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MODELING THE ADAPTIVE TELEMEDICAL SYSTEM WITH CONTINUOUS DATA-DEPENDENT QUALITY CONTROL

Piotr Augustyniak

AGH University of Science and Technology, 30, Mickiewicza Ave. Krakow, Poland, august@agh.edu.pl

***Abstract* – This paper presents the computational modeling technique used to investigate the behavior of data-adaptive ECG interpretation system. The decision of interpretation process adjustment is based on present patient status, diagnostic goals and experimentally derived data relevance. The multidimensional adaptation and mutual relationships can hardly be expressed in a precise mathematical way, and thus results of modeling provide estimated system behavior at various level of complexity.**

Introduction

Telemedical systems are currently considered as very interesting applications because of their direct impact to the life quality. Actually, in the area of vital signs-based diagnoses and monitoring, the difference between the stationary or bedside [1-5] and the telemedical recorder [6-10] consists in just applying a wireless digital data link. In several developed countries the commercial offer of telemedical surveillance or home care include continuous distant interpretation of the electrocardiogram (ECG), respiration or blood saturation. In case of the ECG, however, conventional systems have to meet a compromise. The centralized signal interpretation involves significant costs of the data stream transmission, while the remote interpretation has low reliability in a wearable battery-operated recorder with limited resources. In that case no personalization or diagnosis-oriented processing is possible. Disregarding the patient status and diagnostic aims, the interpretation always uses rigid procedures based on averaged medical knowledge.

Our approach, presented in this paper, assumes the reprogrammability of the remote recorder and the adaptation of the signal interpretation process to several prioritized criteria of medical and technical nature [11]. The ECG interpretation is designed as a distributed process performed partially by separated thread on the supervising center and partially by the adaptive software of the remote recorder [12]. The digital wireless link is used in bi-directional mode for patient and device status reporting but also for control of the remote software, requests for adaptation of report contents and data priority and reloading of software libraries as necessary. This innovation assumes deep modulation of remote recorder functionality by the software and its main challenge is the simulation of continuous presence of cardiology experts without limitation of patient's mobility.

Since the approach is original, some of constraints and dependencies existing in such a distributed system are undefined. Besides of prototyping systems of limited functionality that reveals the feasibility of some ideas, mathematical modeling of the system behavior is a very interesting source of knowledge. The proposed system requires the use of new medical knowledge, already used in practice, but not formalized yet. Our request motivated the ongoing investigation of optimal patient description including priority and relevance of particular diagnostic parameters as dependent on the patient status. The development of technical issues is possible in parallel due to modeling of medical and technical dependencies at various levels of complexity. The models also reflects the hypotheses derived from analysis of cardiologist's behavior during the manual interpretation of the ECG, but not formally accepted as medical procedures. In the future, the medical investigation results will replace the modeled dependencies by their actual counterparts and the performance of the distributed system will be closer to human results.

The auto-adaptive surveillance system for cardiology, unlike its predecessors, uses a closed feedback loop modifying the performance of interpretation subroutines on the basis of recently calculated diagnostic results. As in the classical control theory, the issues of stability, data convergence and final result inaccuracy should be defined and solved in proposed system. Here again, modeling of complex dependencies in the system is an effective tool for detection of unwanted behavior and for estimation of its medical consequences. This aspect is also presented in this paper.

Materials and Methods

The idea of auto-adaptive ECG interpretation system

The basic unit of auto-adaptive surveillance system uses star topology and consists of three kinds of devices: supervising server (SS), remote recorder (RR) and wireless link (WL). Since patients supervised in parallel are independent, we can limit the consideration to a single RR, corresponding WL and a separate software thread run on SS. Each part has been described by a set of equations simplifying its behavior in the software adaptation process. Some functions are destined uniquely for the SS, some uniquely for the RR and some may be assigned to the RR or SS by the task sharing procedure (fig. 1). The randomly assignable procedures should have fully compatible versions despite of significant platform difference.

