Telemonitoring system for complex telemedicine services

HARITON COSTIN[1], CRISTIAN ROTARIU[1] - BOGDAN DIONISIE[2] - ROXANA CIOFEA[2] - SORIN PUSCOCI[3]

[1]Faculty of Bioengineering, Iasi
[2]Faculty of Medicine, University of Medicine & Pharmacy “Gr.T.Popa”, Iasi, Romania
[3]National Institute of Studies and Researches in Communications, Bucharest, Romania

Abstract

In spite of decreased mortality, coronary artery disease still remains the leading cause of death almost all over the world. The existence of silent myocardial ischemia emphasizes the need for monitoring of the asymptotic patient. Extended patient monitoring during normal activity has become increasingly important as a standard preventive cardiological procedure for detection of cardiac arrhythmias, transient ischemic episodes and silent myocardial ischemia. Existing holter devices mostly record "24 hour activity" and then perform off-line record analysis, so they are not real-time.

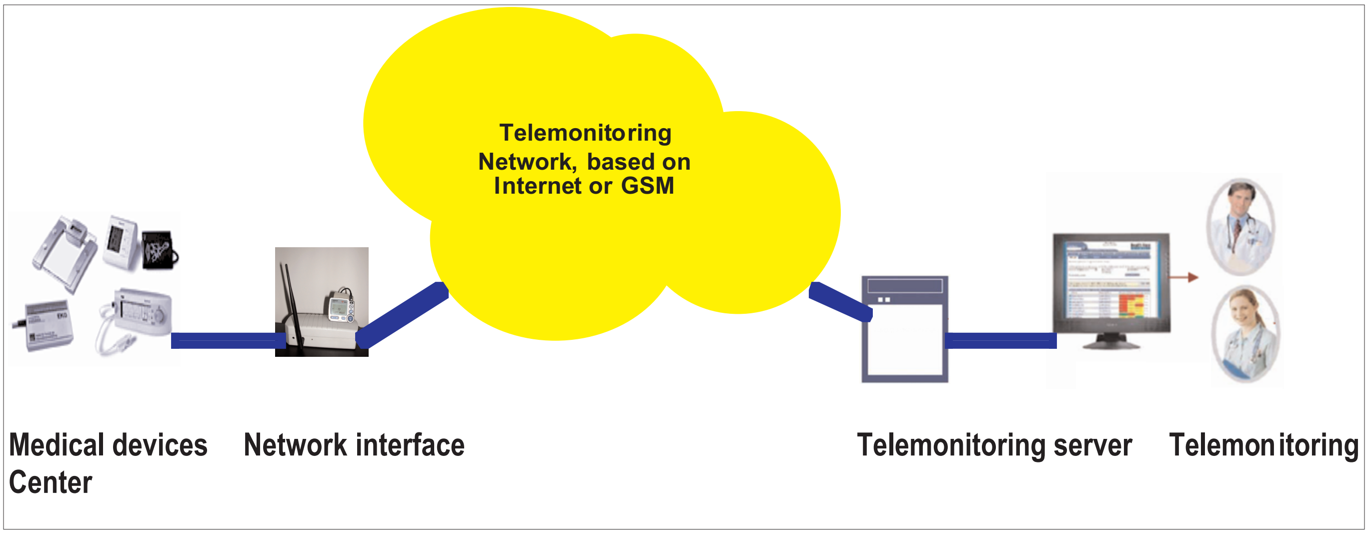
A telemonitoring network devoted to medical teleservices will enable the implementation of complex medical teleservices (teleconsulations, telemonitoring, homecare, urgency medicine, etc.) for a broader range of patients and medical professionals, mainly for family doctors and those people living in rural or isolated regions. Thus, a multimedia, scalable network, based on modern IT&C paradigms, will result. A first attempt for real-time electrocardiogram (ECG) acquisition, internet transmission and local analysis was already successfully done for patients monitoring.

1. Introduction

In spite of decreased mortality, coronary artery disease still remains the leading cause of death almost all over the world. The existence of silent myocardial ischemia emphasizes the need for monitoring of the asymptotic patient. Extended patient monitoring during normal activity has become increasingly important as a standard preventive cardiological procedure for detection of cardiac arrhythmias, transient ischemic episodes and silent myocardial ischemia. Existing holter devices mostly record "24 hour activity" and then perform off-line record analysis, so they are not real-time.

The task may also be achieved by telemedicine (enabling medical information-exchange as the support to distant-decision-making) and telemonitoring (enabling simultaneous distant-monitoring of a patient and his vital functions), both having many advantages over traditional practice. A telemonitoring network (Fig.1) devoted to medi-

Figure 1. Medical telemonitoring network - general structure



cal teleservices, will enable the implementation of complex medical teleservices for a broader range of patients and medical professionals, mainly for family doctors and those people living in rural or isolated regions.

