Automatic Management of Tele-Interpretation Knowledge in a Wearable Diagnostic Device

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Abstract: This paper presents the aspects of remote management of interpretation knowledge embedded in a wearable health monitor based on vital signs. Expected high autonomy of a wearable device and the reliable interpretation intelligence requiring computation power are opposite requisites. The presented concept of programmable recorder assumes high flexibility of the remote device, however only certain aspects of adaptation were implemented up to today. The device programmability is implemented on the software platform and applied to the processing and transmission functions with the aim of continuous optimization of resources use towards the best diagnosis quality. The prototype was designed as an ECG-oriented monitor, but the application of spread intelligence-based monitors extends beyond the traditional long term ECG recording and covers the area of exercise, emergency and elderly people surveillance in various combinations.

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

1 Introduction

The telemedicine based on remote acquisition of various vital signs [4] [10] opens wide application area ranging from the equipment for clinical use to the home care devices [5], [9]. Several telediagnostic services commercialized recently in US and Europe, offer the continuous monitoring of cardiac risk people. Such services typically use closed wireless networks of star topology. The interpretive intelligence aiming at derivation of diagnostic features from recorded time series is implemented in the recorder or in the supervising server. Both approaches have serious limitations. The *central intelligence* model uses the communication channel continuously to report raw signals and needs the uninterrupted carrier availability which makes the transmission cost very high. The *spread intelligence* model assumes that the capturing device interprets the signal and issues an alert message in case of abnormalities. Although the *spread* interpretation *intelligence* reduces the communication costs, the diagnosis quality is affected due to resources limitation typical to a wearable computer. Other alternatives, like a triggered acquisition method typical for the ECG event recorders, suffer from poor reliability since a manually operated device risks to miss an event when the patient in pain is unable to start the capture session.

Our research aims at combining the advantages of both interpretive intelligence models. This could be achieved by extending the adaptivity of spread interpretation procedures and complementing the remote interpretation by server-side analysis with result-dependent task sharing. The consequence of such extensions is the event-dependent report content and reporting frequency. The operating principle of interpretation task sharing follows generalized relations between human cardiologists.

The design of remotely controlled interpretive device includes three essential prerequisites:

- the automatic interpretation is supervised by the experienced staff with support of technically unlimited knowledge base with respect to the context of previous results.
- the signal is interpreted in real time and conditionally transmitted without delay, so any medical intervention necessary may start immediately.
- the recorder is marketed as low-cost general-purpose interpretive device and remotely personalized accordingly to the patient status and diagnostic goals.

Two dimensions named here: '*levels*' and '*aspects*' of adaptation are highlighted in this paper. They are discussed in details throughout chapter 2 in context of processing and throughout chapter 3 in context of data representation. In chapter 4 an experimental biosignal recording device and the result of the in-field tests are presented. Conclusions, perspectives and final remarks are summarized in chapter 5.

2 Adaptivity of the Hardware and the Software

In a typical star-shaped topology of distributed surveillance network (fig. 1) patient-side wearable recorders are supervised and controlled by a central node server archiving the captured information as signals and data. Assuming both device types are equipped with signal interpretation software, optimization of the task sharing between them affects directly the remote power consumption and the costs of digital communication. One of the principles of our design is the continuous adjustment of this balance, as the interpretation goals and priorities vary with time and patient. Considering many factors known before the examination begins, but also relying on directly preceding diagnostic results, the task sharing accustoms the general-purpose recorder to a particular case.

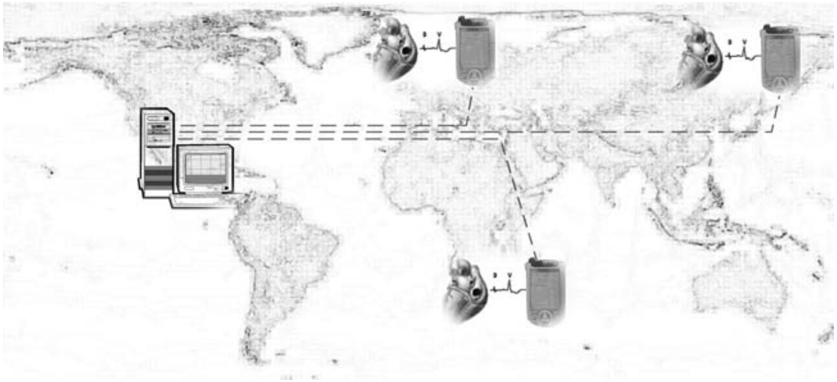

Fig. 1. Typical topology of surveillance network using wireless digital communication

