Proceedings of the Eighth IASTED International Conference
SIGNAL AND IMAGE PROCESSING
August 14–16, 2006, Honolulu, Hawaii, USA
ISBN Hardcopy: 0-88986-583-3 / CD: 0-88986-585-X

ECG INTERPRETATION TASK SHARING RULES IN A DISTRIBUTED WEARABLE MONITORING SYSTEM

Piotr Augustyniak, Andrzej Izworski
AGH University of Science and Technology
30, Mickiewicza Ave., 30-059 Krakow
Poland
august@agh.edu.pl

ABSTRACT
This paper addresses the problem of interpretation task sharing between the central server and the remote wearable ECG recorder. Adaptive task sharing is presented as an alternative to the remote embedded and to the centralized interpretation commonly used today. The patient-dependent adaptation of the task sharing needs an extreme care, since it is advantageous only if based on medically justified rules. Three procedures are involved in optimization and control of the task sharing: human expert-derived diagnosis priority, statistic-based automatic assessment of result reliability and machine estimation of remote resources availability. The paper discusses these procedures and their impact to the distant interpretation performance and diagnosis reliability. Presented approach was designed and programmed in C++ language and consists an integral part of distributed architecture of the ECG interpretive software. The prototype implemented in the PDA-based ECG monitor and the stationary server enabled the assessment of the task sharing correctness for standard test signals. With the promising results achieved with the prototype we plan to transfer the task sharing rules to a multithreaded man-supervised server.

KEY WORDS
e-health, home care, pervasive ECG monitoring, distributed systems, ubiquitous computing,

1. Introduction

Recent progress of wireless communication technology justifies considering of the ubiquitous vital signs monitoring as the most safe and convenient solution for elderly people or home care patient independent life [1]-[6]. The wearable recorders allow full range of everyday activity while the embedded intelligence simulates well the continuous assistance of medical experts.

The early solutions of continuous cardiac monitoring used compactized versions of standard digital interpretive electrocardiographs or simple general purpose biosignal recorders sending raw data over a wireless channel [7]-[11]. The basic functionality of monitoring networks is achieved, however several drawbacks can easily be pointed out. The most conspicuous are: unnecessary computing, low reliability of remotely computed diagnoses and wireless channel overload.

Our alternative approach consists of using bi-directional communication channel and considering the ECG interpretation as distributed computing problem [12], [13]. This approach presented througout this paper requires task-sharing rules to be specified on medical and technical backgrounds.

As an introductory remark let us notice that a general purpose interpreting device, unlike a human expert, usually makes all available signal analyses [14]. A considerable reduction of the resources use may be achieved by avoiding unnecessary or redundant computation. Moreover, simple remote devices use a wideband transmission channel raising the monitoring costs and sophisticated wearable monitors embed a constant (i.e. non-modifiable) intelligence trying to interpret all events and fit to an average patient rather than to a particular patient disease.

The concept and prototype of adaptive remote recorder for seamless ECG monitoring developed in our laboratory since three years makes the following general assumptions:

– high reliability of the diagnostic outcome,
– optimization of resources use, particularly focused on the expensive wireless connection,
– use of bi-directional wireless channel,
– re-programmability and customization of the remote recorder
– asymmetrical interpretation task sharing between the remote device and the central server.

The last issue is discussed in this paper in details.

Every ECG interpretation software consists of a processing chain following given sequence of executed procedures. Procedures initiating the chain transform the raw signal to meta-parameters, while procedures terminating the chain issue diagnostic outcome on a basis of meta-parameters fed to their inputs. For the sake of supporting wide range of medical cases, the processing

chain conditionally branches into paths following some medically justified assumptions.
The statistics of procedures use and data flow in the ECG interpretation software from different independent manufacturers reveal three common rules:

- the data volume is reduced at subsequent interpretation stages,
- the simple procedures are commonly used whereas sophisticated and computationally complex procedures are used rarely,
- the interpretation reliability for common diseases is significantly higher than for very rare diseases.

Observing these remarks our concept assumes the interpretation process is adaptively distributed between the remote recorder and the central server (fig. 1). The task distribution is asymmetrical in two aspects:

- the resources of a remote recorder are limited and technical constrains have to be considered while planning task sharing rules,
- the diagnostic information flow is uni-directional, thus the remote recorder initiates the interpretation process while the central server completes it when necessary.