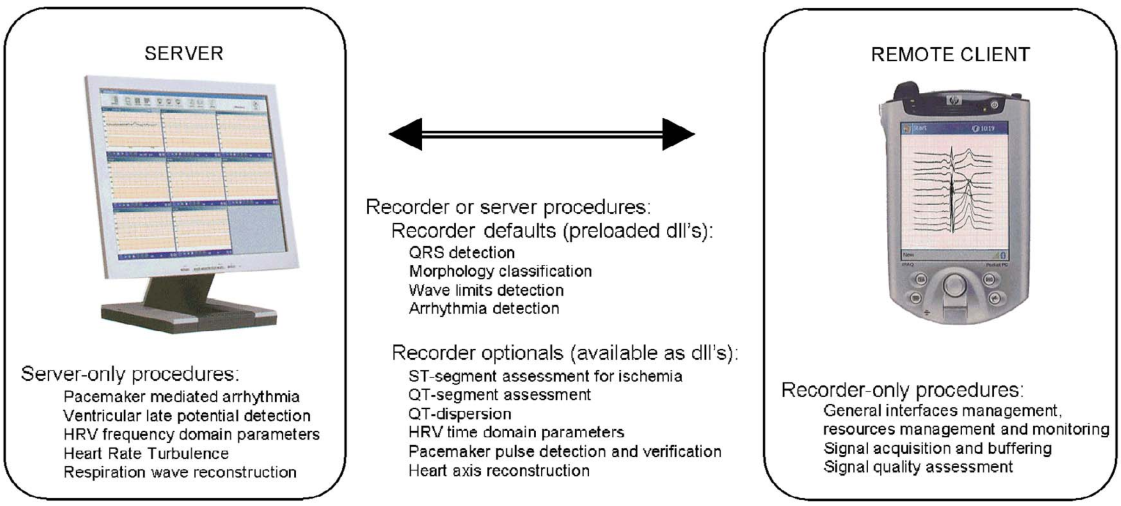

Fig.1 Task assignment in a distributed interpretive cardiac surveillance system

The SS is not only archiving data, but performs many important tasks including monitoring the result quality, estimating the optimal description of the patient status and management of the randomly assignable interpretation procedures. The RR buffers the raw ECG signal and is performing basic interpretation procedures necessary for the emergency detection. Further processing, report contents and frequency depend on the request received from the SS. It consists of signal and data transmission, loading and unloading specialized libraries of interpretation software and prioritized data-dependent reporting. The role of WL is limited to a passive transmission medium and described by transmission speed increasing with the reduction of data packet size, and transmission cost increasing proportionally with the data packet size.

Beyond splitting the interpretive software into two complementary parts implemented on different platforms, main challenge and important novelty of the project was the design of adaptation management procedures. Adaptation by itself does not imply the improvement of interpretation unless it has medical foundations and observe technical constraints, very tight in a wearable, battery operated recording device. The adaptation uses different input information:

1. Difference of actual and expected patient description; the difference is defined in terms of missing diagnostic parameters and parameters computed with threshold-exceeding inaccuracy weighted by their relevance with regard to the present patient's status.

2. Diagnostic procedure issuing results of threshold-exceeding inaccuracy, other procedures of the same purpose available in the repository and expected consequences in terms of diagnostic improvement and resources requirement.

3. Available resources of the remote recorder including battery, CPU and memory usage as well as quality of the wireless link.

The management of the automatic adaptation of interpretive software most benefit from the modeling of particular system components (fig. 2)

