DOI 10.1007/s10527-015-9485-y
Biomedical Engineering, Vol. 49, No. 1, May, 2015, pp. 7-11. Translated from Meditsinskaya Tekhnika, Vol. 49, No. 1, Jan.-Feb., 2015, pp. 5-8.
Original article submitted November 25, 2014.

Mobile System for Automated Remote Monitoring of Cardiac Activity

V. P. Bessmeltsev[1]*, D. N. Katasonov[1], B. S. Mazurok[1], I. V. Makeev[1], V. A. Sluev[1], V. V. Morozov[2], and A. I. Shevela[2]

A prototype of a diagnostic complex for continuous monitoring of patient's cardiac activity (electrocardiography, heart rate) is described. The complex contains an intelligent-sensor data acquisition system, a processing system based on a Bluetooth piconet-microserver, and a communicator for transmitting data from the data acquisition and processing system to a medical server. The algorithms of preprocessing of the sensor signals and the structure of the mobile application of the communicator and medical server are also presented. Structural, hardware, and software solutions presented demonstrate the feasibility of a complex with sensors that allow patients to perform their usual daily functions.

Introduction

A serious problem for successful prevention and treatment of cardiovascular disease is the absence of reliable means for rapid diagnostics of threatening conditions associated with cardiovascular disorders and, consequently, the inability to provide prompt professional assistance. Modern diagnostic systems are based on electrocardiographic monitoring, including long-term continuous monitoring. The Holter method is widely used throughout the world for monitoring ECG, heart rate, and blood pressure in modifications of duration from one to seven days [1]. Miniature and contactless ECG sensors are now being developed that are comfortable enough for constant or prolonged monitoring of the cardiovascular system. Development of software and hardware for wireless personal area networks and their wide distribution by means of personal cellular communication enables the construction of a wireless monitoring system [2-4]. However, prototypes of such systems manufactured to date have low reliability and are virtually inoperative during the daily routine of a person or when working in difficult conditions. Therefore, the problem of creation of hardware and software without these disadvantages is urgent. This article presents the results of designing of a miniature autonomous wearable monitoring complex with the means to improve its reliability; the complex continuously records and broadcasts to the medical server key indicators of cardiac activity of the person with an additional option in the event of a potentially dangerous situation to send an emergency call to the medical service or to inform the patient. The main problems solved using the presented system are improvement of quality and speed of diagnosis of cardiovascular disease, as well as reducing the response time in the event of a situation that is potentially dangerous for the patient.

Structure of the Mobile Monitoring System

The diagnostic system, designed as part of an integration project of the Siberian Branch of the Russian Academy of Sciences, "Remote Monitoring of Human Cardiovascular Activity Based on Miniature Wireless Sensors and Personal Cellular Communication with Embedded Computing Means", includes intelligent sensors, a system for data acquisition and processing based

[1] Institute of Automation and Electrometry, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia; E-mail: bessmelt@iae.nsk.su
[2] Institute of Chemical Biology and Fundamental Medicine, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia.
* To whom correspondence should be addressed.

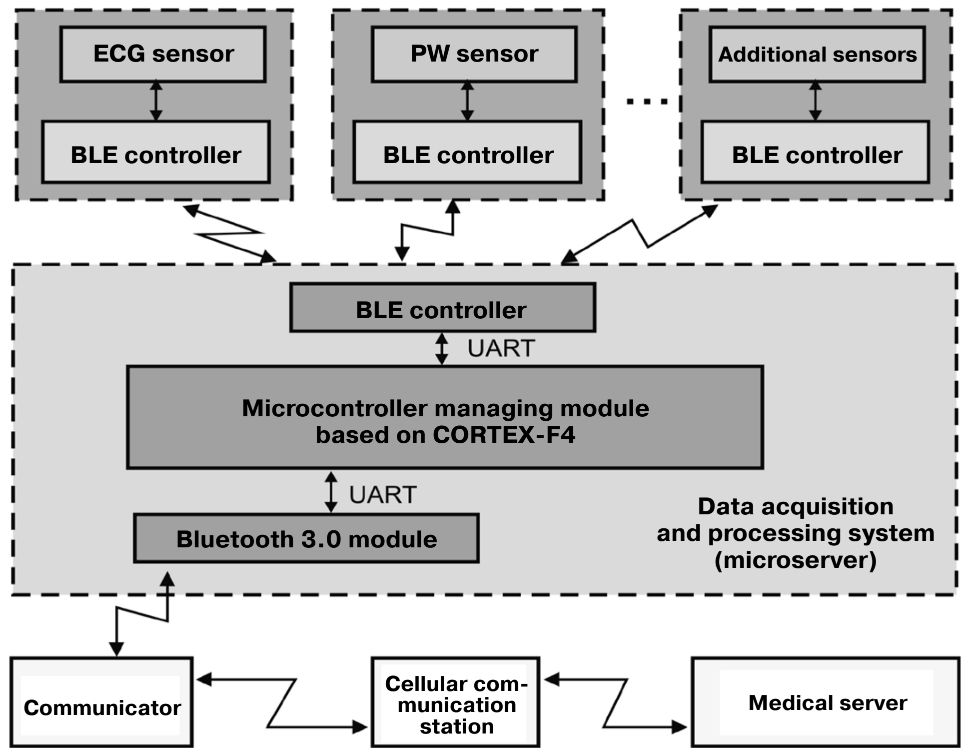

Fig. 1. Monitoring system using cellular communication and microserver: ECG, electrocardiogram; PW, pulse wave.

