Quality-Driven Continuous Adaptiation of ECG Interpretation in a Distributed Surveillance System

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Summary. Principal rules defining the adaptation of ECG interpretation software in a distributed surveillance network are presented in this paper. Thanks to the pervasive access to wireless digital communication services, the intelligent monitoring networks automatically solve difficult medical cases thanks to the auto-adaptation of data interpretation and transmission to the variable patient status and technical constrains. The foundation of this innovative approach is the use of selected diagnostic parameters in a loopback modifying the running interpretive software. The auto adaptive process maximizes the general estimate of patient description quality aggregating the divergence values of particular parameters modulated by the medical relevance factor dependent on the status of patient. Our approach is motivated by the outcomes from the research on human experts behavior, statistics of the procedures reliability and usage as well as tests in a prototype client-server application. The tests yielded very promising results: the convergence of the remotely computed diagnostic outcome was achieved in over 80% of software adaptation attempts. Comparing to the rigid reporting mode, avoiding unnecessary computation extends the autonomy time by 65% and the transmission channel occupation was reduced by 3,1 to 5,6 times

1 Introduction

Thanks to the wide accessibility of wearable computers and wireless digital communication, distant diagnostic tools for cardiology are already commercialized with success [6] [14]. The advantages of this technique are usually stressed in context of cardiovascular out-hospital patients [9] [11] [13]. Recent reports show that it has a much larger impact on the quality of live [18] [23]. Very similar from a technological viewpoint are applications for a seamless monitoring of vital signs from sportsmen, elderly people living on their own or members of services exposed to danger. The artificial intelligence embedded in wearable recorders simulates well the continuous assistance of medical experts without imposing limits on the everyday activity or mobility range.

A conventional star-shaped topology is usually applied in the surveillance networks. The management is performed by the central server which cooperates with several remote wearable recording devices over a digital data link. Two approaches to the automatic signal interpretation, currently represented in marketed systems, employ either the transmission of raw signal to the center or the signal processing embedded in the remote device. The first method involves high cost of telecommunication service paid for the amount of the data sent. In the case of the second method, the limitation of the quality and reliability is implied by a compromise between the computational power and the energy consumption.

Our approach postulates the interpretation task sharing between the remote recorder and the central server. This process is flexible and automatically controlled by the central server via bi-directional digital wireless transmission channel. The interpretation of the recorded ECG signal and the adaptivity of diagnostic report content are driven by multicriterial optimization including following aspects:

- Assessment of the reliability of remote interpretation with consideration of the received diagnostic data consistency and with the reference to redundant interpretation results computed by the central server from a copy of raw ECG signal occasionally pulled from the remote recorder.
- The evaluation of the patient status and projection of the most probable further diagnostic goal made on a background of human experts guidelines, preference factors and behavior statistic studies.
- The estimation of the remote resources availability such as battery status, CPU workload, memory usage and wireless link quality.

The distributed process of ECG interpretation is asymmetric. It is always initiated in the remote device in consequence of signal acquisition and continued as far as necessary and possible. Technical limitations of the resources available from a remote recorder, causing certain interpretation tasks to be too difficult for such a small battery-operated wearable device, are compensated by the complementary interpretation thread running in parallel on the server. The server collects medical data at various possible processing stages ranging from a raw ECG signal to a full diagnostic outcome. Consequently, it continues the interpretation towards the final verdict and helps to clarify ambiguous or remotely unresolved records. The adaptation of remote interpretation process is achieved in real time with the use of diagnostically-oriented libraries of subroutines. The selected functions are uploaded from the repository managed by the supervising central server [26] and dynamically linked with the running software. The adaptation is performed automatically, but occasionally, in critical cases, it is supervised by a human expert.

Three innovative concepts were a background for our interdisciplinary research:

- The application of medical results and statistics concerning the human experts behavior to the modification of the ECG interpretation process.

- The use of wireless feedback and dynamically linked libraries for modification of the interpretation software in the run. The feedback transmits control data, executable code of software libraries as well as messages to the patient.
- The use of seamless optimization of the processing, which implies the flexibility of data transmission format.

The idea of a distributed ECG interpretation assumes the application of human experts skills in the signal interpretation and rules of knowledge exchange. Studies carried out within the framework of presented research included:

- analysis of human experts behavior and their mutual relations,
- research on visual ECG trace conspicuity and scanpath-based identification of interpretation strategies in human [3], [4],
- procedure reliability and usage statistics, processing error propagation studies [24], [25] and others.