New concept of adaptive vital signs recorder for ubiquitous health care emerges from the above remarks. Our proposal joins the artificial intelligence approach to both cooperating device types and the generalized tasks sharing rules practiced by human medics. It is assumed that the automatic interpretation task is partly performed by the remote device and than complemented by a software thread running on the supervising server. For the transmission, intermediate results are prioritized accordingly to the changes of diagnostic goals and current patient state. The adaptivity concerns also the communication data format, so the actual report content and frequency are negotiated between the supervising server and each remote monitor independently. This is a distributed optimization process considering multiple criteria such as diagnosis quality, transmission channel use and power consumption.

2.1 Adaptation Levels

Adaptation levels are used to describe the extent and technical measures used for modification of remote recorder functionality. Three *adaptation levels* combine hardware and software solutions are ordered by potential flexibility:

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

2.2 Adaptation Aspects

Adaptation aspects are used to describe the medical application range that the remote device may cover due to its adaptivity. Our current viewpoint allows to enumerate several *adaptation aspects*, however the list would be completed by future users:

- 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 the supervising server as a transparent recorder, in a partial autonomy with optimized interpretation task share or as an independent remote device performing full signal interpretation.
- 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 the interpretation depth following the patient status and the diagnosis goals.

3 Adaptive Data Formats

A side effect of remote intelligence flexibility, however very interesting in the resources optimization aspect, is the multitude of output data formats ranging from the raw electrogram to the sparse medical parameters (e.g. heart rate). The modifiable communication protocol helps avoiding the unnecessary data transmission and impacts both the power consumption and the wireless channel use and consequently reduces the monitoring costs to the acceptable level. Basic interpretation result consisting of few universal diagnostic parameters is reported continuously and more detailed reports for short time intervals are issued on demand. Every occurrence or suspicion of any abnormality is reported with a more detailed representation of less processed data accordingly to the limitation of interpretation capacity by available resources. For difficult but rare events of short-time duration, the report includes a corresponding strip of raw signal. The machine description of the electrocardiogram contains all meta-information interfacing the non-assisted signal interpretation routines and the semi-automatic or manual diagnostic decision making. The flexible transmission formatting algorithm includes the result of our previous studies on cardiologist's relations. The report formatting procedure can be remotely reprogrammed upon request, because the goal of accurate reproduction of the expert reasoning process in a computer algorithm may be achieved by several approaches differing in the final data set contributing to 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.

$$d \in \mathbf{D}^n : d \to w_1 \cdot f_1(s) \otimes w_2 \cdot f_2(s) \otimes, \ldots, \otimes w_n \cdot f_n(s) \tag{1}$$

where f_i are heuristic signal transforms and w_i are corresponding weighting functions. This approach is commonly used in the ECG-dedicated hardware-embedded procedures for bedside interpretive recorders. 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 most of extracardiac variability sources. The matching coefficients R^n estimate how far the signal f could be explained by a given pattern set. The decomposition procedure starts with the best fitted pattern

$$f = (f, g_{\gamma 0})g_{\gamma 0} + R^1 f \tag{2}$$

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

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

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

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

The inverse of *unexplained 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 and 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. Some ECG-dedicated compression methods use pre-calculated rough estimate of local signal importance and the compression applies a non-uniform data loss strategy compromising high reduction rate at high fidelity of medical contents [2].

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.

$$\mathbf{V} = \{x_1 ... x_n\} \tag{5}$$

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 $G_A = (V_N, V_N, S_{out}, S_{in})$ accordingly to its syntactic and semantic rules.

$$X \rightarrow a, for X \in V_N \; and \; a \in V_N \cup V_T \tag{6}$$

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

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 [3], [11], [12].