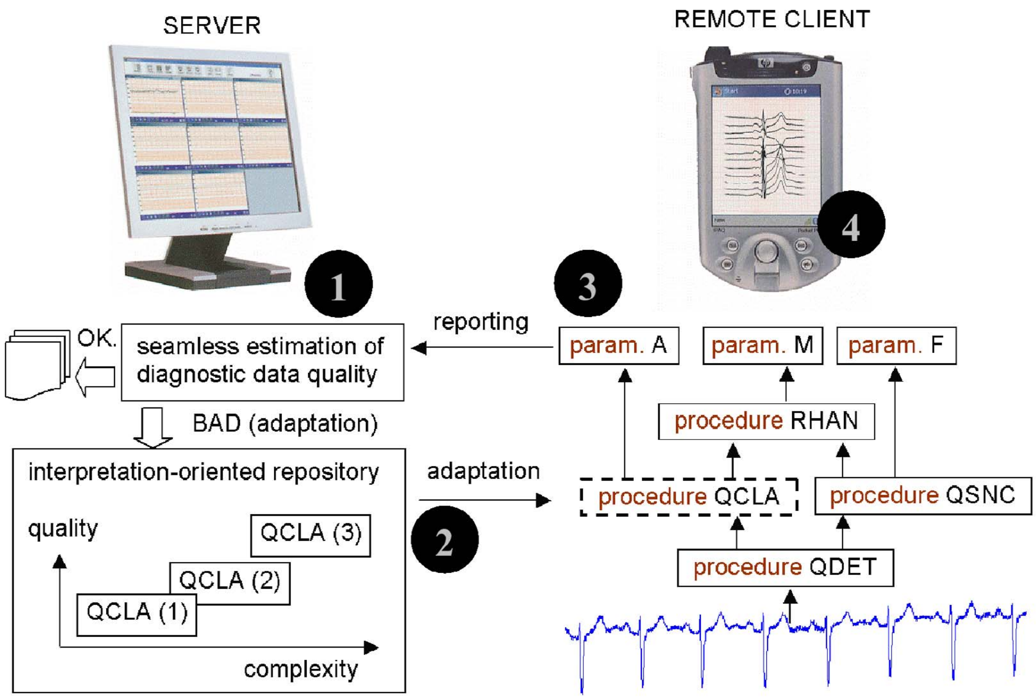

Fig.2 Crucial aspects of automatic adaptation of interpretive software developed with use of modeling: 1-detection of auto-adaptation necessity; 2-selection of appropriate subroutine from repository; 3-considering of data priority in the report; 4-estimation of resources availability

Due to the lack of reference for live-collected electrocardiogram, we assume the technically unlimited and expert-supervised software thread interpreting recorded signal strip on SS issues results of adequate reliability to be considered as absolute true values. The estimation of diagnostic result quality was based on the convergence of the remotely issued result to the reference locally computed by the SS on the same signal strip. This convergence was also used as a feedback for the management of assignable interpretation procedures. The management procedure is based on the assumption that the result reliability is proportional to the computational complexity and the use of remote resources. It is a common practice that the software manufacturers having several subroutines for calculation of a specific diagnostic parameter use them alternatively depending on system purpose (handheld recorders, interpretation workstations, real-time exercise monitors etc., fig. 3)

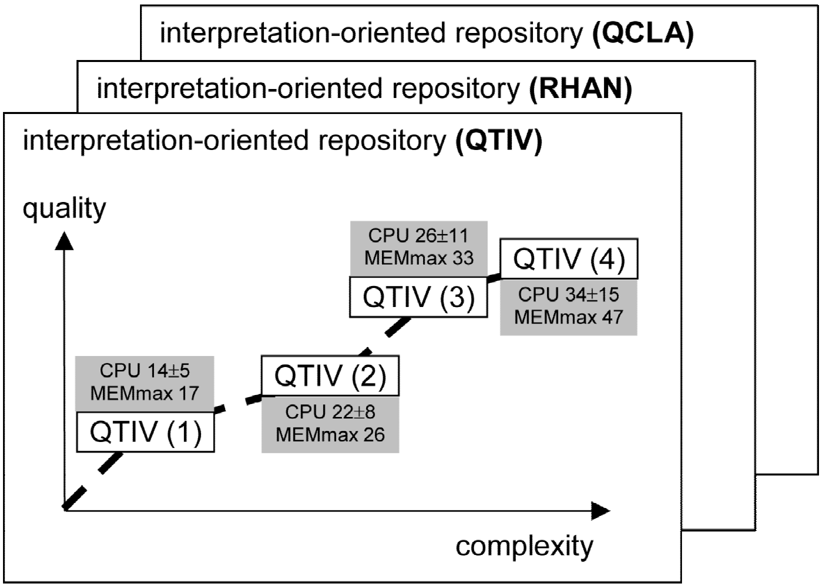

Fig.3 Structure of example repository of QT interval analysis procedures; each procedure is attributed by the statistical parameters of reliability, accuracy, expected memory usage and computation complexity.

Definitions of principal control parameters

The fixed interpretation software is usually tested for yielding the results within the tolerance margins specified on a physiological background. In adaptive software, more interesting is the dynamic aspect of adaptation and thus new parameters should be added to the global estimate of method performance.