on the Bluetooth piconet (microserver), and a communicator for transmitting data from the data acquisition and processing system to the medical server [5]. The structure of the complex is shown in Fig. 1.

Intelligent sensors were developed for ECG registration (Fig. 1 – ECG sensor), which consist of a capacitive proximity sensor EPIC PS25201 [6], and a wireless module based on a TI25xx microcontroller with an ADC and Bluetooth LE (BLE) interface built-in directly on the crystal. The pulse sensor (Fig. 1 – PW sensor) is based on an optoelectronic converter of pulse wave of the radial artery and includes processing and communication means of the BLE standard. The principle of the sensor is based on transillumination of the blood vessel and measuring reflected or transmitted light flux by a photoelectric transducer. Sensors using this principle are produced by various manufacturers, are highly reliable, and can operate when the patient performs daily duties as well as exercises. Typically, such a sensor is mounted on the wrist like a watch without restricting the patient's mobility and, consequently, does not result in a substantial number of artifacts. Currently, these devices are present on the open market. For example, the Alpha Mio device, made in the form of a wristwatch, is fixed on the wrist by an elastic strap, which ensures secure fit. This device enables evaluation of the heart rate when running or training in a swimming pool. Experimental use of this device as a sensor for mobile monitoring system has shown that it is compatible with the wireless interface used in the monitoring system, as well as the adequacy of heart rate assessment in a person during daily duties [7].

The monitoring system independently registers pulse rate and ECG. The combined use of pulse sensor and ECG sensors, first, enables evaluation of pulse deficit and, second, increases the likelihood of identifying distorted ECG regions. Using two or more ECG sensors improves the likelihood of correctly identifying distorted regions by joint analysis of data from various sensors, similarly to Holter monitoring: ECG changes occurring synchronously in all leads are registered [1]. To ensure better monitoring of the human condition, it is intended to include other sensors into the diagnostic system, such as temperature and blood pressure sensors.

The operation of the system is described as follows. After turning the system on, the microserver searches for wireless sensors and, on recognition of a response signal, starts the procedure of sensor setup and receives, compresses, and stores digitized ECG data in a largecapacity flash memory. Compressed data is stored for the last 30 days.

A microserver with frequency of at least 0.1 Hz receives data from the PW-sensor (heart rate during this period). The microserver processes and analyzes the data from various sensors, and in the case of deviations from specified settings will sound an alarm with simultaneous activation of the communicator device, which transmits the data to the medical server. During analysis, performance of each component of the system is evaluated, corresponding messages are sent to the communicator, and through it to the medical server. A 32-bit ARM microcontroller with ultra-low power consumption is used as the calculating component of the microserver.

Algorithms for Preprocessing of Sensor Signals

A block diagram of the algorithm of ECG signal preprocessing is shown in Fig. 2. The analog signal from the output of sensor 1 is processed by the analog low-pass filter 2 with cut-off frequency of 500 Hz to suppress aliasing [8]. The typical form of filtered signal *P* is represented on the graph. After filtering, signal *P* is processed by the microcontroller of sensor 3 in which analog-to-digital signal conversion (ADC) 4 is done, with subsequent processing by digital filter module 5 and precompression 6. Digital filtering is performed by filters with linear phase characteristic, which suppress the frequency multiple of the electrical network frequency, as well as by the low-pass filter to suppress the effect of muscular tension. Next, the data are transmitted wirelessly to microserver 7, where drift of the isoelectric line is compensated by module 8. Drift compensation is necessary to ensure a stable PQRST-complex classification. The drift compensation algorithm is based on the formation of compensating signal by separating the signal drift from the original data. The signal type after the suppression of the isoelectric line drift and the point of its recording are noted as *Q*. The signal *Q* is then processed by distortion detection module 9. The distortion detection module determines zones unfit for processing due to external disturbances of the sensor, loss of contact between sensors and the patient's body, and other artifacts. The result of its work is shown by curve *Y*. Contact loss detected by the distortion detection module enables changing of the operation mode of the system – shift to the control of the data derived from the optical pulse sensor only, as long as