This paper presents first the principal aspects of adaptivity: interpretation procedures optimization, flexible reporting format and non-uniform sampling of the ECG signal. In the second part, main adaptation management procedures are explained: implementation of expert-derived diagnosis priority, automatic assessment of result reliability and estimation of available remote resources. Results of the first prototype adaptivity test, the discussion and considerations for further research close the paper.

2 Principal adaptivity aspects

2.1 Modifications of processing parameters

The ECG interpretation algorithms performs detection and recognition processes based on heuristically determined values of factors and thresholds. In a rigid architecture software they are often referred as constants, because their values are not modified in course of processing [16]. Typical examples are normal-abnormal limits depending on sex, race or medication. The modification of ECG interpretation software is possible by setting conditional rules of adjustment for these "constants" values in particular procedures. The advantage of this method is a very little amount of data necessary to be sent from the supervising center to the remote recorder, so changes in the software are applied immediately. Due to limited influence on the signal processing, the modification of parameters is applicable rather to the recorder customization than to the radical adaptation of its functionality.

2.2 Rearrangement of the processing chain

The architecture of a typical ECG interpreting software is designed with the aim of issuing an universal diagnostic outcome. Specialized recorders for exercise test or Holter monitoring often use an alternative application-specific processing chain [15], [12], [20], [22], [8], [10], [19]. Considering the constraints of computational resources in a remote wearable recorder [21], the universal processing has to be based on average quality procedures. Such universal solutions are outperformed by task-oriented routines in a dynamically modified processing chain. Consequently, our first step towards the agile implementation was the detailed analysis of data flow, in particular data stream reduction at subsequent stages of the interpretation process and cumulation of the processing error. This analysis yielded a new software processing architecture (fig. 1) composed of mandatory basic procedures and facultative specialized libraries of functions.

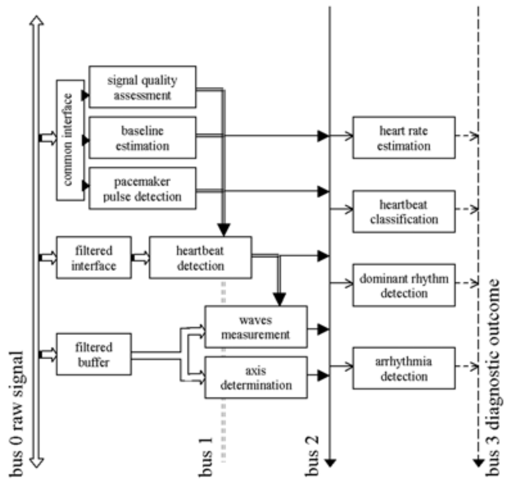

Fig. 1. The architecture of remote ECG recorder interpretation optimized for the data flow and processing error propagation

The proposed architecture offers following advantages:

- Defines mandatory and optional procedures and their reciprocal dependences,
- Minimizes processing error propagation through the interpretation chain,
- Allows considerable reduction of data stream on early stages of the interpretation process.

All the ECG interpretation procedures were classified to one of the following categories:

- Recorder-only procedures.
- Recorder defaults (preloaded dll's)
- Recorder optionals (downloadable dll's)
- Server-only procedures

The range of ECG interpretation modifications is determined by the contents of two middle categories. All these subroutines are compiled as dynamically linked libraries for two platforms: the remote recorder and the server. Requirements concerning simultaneously linked libraries and intermediate results that must be available in a compatible format for both platforms for correct processing are defined by a global cross-dependence table.

2.3 Report contents and frequency adaptation

Inside the ECG interpretation process, the medical information is represented in various data forms including signals, meta-data and final diagnostic parameters. Transmission of the data at various processing stages is therefore an intrinsic necessity of the distributed software architecture with adaptive task sharing [5]. The flexible communication format contains mandatory data description fields and optional data containers of variable size (fig. 2). For future extensions, it also provides a support for various data types (e.g. patient communications, global positioning coordinates etc.). The modifiable communication protocol is very useful for optimization of wireless channel use and helps maintaining the monitoring costs at a commonly acceptable level. Basic interpretation results are usually delivered for all the monitoring time and more detailed reports are occasionally issued for short time intervals. The delivery of detailed reports can be initiated by the server or by the remote recorder in case of occurrence or suspicion of any event. The report includes interpretation results and all the data required for their verification. It may also include a corresponding strip of raw ECG signal. The processing and reporting modifications are based on the implementation of rules derived in results of cardiologist's behavior analysis.