Recorder-only procedures:
General interfaces management,
resources management and monitoring
Signal acquisition and buffering
Signal quality assessment

Recorder or server procedures:
Recorder defaults (preloaded dll's):
QRS detection
Morphology classification
Wave limits detection
Arrhythmia detection

Recorder optionals (available as dll's):
ST-segment assessment for ischemia
QT-segment assessment
QT-dispersion
HRV time domain parameters
Pacemaker pulse detection and verification
Heart axis reconstruction

Server-only procedures:
Pacemaker mediated arrhythmia
Ventricular late potential detection
HRV frequency domain parameters
Heart Rate Turbulence
Respiration wave reconstruction

Fig. 1. Interpretation task allocation in distributed ECG monitoring system.

Various implementations imply individual approaches to the interpretation task sharing specifying the processes running on remote device, on central server or on either of these devices. The important point is that the procedures implemented for both platforms have to perform identically, regardless the hardware differences. Otherwise, the complementary task allocation or redundant signal re-interpretation for assessment of result reliability (see. 2.2) would produce ambiguous results.
It is worth a remark, that the asymmetrical task sharing is very advantageous at least in following aspects:

- the remote device performs easier and most common operations requiring less computational power and less susceptible to errors,
- the captured data stream is fairly reduced at the initial stages of interpretation in the recorder and the required wireless channel bandwidth is fairly low.

The task sharing in distributed ECG interpretation system is an important problem, since it influences the monitoring costs and diagnostic reliability. The compromise is pursued perpetually with consideration of human expert-derived diagnosis priority, statistic-based automatic assessment of result reliability and machine estimation of available remote resources.

2. Components of interpretation task sharing rules

2.1 Expert-derived diagnosis priority

It seems obvious, that for a human expert some diagnostic results are more important than others. However, the systematical research on the diagnostic statement hierarchy can hardly be found. For the purpose of building such priority list we studied the Cardiology Societies Standards and analyzed doctors' choice about the report contents in a series of clinical trials.
Many Standards issued by Cardiology Societies formally define the diagnostic path with conditional branches that direct the subsequent steps of ECG analysis depending on the results of precedent stages. Although different approaches were found in the literature, a rough common diagnostic path was estimated and re-arranged as a binary tree. Its nodes define medically justified conditions for selecting a particular way believed as optimal for the further ECG interpretation efficiency.

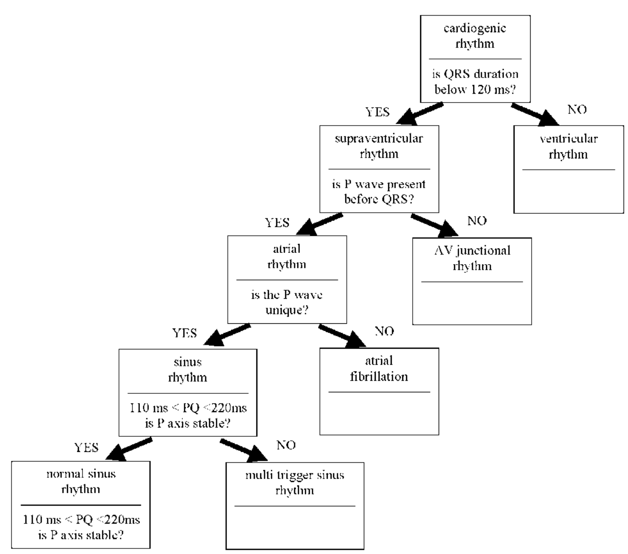

Fig. 2. Example of processing tree in the ECG rhythm classification

For the studies concerning doctors' choice on the report contents, we asked from a commercial ECG interpretation software manufacturer to replace the default selections of final report contents menu by a random proposal. Each time the interpretation is completed, all possible report items appear together on the screen randomly pre-selected and the doctor is prompted to include or exclude items to/from the report contents. The order of selection and the prefered items are memorized with the diagnostic outcome and thus after statistic processing of these data we had a clear knowledge about doctors' preferences in most common diseases.