4 Experimental Recorder for Cardiology - Design and Tests

A portable ECG recorder was developed in our Laboratory in collaboration with cardiology researchers. The design includes a limited subset of the prerequisites considered above for an adaptive remote monitoring device. The prototype meet the following criteria:

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

The recorder was designed for medical experiments. For the maximum flexibility and hardware-independence of the interpretation process, all the algorithm was implemented in a cooperating PDA. 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 with use of the popular *MicroConverter* [1] circuit integrating analog to digital converters, serial communication interfaces, internal flash memory and a '51-type processing kernel running at 2,7V. The design follows the general guidelines for real-time portable devices where the speed and the power management are both critical. Moreover, during all the development process the requirements of international standards for medical devices and electromagnetic compatibility [6], [7], [8] were carefully observed. The diagram of the recorder's circuitry is displayed in figure 2.

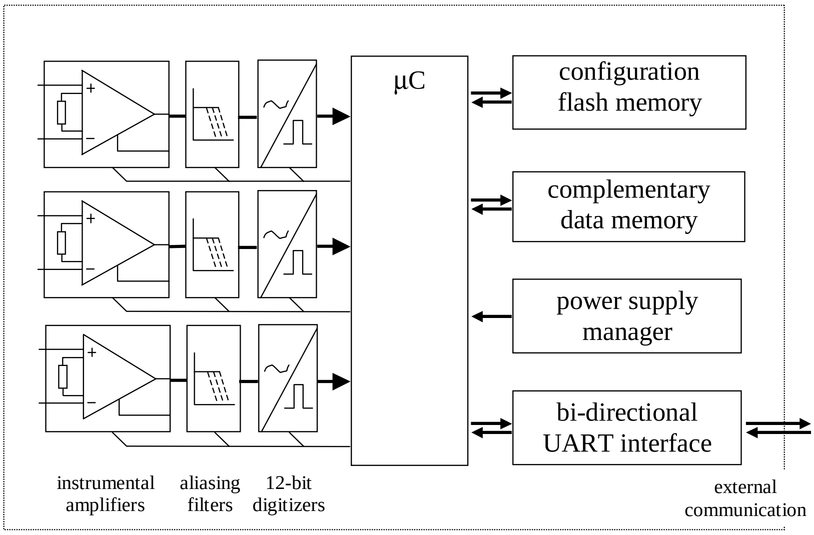

Fig. 2. The block diagram of the recorder's circuitry

The analog circuitry repeats the same architecture in each recording channel and uses micropower (230 μW) instrumental amplifiers with rail-to-rail input and output signal swing. The digitizers embedded in the *MicroConverter* chip guarantee 12-bits resolution. The effective input voltage range is adjustable from ±2mV to ±16mV in order to cover wide area of applications.

The use of the bi-directional UART interface enables a direct connection to a PDA computer or to a mobile telephone for independent wireless communication. The communication channel transfers the captured data and signals to the supervising server as well as textual messages and configuration data in the opposite direction.

The prototype features a complementary memory lasting for data storage (ca. 12 minutes) or data buffer depending on the recording mode or for a closed-loop buffer of user-defined length for the pre-trigger data. The internal non-volatile memory stores the recorder's configuration and maintains the device status, the data organization and other settings in case of power failure.

Extensive tests were performed in order to confirm the recorder's ability to deliver a medically meaningful signal representation. The electrical tests were performed in a specialized laboratory complying with TUV/ISO measurements standards. We applied typical testing procedure for ECG long-term recorders. Electrical tests of the transmission channel were limited to the electromagnetic compatibility (EMC) and interference immunity issues. Main results of these measurements are displayed in table 1.

Table 1. Selected results of recorders electrical tests

parameter	value	conditions
bandwidth	0.03 ÷ 100Hz	-3 dB
1 LSB linearity range	-1.87 ÷ 1.83 mV	2mV range
voltage noise (ref. to input)	8.3 μV	0.1 ÷ 10 Hz
CMRR	92 dB	DC ÷ 100 Hz (worst case)
channel crosstalk	-77 dB	DC ÷ 100 Hz (worst case)

First part of tests concerned the use of remote recorder in the independent transmission mode. The support of the following functions was found operating exactly as intended: 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; changing of the configuration memory contents over a GSM telephone. The complimentary set of embedded functions manage the recorder's operation in some unlucky situations. 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 server, however sudden power failure (battery disconnection) occurs too fast to be serviced correctly.