Doctors can receive information that has a longer time span than a patient's normal stay in a hospital and this information has great long-term effects on home health care, including reduced expenses for health care. Physicians also have more accessibility to experts, allowing the physician to obtain information on diseases and provide the best health care available. Moreover, patients can thus save time, money and comfort.

As for patient monitoring, we propose the development of a flexible environment based on an acquisition module and an embedded system for real-time biosignals processing and transmission through Internet, GPRS/3G (mobile telephony) or radio networks already existing in each Romanian county.

2. Materials and methods

Our telemedicine module is based on an ECG / biosignal acquisition module and an embedded system, for real-time signal processing and transmission through Internet (Figure 2). The telemonitoring system is built by using custom developed hardware, open-source and application software.

For instance, the monitoring device could be used either for acquisition of anomalous ECG sequences (e.g. with arrhythmic events, ST segment deviation, etc.) and storing to a compact flash memory, as a warning device during normal activity, or an exercise stress test.

The hardware part is mainly based on biosignal amplifiers, an autocalibrating 16-bit analog I/O PC/104 module and an embedded Internet interface subsystem (MOPS/520). The device has as features: real-time ECG / biosignal acquisition and processing, executes the operator's commands, monitors the system's overall performance, acts in emergency situations, and aids the diagnostic.

In the following, we refer to the ECG acquisition, transmission and analysis application, already achieved by our team.

2.1. The ECG monitoring unit

The 12-leads ECG amplifier has for each channel a gain of 1000, is AC coupled and has a band limited to 0.05 - 150 Hz. The high common mode rejection (>100dB), high input impedance (>100 M?), the fully floating, isolated and defibrillation protected patient input are other features of the ECG amplifier.

The biosignal / ECG acquisition module is built around Diamond-MM-16-AT, a PC/104 expansion board offering a full feature set of data acquisition capabilities. It is used in any PC-compatible embedded computer with a PC/104 (ISA-bus) expansion connector. Its key features include: 16 single-ended /8 differential and autocalibrated inputs, 16-bit A/D resolution, 100 KHz maximum A/D sampling rate, programmable input ranges with maximum range of +/-10V, 4 optional analog outputs, user-programmable output ranges, 8 dedicated digital inputs and outputs, TTL compatible.

The Internet interface MOPS/520 is based on a microcontroller (32-bit Am5x86® CPU) that runs at clock speeds of 133 MHz. The system integrate the complete functionality of motherboard and include: CPU, system BIOS, up to 64 MB SDRAM, keyboard-controller, and real-time clock. Additional peripheral functions include: 4 serial, one parallel and 2 USB ports, IDE-hard disk interface, Ethernet access and CAN bus interface.

The used display is a LCD Seiko 628-G321 having dot pixels 320 x 240.

To make a simple software implementation, we choose to use the standard TCP/IP network protocol as the link provider, a scalable and economically feasible tool.

For DAQ applications in real-time, such as ours, one must use real time (RT), multitasking operating systems. A modern and economic solution is

Figure 2. The biosignal / ECG monitoring unit

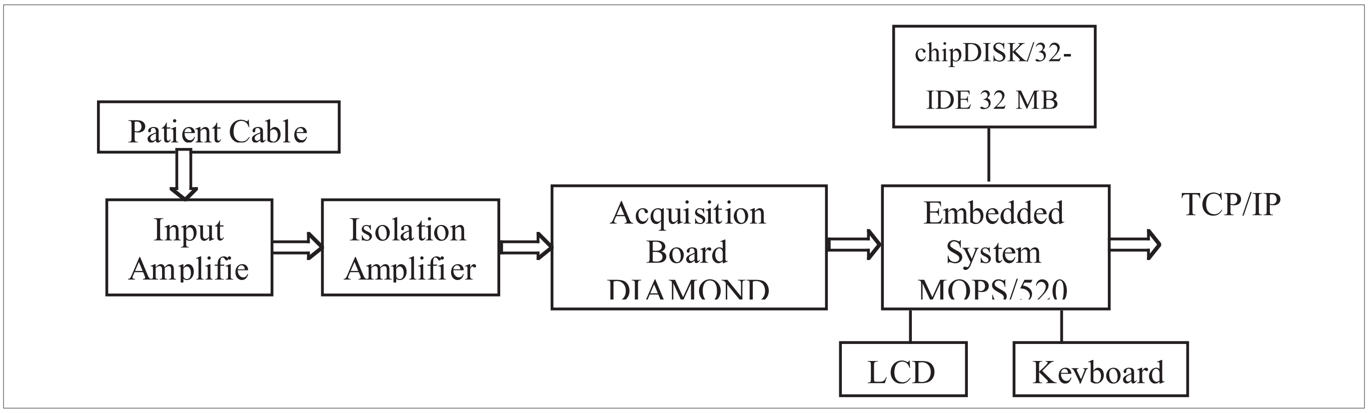


Figure 2. The biosignal / ECG monitoring unit

to choose an open source (free) RT-OS, such as RT-Linux. It is comprised of a small RT kernel which runs: (i) a C/C++ RT process at top priority, and (ii) the standard Linux kernel as a fully preemptable low priority task. High speed (low interrupt latency) and predictable timing are achieved by limiting the RT process to functions that are essential to real time.