Asymptotic accuracy Q is the absolute value of diagnostic error when the transient-evoked software adaptation is completed. Assuming no other transient is present in the subsequent signal it may be expressed as:

$$Q = \lim_{t \to \infty} \left| v(t) - v_0 \right| \tag{1}$$

where $v(t)$ is subsequent diagnostic outcome and v_0 is the absolute correct value.

Adaptation delay D is defined as the time period from the transient occurrence t_0 to the moment t_D when the diagnostic outcome altered by the interpreting software modification starts falling into a given tolerance margin ε around its final value.

$$D = t_D - t_0 : \forall t > t_D \ v(t) \in (v(\infty) - \varepsilon, v(\infty) + \varepsilon) \tag{2}$$

As a general estimate of **convergence quality**, we propose the value C being a weighted sum of relative error of 12 most frequently used diagnostic parameters (HR, rhythm estimate, wave lengths and axes etc.). Weighting coefficients are calculated on a background of the use statistics and their sum is normalized to 1.

$$C = \sum_{i=1}^{12} \Delta p_i \cdot w_i \text{ , where } \sum_{i=1}^{12} w_i = 1 \tag{3}$$

The convergence represents the correctness of decisions made by the management procedure about the interpretation processing chain. Taking the analogy from the theory of control, the software adaptation plays the role of a feedback correcting the diagnoses made automatically. If the software modification decisions are correct, the outcome altered by the interpreting software modification approaches to the true value, the modification request signal is removed in consequence of decreasing error and the system is stable. Incorrect decisions lead to the growth of diagnostic outcome error and imply even stronger request for modification. The outcome value may stabilize on an incorrect value or swing the measurement range in response to subsequent trials. In such case the system is unstable and the diagnostic outcome does not converge to the true value (fig. 4).

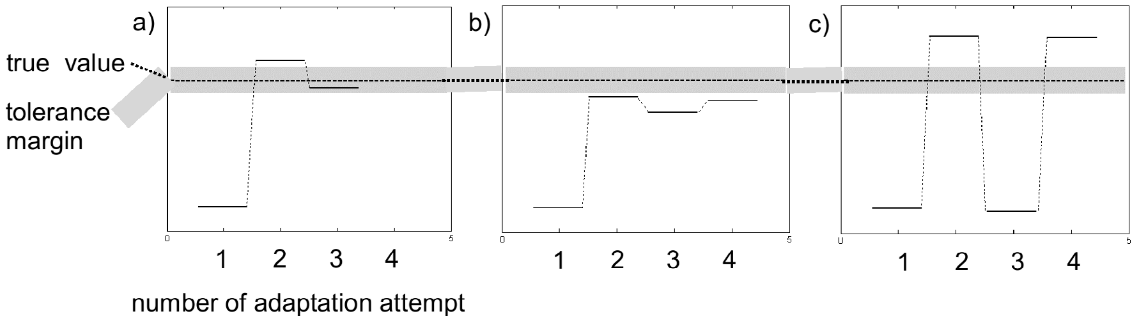

Fig.4 Convergence of the remotely derived diagnostic result with the reference calculated in an unrestricted system: a) converging and stable, adaptation ends in 2 iterations; b) stable but not converging - the data error still results in adaptation request; c) not stable and not converging

Uniformization and quality assessment of the diagnostic outcome

Since the adaptive interpretation systems allow non-uniform asynchronous updating of particular diagnostic parameters, direct comparison to the reference values is not possible. At each data point the reference results are available, the patient status has to be estimated from the irregular series of data issued by the adaptive system under test.

The diagnostic outcome of the adaptive interpretation being non-uniformly sampled time series $N_j(\{n, v(n)\})$ was first uniformized with use of the cubic spline interpolation [13] given by a continuous function:

$$S_i(x) = a_i + b_i(x - x_i) + c_i(x - x_i)^2 + d_i(x - x_i)^3 \quad (4)$$

$x \in [x_i, x_{i+1}]$, $i \in \{0, 1, \ldots, n-1\}$ best fitted to the time series N_j.

$$N'_j(m) = \sum_m S_i(x) \cdot \delta(x - mT) \quad (5)$$

The interpolation yielded the uniform representation of each parameter by sampling the $S_i(x)$ at the time points m corresponding to the results of the fixed software:

These points in turn were compared to the reference. The assessment of data conformance has to consider three quality factors:

- reference data accuracy,
- tested data inaccuracy at their individual sampling points,
- interpolation error.