2.2. Automatic assessment of result reliability

In a typical case, the ECG is completely interpreted by the remote device, and thus only the diagnostic results of minimum data volume are transmitted to the center. Unfortunately, the remote recorder resources are limited and occasionally the interpretation of altered signal may not be as reliable as required for medical diagnosis.
Two processes are proposed for continuous monitoring of remote interpretation reliability: random redundant signal re-interpretation and knowledge base search for similarity.
Redundant signal re-interpretation uses bi-directional transmission and begins with the raw signal request issued by the central server. The remote recorder does the interpretation independently and besides the diagnostic result returns the raw electrocardiogram as well. As the signal is coded into a large data packet of low priority it may reach the server with a significant delay. The requested signal is next interpreted by the server software thread and the results are compared to those received form the remote interpretation. Any difference is carefully analyzed, statistically processed and compared to the tolerance thresholds. Every outstanding value is a background for modification of the remote recorder interpretation software. This process requires additional load of the wireless channel and slightly increases the computational complexity assigned to the particular client. Therefore the redundant re-interpretation rate should not exceed the value of 1/20 packet frequency.
Knowledge base similarity check is much simpler for implementation and does not overload the transmission channel. Therefore it is performed for every data packet received. Each time a new packet arrives, the central server accesses the database for two reasons: verifying the consistency of the received data by comparing it to the most similar database record and estimating the trends of diagnostic parameters from changes observed in similar records. In order to reduce the database search, the compared data are prioritized by disease history, sex and fundamental ongoing findings (e.g. heart rate or rhythm type). In case the packet contains 'expected' data, no action is taken and the remote diagnostic results are considered reliable. In any suspicious case, often triggered by sudden nature of cardiac events, the server assumes that the remote interpretation failed and issues the raw signal request. Since the raw ECG is buffered in the remote recorder, the signal being background for suspicious data is retrieved, transmitted and then interpreted by the server for reference.

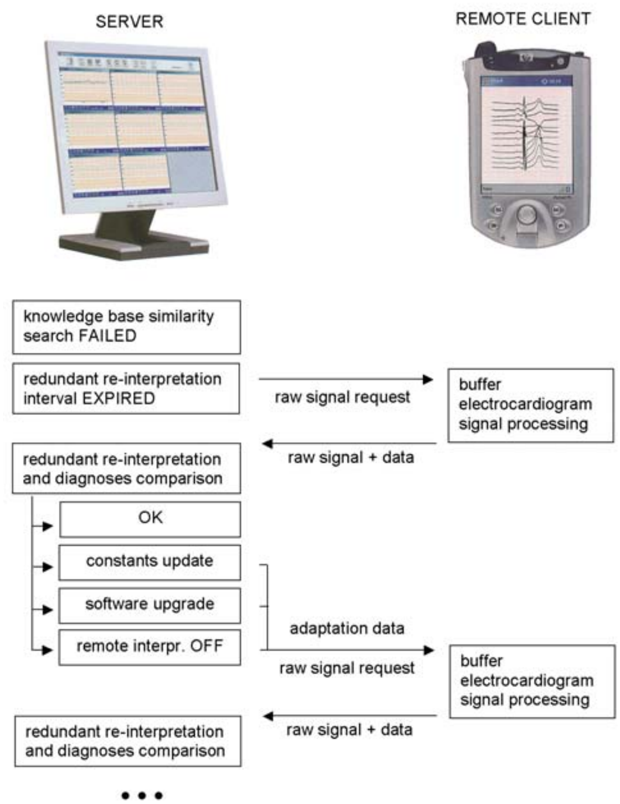

Fig. 3. Flow diagram of knowledge base similarity check and redundant signal re-interpretation for automatic result reliability assessment.

2.3 Estimation of available remote resources

The remote recording device is based on a PDA class computer running Windows CE operating system. During the monitoring process, execution of any third-party software is excluded in order to enable proper management of all available resources. The biggest part of system memory is allocated for the raw ECG buffer. Raw signal buffering is used for delayed signal transmission in case of central re-interpretation and for repeated remote interpretation each time the recorder software is modified. Second largest memory block is allocated for executable code of interpreting software. Since many interpreting modules are programmed as dynamically linked libraries (dll's), the size of program memory is variable and thus high functional flexibility is achieved at the price of constant resources monitoring.