2.2 ECG acquisition and processing

The most important ECG phases for morphological analysis are [1]:

- P-wave (representing contraction of the atria);
- QRS complex (representing contraction of the ventricles);
- T-wave (representing the recovery of the ventricles).

Typical ECG processing algorithms consist of the following steps:

a) Initialization - Used to determine initial signal and timing thresholds, positive/negative peak determination, automatic gain control, etc.

b) Filtering - This is performed first as analog filter on ECG amplifier board, and then as digital filter on acquisition board. In addition, a 50 Hz notch filter is used to reduce power line interference.

c) QRS complex detection - Reliable detection of R-peak is crucial for morphological analysis [3].

d) Baseline correction - Compensates for low-frequency ECG baseline drift.

e) ST segment detection [6].

2.3 Detection of QRS complexes

An adaptive thresholding technique with searchback serves as the primary method for QRS detection. The thresholds are based on the most recently detected signal and noise levels to react to changes in the patient's heart rate, as well as to signal and noise levels.

The QRS complex is the most significant feature in the ECG signal. Being characterized by sharp slopes, its duration is about 70 - 130 msec and its energy spectrum is mostly between 1 and 40 Hz. The input of the QRS detector is the digital ECG signal, sampled at 250 Hz and quantized with 12 bits/sample by A/D converter. The outputs are the limits of the QRS complex (QRSon and QRSoff), the location of the R wave, and location of the QRS peaks and notches (if they exist) of every beat (complex) [4][5]. The QRS detection algorithm consists of three steps: (1) coarse QRS limits determination; (2) peaks and notches determination, and (3) exact limits determination.

2.4 ST segment analysis

The ST-segment begins 40 milliseconds after the R-peak in the event the heart rate is more than 100 bpm, or 60 milliseconds after the R-peak otherwise. ST-segment has normally a predefined length of 160 milliseconds. The normal ST-segment template is constructed for each patient as the average of the first ten normal ST-segments. Baseline drift is compensated according to the slope between the isoelectric levels of the two beats. Standard annotated databases, such as the European ST-T Database and the MIT/BIH Arrhythmia Database, provide means for algorithm evaluation. In order to compute ST-segment length, a T wave detector must be implemented [2].

2.5 Data compression and error rate

Experiments revealed the necessity for data compression, in order to make a real-time ECG transmission. We used Linux Gzip programme, that yields about 2:1 average compression ratio by means of Lempel Ziv algorithm. Table 1 presents results obtained for a resolution of 12 bits/sample and 250 Hz sampling rate, for a 3 leads ECG. Thus, only 6 KB/s bit rate was enough for a real-time 3 leads ECG transmission !

The quality of data transmission was evaluated by computing PRD (percentage rate of distortion, a kind of root mean square), according to formula below. Table 2 shows a PRD level under 10%, a value accepted by clinicians for expressing a correct diagnosis.

Table 1 – Compression results for different sizes of TCP/IP buffer

Time (sec.)	Uncompressed size (bytes)	Compressed size (bytes)	Compression ratio (%)
10	60000	26592	55.7
9	54000	24125	55.3
8	48000	21681	54.9
7	42000	19027	54.8
6	36000	16541	54.1
5	30000	14061	53.2
4	24000	11502	52.2
3	18000	8904	50.7
2	12000	6123	49.2
1	6000	3205	47.0

Table 2. Error rate for different signals from MIT/BIH Arrhythmia Database

$$PRD = \sqrt{\frac{\sum_{n=1}^{N}[x(n)-\tilde{x}(n)]^2}{\sum_{n=1}^{N}x^2(n)}} \times 100$$

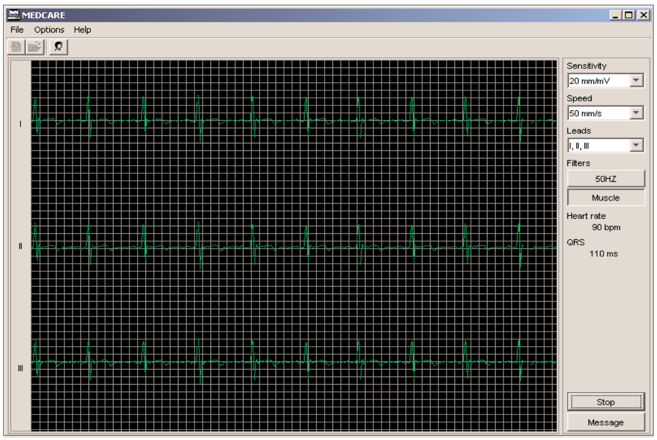
Nr.	Signal	Time (min)	PRD
1	No.100	1	6.2
		2	6.9
		3	7.2
2	No.201	1	6.3
		2	7.1
		3	7.9
3	No.107	1	2.1
		2	2.2
		3	2.4