The temporal variability significantly differs for particular diagnostic parameters. The reporting frequency, considered as a minimum update rate satisfying the Shannon theorem for cardiac series, ranges from 3 Hz (once per a heart beat) for the heart rate (HR) to 0,0033 Hz (once per a 5-minutes strip) for the ST-segment depression. The variability statistics studied in a short-time context of abnormal events show increased probability of further variations. Consequently, the frequency of patient status sampling is determined individually considering the past and present values of each parameter. The report format flexibility supports the transmission of each diagnostic parameter with its appropriate sampling interval. In the case the mid-point samples need to be estimated (e.g. for comparizon with another data set), irregularly sampled data streams are interpolated by the recipient. The supervising server controls the reporting frequency independently for each co-operating remote

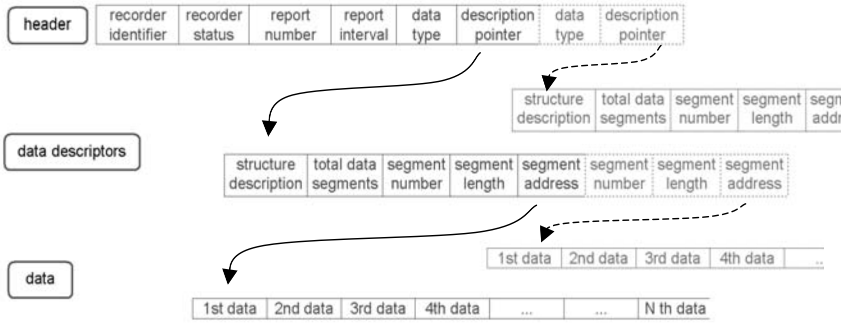

Fig. 2. Data communication format; mandatory fields are bordered by the solid line, optional fields are bordered by the dash line

recorder. Diagnostic reports are delivered with the frequency determined by the server in the context of previous diagnostic data. Reports accidentaly missing (e.g. due to communication failures) are easily detected by the recipient and re-transmitted. In the case of difficult signals, whose interpretation exceeds the capacity of the remote recorder, the raw signal is appended to the report. This allows the complementary processing thread running on the server to complete the ECG interpretation. Once the server determines the patient status, new remote interpretation tasks and reporting interval are accordingly imposed to the remote recorder over the wireless feedback. In very rare cases, the interpretation requirements exceed the availabile resources in the remote recorder. In such case the recorder calculates only basic diagnostic parameters (e.g. heart rate) in real time. The report is sent continuously and contains the raw signal, so the whole interpretation is performed by the server thread. The diagnostic outcome is validated in order to determine whether the patient status allows for returning to the remote interpretation mode. Figure 3 summarizes all modes of reporting frequency control.

2.4 Expert-derived diagnosis priority

The automatic management of interpretation task sharing directly influences the monitoring costs and diagnostic reliability. Implementation-dependent approaches specify the processes running on the remote recorder, on the central server or shared between these devices. For the last category, task sharing rules define the medically-derived conditions for processing adaptation and algorithms for automatic data verification. Diagnostic interpretation flow charts, specified in standards and professional guidelines, usually have a form of path with conditional branches. These expresses the dependency of subsequent ECG analysis steps of precedent stages' results. Studying different approaches found in the literature, we found useful to transform a common

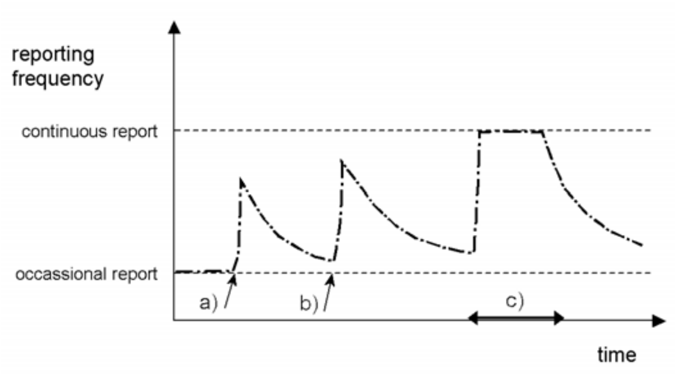

Fig. 3. Examples of reporting frequency control a) and b) - pathological ECG interpreted remotely, c) - unexpected event causing raw signal transmission and server-side interpretation

diagnostic path to a binary tree. Its nodes define medically-justified conditions where an automatic choice is made for the most appropriate way of further ECG interpretation.