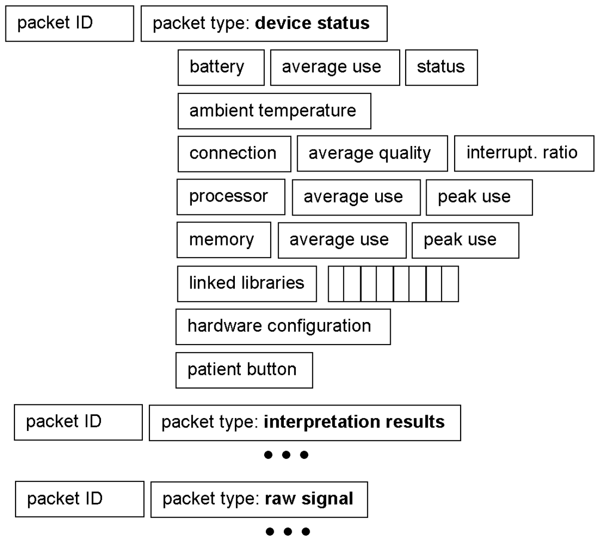

Fig. 4. Resources report format

The resources report included in the remote device status word is a mandatory part of every data packet. Whether the diagnostic packet rate may be set very low, there is an independent way to pool the monitor status on the server-issued request. The resources report contains few variables representing battery use and status, ambient temperature, connection quality, processor usage, memory allocation and codes of linked libraries. Reception of this information, is for the server a background for estimation of available resources and modification of remote interpreting software accordingly to the current diagnostic goal and the extent it was fulfilled by the recorder. In case of poor reliability or inconsistency found in automatic assessment diagnostic outcome (see 2.2.), the remote recorder software adaptivity provides a choice of four procedures up to the problem severity and available resources (tab. 1).

Table 1. Simplified decision matrix for the remote interpretive software adaptation

interpretation error severity	resources available memory+processing / transmission			
	+ / +	+ / –	– / +	– / –
low	CU	CU	CU	CU
intermediate	SU	SU	CI	SR
high	CI	SU	CI	SR

Abbreviations:
CU – calculation constants update
SU – software upgrade; linking supplementary interpretive library
CI – central interpretation; the remote interpretation is overwritten by the results issued by the server
SR – software replacement; unlinking an existent interpretive library of lower results priority and linking supplementary interpretive library
Note that CU, SU and SR always require remote re-interpretation of buffered ECG and a redundant central re-interpretation for automatic assessment of result reliability

The decision on remote interpretive software adaptation is always taken by the central server software. With use of the bi-directional wireless channel, the modifying data are sent to the remote device. The data exchange takes a considerable time (up to several seconds) thus the monitoring system response time may be insufficient for sudden cardiac events. However, thanks to signal buffering, the continuity of monitoring is maintained.

3. Results

The ECG interpretation task sharing rules were designed, programmed in C++ language and tested in a prototype implementation in the PDA-based ECG monitor and the stationary server for the set of standard test signals. The reference medical findings were known from the test signal database. However, the tests were focussed on the task sharing rules and thus the diagnostic correctness was of secondary importance. Several aspects were investigated during the test procedure:

- the convergence of remote recorder-issued diagnostic results to the server-computed results on the same signal after the remote calculation constants update.
- the correctness of software upgrade and replacement in technical and medical aspects,
- the delay since first detection of remote interpretation inaccuracy to the completion of remote recorder adaptation in case of calculation constants update, in case of software upgrade and in case of assignment of erroneous task to the server,
- the correctness of software replacement decisions in aspect of expert-derived diagnosis priority

3.1 Convergence of remote diagnostic results

The remote software update process is initiated if remote-issued diagnostic results differ from the server-calculated reference by more than a threshold defined accordingly to the diagnosis priority in four categories (tab. 2).