Results

Adaptive interpretation methods are recently introduced and were not considered by worldwide-recognized standard databases such as MIT [14] or CSE [15]. Therefore, ECG test signals representing various pathologies and transients were artificially combined from custom-recorded signals.

The total of 2751 one hour 12-leads ECG records were processed off-line in the modeled system. 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 (fig. 5).

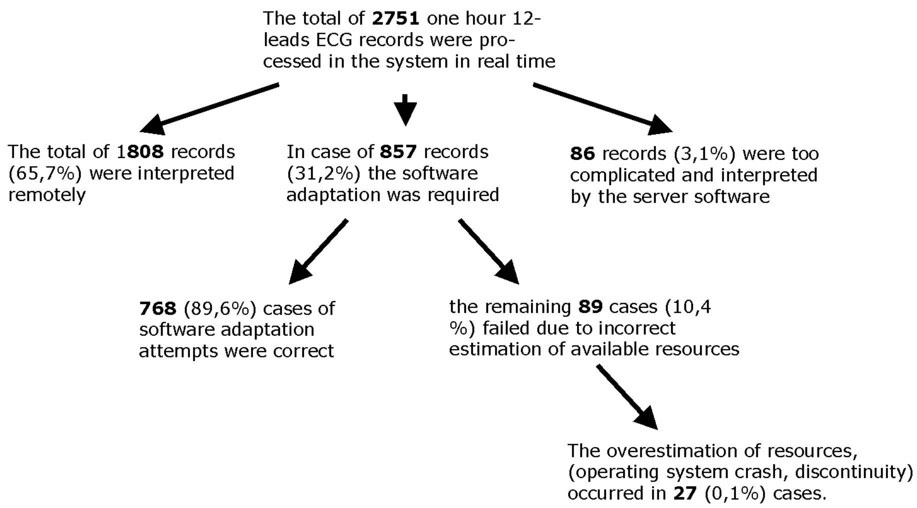

Fig.5 Diagram of adaptation correctness for the whole experiment

The convergence of diagnostic results was observed after the first modification step in 63,1% of software adaptation attempts. This fraction increased to 74,5%, to 79,1%, and to 80,7% after the second, the third, and the fourth modification steps respectively (tab.1).

Table 1 Results of remote diagnostic results convergence test after the consecutive steps of interpretation software modification

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

Discussion

The behavior of the adaptive telemedical system was modeled in order to study the influence of medical and technical dependencies to the diagnostic result quality. Some relationships had to be separately studied using various investigation methods from technical and medical domains as well as from the sociology. Despite of some assumptions simplifying complex dependencies between the system elements, medical contents of the signal and desired quality, the modeling contributed to several practical aspects. Principal examples are: formal relationship between the patient status and optimal subsequent diagnostic steps, or the concurrence between diagnostic procedures aiming at optimization the diagnostic quality in conditions of limited resources.

Modeling of principal technical and medical relationships also led to assessment of the system behavior in critical circumstances. In the complex-dependencies system the analytical estimation of convergence and stability conditions is not practical, hence modeling is a useful tool to assess the variability range of main system descriptors guaranteeing stability of main feedback loop. The consequences of non-stable system behavior were also studied: the adaptation failure ratio was 10,4% of attempts leading to degradation instead of improvement of diagnostic quality. The worst case were 27 records (0,1% of the total processed signal) in which the software modification attempt used incorrect estimate of available resources and led to memory violation ending up with remote recorder OS crash, and monitoring discontinuity.

The results of research on human strategy on perception and interpretation of the electrocardiogram and on human expert practice of information interchange and priority were considered as foundations of the automatic distributed interpretive system for continuous cardiac surveillance. In author’s opinion, this approach opens a new investigation direction towards systems replicating human experts collaboration rather than emulating multiple independent doctors. Its main advantage is that the biomedical engineering solutions may benefit from long history of medicine in optimizing the procedures and their interactions.

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