without delay and the reanimation may start immediately if necessary
- 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 should be point out: the levels and the aspects of adaptation. They are discussed in details throughout chapter 2. Chapter 3 presents an experimental biosignal recording device partially meeting the challenge of assumed adaptability and the preliminary result of the in-field tests. Conclusions, future plans and final remarks are included in chapter 4.

2 Adaptivity Concept

In a typical topology of surveillance network (fig. 1) remote wearable recorders are supervised and controlled by a 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 the 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, they depend on many factors known before the examination starts, but also on previous examination results,
- the node has not to be mobile, therefore it benefits from a world wide knowledge resources and can be supported by human experts.

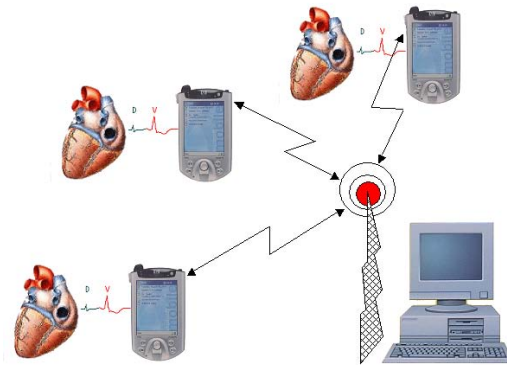


Fig. 1. Typical topology of surveillance network using wireless digital communication

With consideration of these remarks 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. Main assumptions of our concept are the following:

- The interpretation is done 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 actual data contents and format results from negotiations between the node and the remote monitor. The negotiations process may be driven by distributed optimizations of power consumption, transmission channel use and diagnosis quality.

High flexibility of a 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 circuits
- modification of the software structure and functionality by means of dynamically linked libraries,
- modification of interpretation parameters.

Combining these adaptation levels opens the possibility of deep changes of device functionality and purpose. That is called in this paper aspects of adaptation:

- acquisition and interpretation of many different vital signs (ECG, EMG, EOG, blood pressure, phonocardiography, uterine contraction and other signals from the 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 signal interpretation.
- operation in a continuous surveillance mode or as an event monitor triggered manually or by a given physiological event with an optional pre-trigger,
- continuous adaptation of interpretation depth following the patient state and the diagnosis goals.

3 Experimental Device Design and Performance

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.

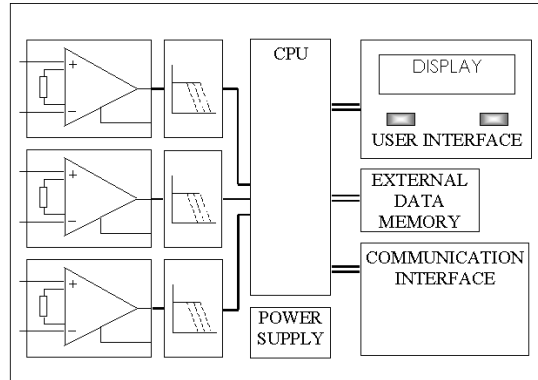


Fig. 2. The block diagram of the recorder's circuitry

The analog circuitry repeats the same architecture in each recording channel and uses micropower ($230 \mu\text{W}$) instrumental amplifiers with rail-to-rail input and output signal swing. This approach maximizes the usable dynamic range of the a/d converter even for low supply voltage. The analog inputs are FET-based and protected by 10mA ESD diodes against the overvoltages up to 20V. 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 a MicroConverter [1] chip guarantee 12-bits resolution (4096 levels) and 1LSB nonlinearity over expected temperature range.

The internal non-volatile memory is used to store the recorder configuration. Therefore, the device status, the data organization and other settings are not lost on power failure.

The external memory is used for data storage in the recording mode and acts as a data buffer in the interactive mode. This function prevents from the

loss of data when the transmission channel is temporarily not available. Third function of the external memory is the closed loop buffer used for defined length of pre-trigger data. The external memory capacity lasts for ca. 12 minutes of data, and is easily extensible with use of MMC or SD memory card thanks to the use of SPI interface.

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. In this case the modem initialization sequence is stored in the configuration area of the internal flash memory. Except for data transmission, the communication channel is used for sending the textual messages to the user and the configuration data to the device.

The user interface is as simple as possible and consists of an alphanumeric LCD module intended for displaying messages and two programmable push buttons. For the applications in animals, the buttons are ignored and the LCD is remotely switched off for the sake of energy saving.

The recorder was designed using surface mount components (SMD) and four-layer printed circuit board. The top layer contains digital components and voltage controllers while the bottom layer is reserved for analog circuits. The high immunity to the electromagnetic interference was achieved thanks to the minimum length of signal wires. 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 [4], [5], [6] 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
1 LSB linearity range	$-1.87 \div 1.83$ mV	2mV range
CMRR	92 dB	DC \div 100 Hz (worst case)
bandwidth	$0.03 \div 100$ Hz	-3 dB
voltage noise (ref. to input)	8.3μ V	$0.1 \div 10$ Hz
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 tests were performed on a single recording device connected to the Siemens S55 mobile telephone. A PC computer equipped with a GSM modem hosted the signal storage and the device control software. 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. Unfortunately, sudden power failure (battery disconnection) is too fast to be serviced correctly.

Separated challenge is the recorder test in a configuration with the interpretation unit based on a PDA computer (HP). This choice was justified by easy software development and interfacing with standard peripherals: wireless transceiver (GSM), signal acquisition module and extensible memory buffer. 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. 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).

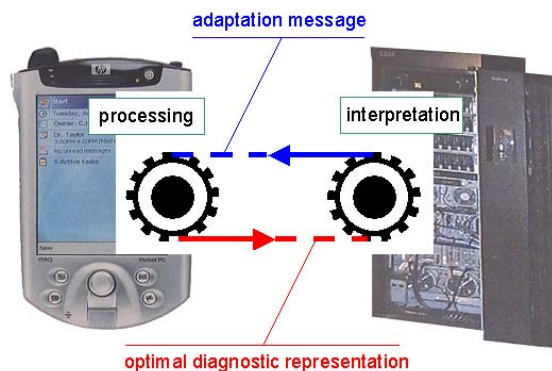


Fig. 3. Cooperation of the remote monitor and the supervising node aiming at optimizations of power consumption, transmission channel use and diagnosis quality

The consequence of interpretation programmability is the multitude of output signal formats ranging from raw electrocardiogram to the sparse da-

ta (e.g. heart rate). The modifiable transmission protocol is very useful for optimization of wireless channel use aiming at keeping the monitoring costs at 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 event 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.

At this 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.

4 Discussion

Except for satisfying the requirements of technical specifications for electrocardiographs, the recorder was evaluated in several applications including daily activity and intensive training of sportsmen. The medical research already completed with use of the recorder include:

- muscle fatigue assessment during training of downhill ski competitors,
- uterine contraction detection based on abdominal potentials in patients at risk of premature delivery,
- the investigation of influence from environmental stress to the physiology of domestic animals.

The concept of wireless physiological monitors proposed in this paper may be extended to open networks providing various medical services and having 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. 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 audiovisual communication with the patient or his attendee provides 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.

Although main scientific goal was achieved, several problems emerged during the design and testing of the vital signs recorder. A majority of them could be resolved by increasing the processing power. Next version of acquisition part should be fit into a standard PCMCIA case after elimination of LCD and charge-pump voltage converter. The user interface provided by the PDA must be programmed to support easy and unambiguous operating by the patient in any condition. The built-in speaker may also be used to generate voice message guiding the operation of the monitor. Another future considerations include:

- 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.

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