Table 2. Expert-derived diagnosis priority and the corresponding diagnostic result tolerance threshold.

category number	procedure example	relative value threshold [%]
1	QRS detection heart rate	2
2	wave limits detection ST-segment assessment for ischemia	5
3	morphology classification arrhythmia detection	10
4	heart axis reconstruction	20

In case the result after a single step is still out of the given tolerance margin, the decision on next constants update is made upon the new value is closer to the reference, and allow up to four consecutive update steps.

Table 3. Convergence of remote diagnostic results after the calculation constants update

calculation constants update steps	cumulative percentage	
	converging	non-converging
first	63,1	36,9
second	74,5	25,5
third	79,1	20,9
fourth	80,7	19,3

3.2 Correctness of software upgrade and replacement

In technical aspect, the correctness of software upgrade and replacement was measured by the percentage of cases where the upgrade causes resources violation (resources overestimation) and cases where the upgrade was possible but suspended due to resources underestimation. The later category also includes cases when software upgrade was possible, but the library replacement was done instead.

Table 4. Technical correctness of software upgrade and replacement

action	upgrade possible	upgrade impossible
upgrade performed	647 (75,5%)	27 (3,1%) resources overestimation
upgrade suspended or library replacement	62 (7,3%) resources underestimation	121 (14,1%)

In medical aspect, the correctness of software upgrade and replacement was measured by the percentage of cases for which the upgrade results the diagnostic parameters approaching to the reference values. The combination of software upgrade and immediate calculation constants update, although possible in a real application was excluded from tests. The overall diagnostic improvement is expressed by the diagnostic parameters error weighted by diagnosis priority.

Table 5. Medical correctness of software upgrade and replacement (only correct upgrade and replacement considered – see table 4)

action	diagnosis improvement	diagnosis degradation
software upgrade	643 (99,4%)	4 (0,6%)
software replacement	97 (80,2%)	24 (19,8%)

3.3 Delay of remote recorder adaptation

The values of the adaptation delay were measured with use of wireless GPRS connection. Estimation of the longest delay is crucial for the design of remote recorder data buffer length and for the assessment of non-response time in case a cardiac event occurs during system reconfiguration.

Table 6. Delay to the remote recorder adaptation in seconds

action	longest delay	average delay	standard deviation
calculation constants update	17,1[a)]	4,3	1,3
software upgrade	6.0	4,4	1,5
software replacement	5,9	4,5	1,5
relocation the erroneous task to the server [b)]	2,4	0,8	0,3

a) four steps of calculation constants update
b) to the remote device software modification

3.4 Correctness of software replacement decisions

The correctness of software replacement decisions from medical viewpoint is summarized in the last row of table 5. Since software replacement favorites certain procedures over the others, the diagnostic parameters error was weighted by diagnostic priority values. In over 80% of cases the software replacement resulted in diagnostic result improvement.

4. Conclusion

The software adaptation and customization of a remote interpretive ECG recorder during the seamless monitoring made on a background of automated diagnosis verification and resources assessment is a complicated and responsible task. Particular procedures were programmed, implemented and tested separately. The software adjustment and test process not described in this paper lasted for 14 months. The total of 2751 one hour 12-leads ECG records were processed in the system in real time. In case of 857 records (31,2%) the software adaptation was required, next 86 records (3,1%) were found too complicated and interpreted by the server software. Among the software adaptation attempts, 768 (89,6%) were correct, while the remaining 10,4 % failed due to incorrect estimation of available resources. The overestimation of resources, resulting in the operating system crash and thus monitoring discontinuity occurred in 27 (0,1%) cases. Future versions of remote recorders should support the data buffer protection that allows re-interpretation of the ECG even after the system restart.

Thanks to adaptive remote recorders, the wireless pervasive cardiovascular monitoring networks offer new opportunities, but also new challenges. The adaptivity itself does not guarantee the improvement, it has to be justified by medical procedures and has to consider technical constraints. The adaptivity is realized by remote software modification resulting in flexible sharing of interpretation tasks between the remote recorder and the central server. Our approach combines advantages of two solutions being in use today:

- The transmission channel load is nearly as low as when remote interpretation was used
- The interpretation reliability and difficult cases resolving resemble a centralized interpretation architecture, not excluding a human expert assistance.