Thanks to a functional modification of the prototyped ECG interpretation software we carried out experimental studies concerning doctors preferences about the contents of ECG diagnostic report. In the selection window, displaying the proposal of final report contents, the default layout was replaced by randomly ordered and randomly pre-selected items. Once the interpretation is completed, the human expert had to select or deselect results he or she wish to include in the printed and saved report. The selected items and the order in which a doctor made the choice were memorized with the diagnostic outcome. Finally, the statistical review of these data in context of 14 most common diseases revealed the knowledge about expected doctors preferences. These studies confirm and quantify the common, but poorly documented belief, that depending on the suspected disease, some diagnostic results are more important than others for a human expert. Moreover, assuming that several common diseases may be reliably diagnosed in course of a fully automated process, our studies result in attributing each disease a hierarchical list of most expected diagnostic parameters and their maximal update interval. This relation allows for disease-dependent report modification, issued by the server as a command to adapt the remote interpretation and to update the data priority list.

3 Results

The prototype scale-limited implementation of a wireless monitoring network used the PDA-based adaptive ECG monitor and the stationary PC-based server with 100Mb static IP Internet connection and Linux OS. The tests were focused on the benefits expected from the processing and transmission adaptivity, and on the correctness of automatic decisions about the adaptivity and interpretation task sharing. The software provided options for selective disabling the adaptivity features. In all experiments we used 58 artificial signals originating from looped normal CSE records with inserts of pathological CSE records [27]. A multi-channel programmable generator reproduced signals of the total duration of 1-1.5 hour. The correct medical findings were known from the test signal database and used in the test result processing as references for diagnoses computed in the distributed architecture. The first group of tests was aimed at the comparizon of agile and rigid procedures implemented on the same hardware platform and at quantifying the advantages of the adaptive interpretation software over the methods being in use today. Two principal benefits are:

- Significant reduction of digital communication costs achieved with content-adaptive signal and data representation.
- Extension of the autonomy time due to avoiding unnecessary computation and data transmission.

With respect to the uniform regular reporting, our tests show significant reduction of transmitted data volume. This is the result of report content management (5.6 times in average), non-uniform signal sampling (3.1 times) and irregular reporting (2.6 times) driven by individual values of expected diagnostic parameters variability. The resulting benefit does not accumulate all these optimization aspects, because the opportunity for using of the last two appears occasionally. Besides the savings on transmitted data volume, the report content management offers an advantage of lower power dissipation achieved by avoiding unnecessary computation and data transmission. In consequence, the remote recorder battery life was extended in average by 65% comparing to the software with all optimization options disabled running on the same P-DA. The total of 2751 12-leads ECG records were processed in the prototyped system. Among them, 1808 records were correctly interpreted by the remote recorder 857 records (31,2%) needed software adaptation for the correct remote interpretation, and 86 records (3,1%) were assessed as too complicated for the remote interpretation. Among the software adaptation attempts 768 (89,6%) cases were correct, while the remaining 10,4% failed due to incorrect estimation of available remote resources. Resources overestimation resulting in the operating system crash and thus monitoring discontinuity occurred in 27 (1%) cases.

4 Discussion

A significant progress has been made with formulating ECG interpretation task sharing rules, and their implementation and validation as a software controlling the distributed monitoring system. The test results show considerable improvement of diagnosis quality in comparison with the rigid software, however for further development the detailed analysis of outliers is highly recommended. The newly proposed adaptive distributed processing combines advantages of methods widely spread today:

- The load of transmission channel is close to the values of remotely interpreting applications,
- The interpretation reliability is close to the values achieved in centralized interpretation architectures with an occasional human expert assistance.

The software adjustment and test process not described in this paper lasted for 14 months. Several unexpected problems emerged so far have to be considered before the common application in clinical practice. The most problematic issue is the compatibility of the interpretive software designed for two different platforms. The points where the interpretation could be taken over from the remote recorder and continued by the server require the server interpretation thread to follow the architecture of remote recorder software. The use of diagnostic results as arguments for processing-modifying functions looks interesting, but it should be more thoroughly investigated to reveal any unexpected system behavior and to predict the possible medical risk.

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