3. Results and discussion

The whole telemonitoring system acts as a client-server application. The server module includes: a database server (using MySQL and open sources for server procedures, tables, restrictions coming from “client” application); an administration/control module that supervises general dataflow; an access/security module; a parameters configuration module a.s.o. Also, it uses HTML and HTTP to send most up to date information on heart care to clients.

The client module comprises the software working on the expert's computer. It is implemented by using Java applets and has the following facilities: GUI (Graphic User Interface) for ECG monitoring (Fig. 3); displays the patient’s ECG in real-time and the extracted ECG segments data; communicates the experts' commands (e.g. remote selection of the ECG lead) and medical decisions to the physician/patient. Also, some off - line processing algorithms are implemented, such as: advanced filtering; morphologic ECG analysis (intervals, amplitudes, electrical axes), average complexes with measurement reference markings; heart rate variability analysis, etc.

Figure 3. User interface for 3 leads ECG acquisition and analysis



Sensitivity
20 mm/mV
Speed
50 mm/s
Leads
I, II, III
Heart rate
90 bpm
QRS
110 ms

We designed and prototyped the monitoring unit for acquisition and real-time ECG processing, the software implementation for the Internet connectivity (the embedded TCP/IP subsystem), and the software for displaying ECG information on the medical doctor’s computer. The average reconstruction error of the ECG signal is about 4.6%. We also tested various algorithms for morphologic ECG analysis with good results on MIT/BIH Arrhythmia Database (Table 3).

Table 3. Morphological analysis of a 12 leads ECG

	Amplitude [µV]										Slope [µV/s]	Duration (ms)		
Lead	P+	P-	Q	R	S	ST20	ST60	ST80	T+	T-	ST	Q	R	S
I	171	0	-76	877	-130	-11	-3	-3	320	0	250	18	42	24
II	248	0	-125	1302	-205	-17	-8	-8	474	0	750	18	42	24
III	77	0	-49	425	-76	-6	-5	-5	154	0	500	12	44	24
aVR	0	-209	0	100	-192	14	5	5	0	-397	-500	-	18	42
aVL	47	0	0	227	-28	-3	1	1	84	0	0	-	38	26
aVF	163	0	-87	864	-140	-11	-6	-6	314	0	750	18	42	24
VI	80	0	-46	451	-72	-6	-3	-3	160	0	250	14	44	24
V2	168	0	-88	908	-143	-12	-5	-4	327	0	750	18	42	24
V3	242	0	-126	1283	-205	-17	-9	-7	463	0	750	18	42	24
V4	375	0	-185	1945	-303	-24	-9	-9	712	0	1000	18	42	24
V5	247	0	-124	1305	-204	-17	-8	-7	477	0	500	18	42	24
V6	182	0	-79	918	-133	-11	-4	-3	338	0	500	18	42	24

Heart Rate	60 bpm
P Dur.	90 ms
PR Int.	164 ms
QRS Dur	84 ms
QT Int.	372 ms
QTc Int.	372 ms
P Axis	43º
QRS Axis	43º
T Axis	44º

4. Summary and Conclusions

Real time personal ECG monitoring, as an important application of telemonitoring system, requires devices with high peak performance and low power consumption. High performance of RT-Linux development environment allows high speed multitasking procedures and real time signal processing. The proposed system could be used as a warning system (Holter-type) for monitoring of arrhythmia or ischemia during normal activity or physical exercise. In addition to monitoring of physiological signals, we plan to use the proposed environment for development of a high performance user interface. New user inputs, including correlates of the user's physiological and emotional states could significantly improve human-computer interface and interaction. Many algorithms for ECG analysis have already been tested with very good results. Moreover, our monitoring system is general enough to enable a wide range of biosignals monitoring and analysis, e.g. ECG, EEG, EMG a.s.o.

ECG tele-monitoring of a patient in real time, according to our project, has as main feature the analysis and transmission of the patients’ biosignals through the Internet, so that experts in cardiology could make the right diagnostic. So, by using the existing web-based and embedded technologies, the quality of medical decision in tele-healthcare and emergency medical services systems can be significantly improved.

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Acknowledgements. This work is supported by a grant from the Ministry of Education and Research, within CEEX programme (www.mct-excelenta.ro), contract No. 604/645/21.10.2005.