In authors' opinion, a significant progress was made with formulating the ECG interpretation task sharing rules, implementing and testing them as a software controlling the distributed monitoring system. The test results show considerable improvement of diagnosis quality in comparison with a 'static' software, however for further development the analysis of outliers is more interesting than the global statistics. The rules just established have to pass extensive clinical tests before the use, and at present may not be applicable yet. More important than the rules themselves may be the description of our investigation for them and with this paper we believe to provoke a discussion and to inspire other scientists to express their ideas. The authors believe that with this research a new investigation direction opens. The history of biomedical engineering shows that the automatic ECG interpretation software was developed to follow a human expert reasoning. Today, multiple intelligent devices collaborate together and thus are expected to follow human experts collaboration rather than to emulate multiple independent doctors.

Acknowledgements

Scientific work supported by the Polish State Committee for Scientific Research resources in years 2004-2007 as a research project No. 3 T11E 00127.

References

[1] S. Puzzuoli, P. Marcheschi, A.M. Bianchi, M.O. Mendez Garcia, D. De Rossi, L. Landini, Remote Transmission and Analysis of Signals from Wearable Devices in Sleep Disorders Evaluation *Computers in Cardiology* 2005;32:53−56.

[2] S. Korsakas, A. Vainoras, V. Miskinis, R. Ruseckas, V. Jurkonis, R. Jurkoniene, K. Berskiene, L. Siupsinskas, V. Marozas, Electrocardiosignals and Motion Signals Telemonitoring and Analysis System for Sportsmen *Computers in Cardiology* 2005;32:363−366.

[3] R. Bousseljot, D. Kreiseler, Telemetric ECG Evaluation Using Einthoven-Leads *Computers in Cardiology* 2005;32:57−60.

[4] R. González, D. Jiménez, O. Vargas, WalkECG: A Mobile Cardiac Care Device *Computers in Cardiology* 2005;32:371−374.

[5] G. Balasz, G. Kozmann, I. Vassanyi, Intelligent Cardiac Telemonitoring System *Computers in Cardiology* 2004;31:745−748.

[6] M. Oefinger, G.B. Moody, M. Krieger, R.G. Mark System for Remote Multi-Channel Real-Time Monitoring of ECG via the Internet *Computers in Cardiology* 2004;31:753−756

[7] D. Télisson, J. Fayn, P. Rubel, Design of a Tele-Expertise Architecture Adapted to Pervasive Multi-Actor Environments. Application to eCardiology *Computers in Cardiology* 2004;31:749−752.

[8] J. Fayn, C. Ghedira, D. Telisson, H. Atoui, J. Placide, L. Simon-Chautemps, P. Chevalier, P. Rubel, Towards New Integrated Information and Communication Infrastructures in E-Health. Examples from Cardiology *Computers in Cardiology* 2003;30:113−116.

[9] R. Bousseljot, U. Grieger, D. Kreiseler, L. Schmitz, H. Koch, S. Beckmann, C. Bethge, H. von Nettelhorst, K. Stangl, Telemetric ECG Diagnosis Follow-Up *Computers in Cardiology* 2003;30:121−124.

[10] F. Chiarugi, D. Trypakis, V. Kontogiannis, P.J. Lees, C.E. Chronaki, M. Zeaki, N. Giannakoudakis, D. Vourvahakis, M. Tsiknakis, S.C. Orphanoudakis, Continuous ECG Monitoring in the Management of Pre-Hospital Health Emergencies *Computers in Cardiology* 2003;30:205−208.

[11] S. Khoór, J. Nieberl, K. Fügedi, E. Kail, Internet-Based, GPRS, Long-Term ECG Monitoring and Non-Linear Heart-Rate Analysis for Cardiovascular Telemedicine Management *Computers in Cardiology* 2003;30:209−212.

[12] P. Augustyniak, Implementing the ECG Interpretation Procedure in a Distributed Wearable Computer Systems *Folia Cardiologica* 12(D), 2005

[13] P. Augustyniak, Content-Adaptive Signal and Data in Pervasive Cardiac Monitoring Proc. *Computers in Cardiology* 2005;32:825-828

[14] P. W. Macfarlane, B. Devine, E. Clark, The University of Glasgow (Uni-G) ECG Analysis Program *Computers in Cardiology* 2005;32:451−454.