Second part of tests concerned the recorder's configuration with a PDA-based interpretation module. In this configuration the adaptivity is significantly extended and includes adjustment of all processing parameters, on-line modification of communication protocol and reconfiguration of processing routines architecture. The applied 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 static process management and communication control kernel and of a set of randomly-linked basic interpretation routines. Depending on the medical need, each routine implemented as a dynamic function library can be adjusted remotely with a vector of interpretation parameters, linked, unlinked or replaced by an alternative routine from the basic set or by the code provided by the supervising server (fig. 3).

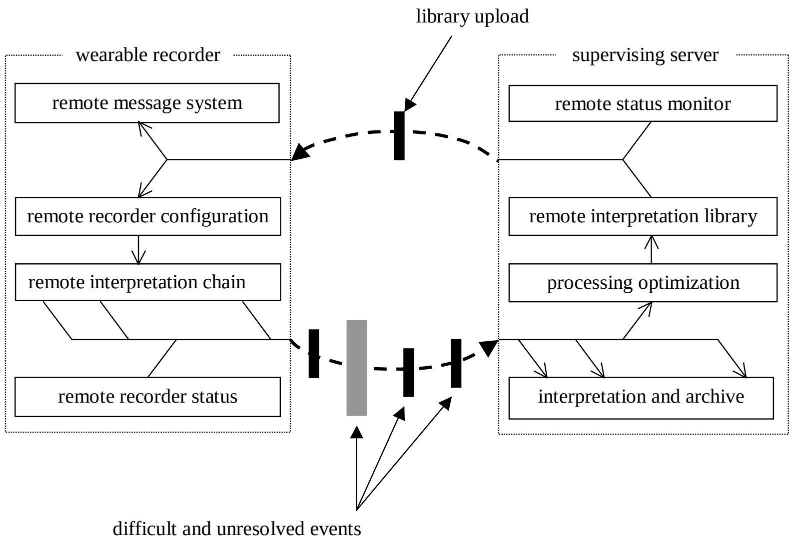

Fig. 3. Cooperation of the remote monitor and the supervising server aiming at optimization of diagnosis quality, transmission channel use and power consumption

5 Conclusions and Perspectives

The wireless physiological monitor for medical experiments was prototyped successfully and fulfills the intended application area in environmental cardiology. The recorder implements main principles of adaptivity and automatic management of teleinterpretation knowledge proposed in this paper. Its principal advantage is the flexibility of automated interpretation very close to the process performed by human medics. The area of application may be thus easily extended to open networks providing various medical surveillance services and having a considerable impact to the health care in the future. The novelty of our approach opens an unexploited area of medical telediagnostics. Certain new aspects are listed below, but many others may emerge in an everyday clinical practice:

- adaptive contents of patient status description varying from a general overview to a detailed report dependent on the result severity assessed by the software or on the extent of matching to a specific diagnostic goal,
- extended adjustability of monitoring and auto-alerting parameters, accordingly to the patient-specific signal, during the initial recording phase and anytime thereafter.
- real-time reconfiguration of interpretive intelligence in pursuit of any unexpected event and completion of the resources-limited remote interpretation by the supervising server software or with intervention of human experts.

Except for the laboratory testing, the recorder was already evaluated in two research projects aiming at muscle fatigue assessment and stress influence on domestic animals.

Although main scientific and engineering goals were achieved, the design and testing of the wearable diagnostic device revealed some issues for future consideration:

- improved compatibility of the interpretive software running on the remote device and on the supervising server,
- investigation of human interpretation process and required reporting format adaptation in context of previous diagnostic results and examination goals.
- supervising of several remote monitors and management of patient's data archive by a multi-threaded software.
- use of interactive communication channel for patient messages interchange (e.g. instructions in case of technical troubles, medical risk or medication intake).

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