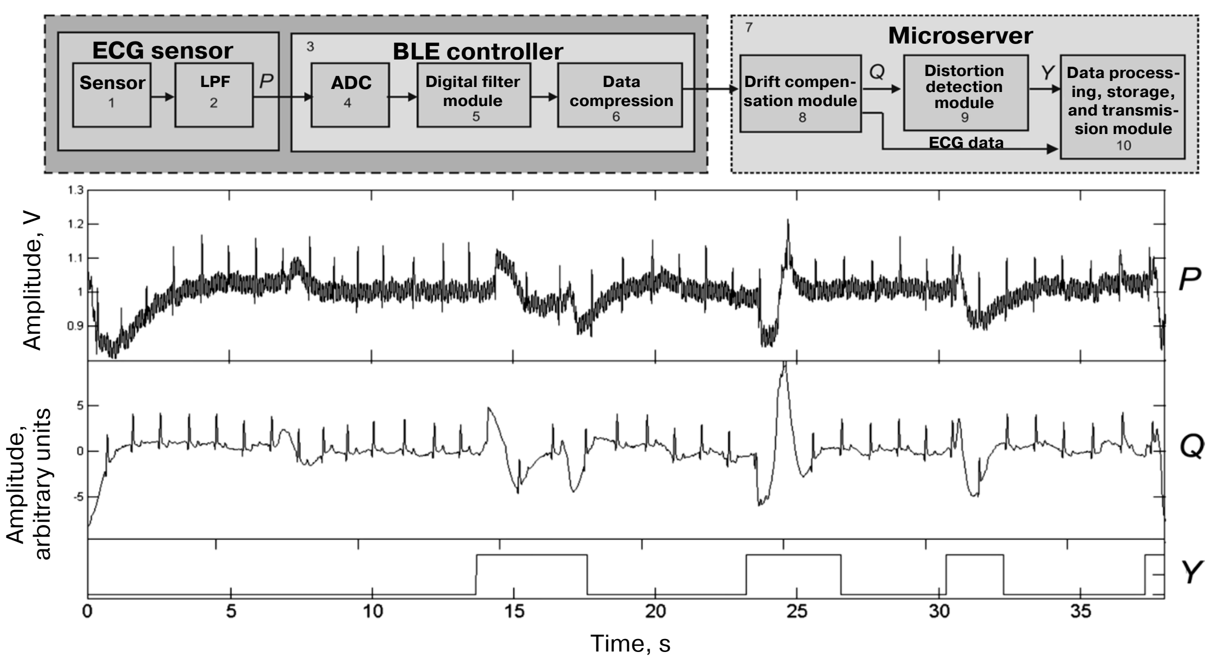

Fig. 2. Flowchart of ECG signal preprocessing and corresponding plots: 1) ECG sensor; 2) analog low-pass filter (LPF); 3) microcontroller; 4) ADC; 5) digital filter module; 6) pre-compression stage; 7) microserver; 8) drift compensation module; 9) distortion detection module; 10) data processing, storage and transmission module; *P*, signal after analog low-pass filter; *Q*, signal after normalization, digital filtering, and compensation of isoelectric line drift; *Y*, result of identifying segments unsuitable for signal processing.

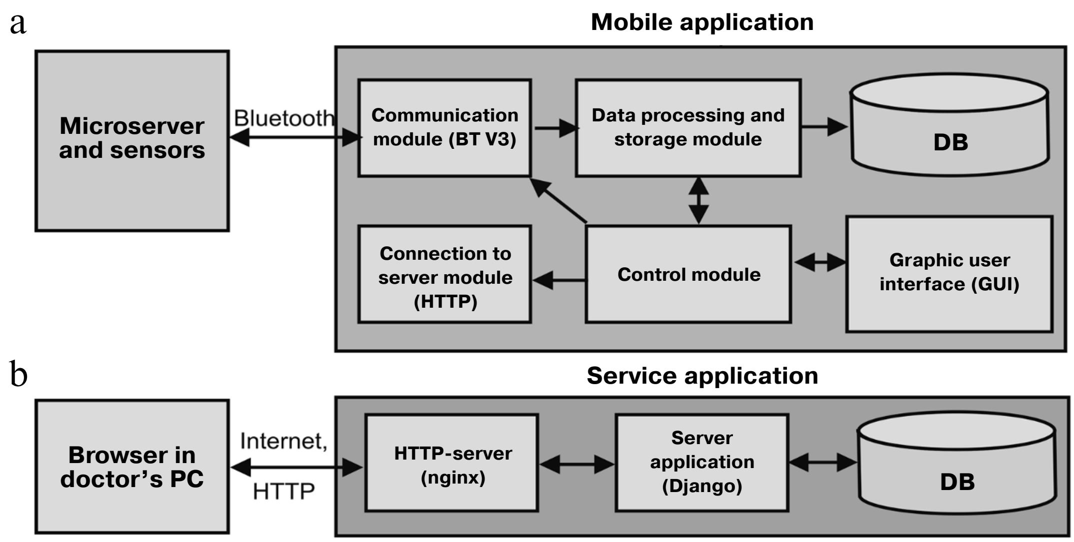

Fig. 3. Architecture of the mobile (a) and service applications (b).

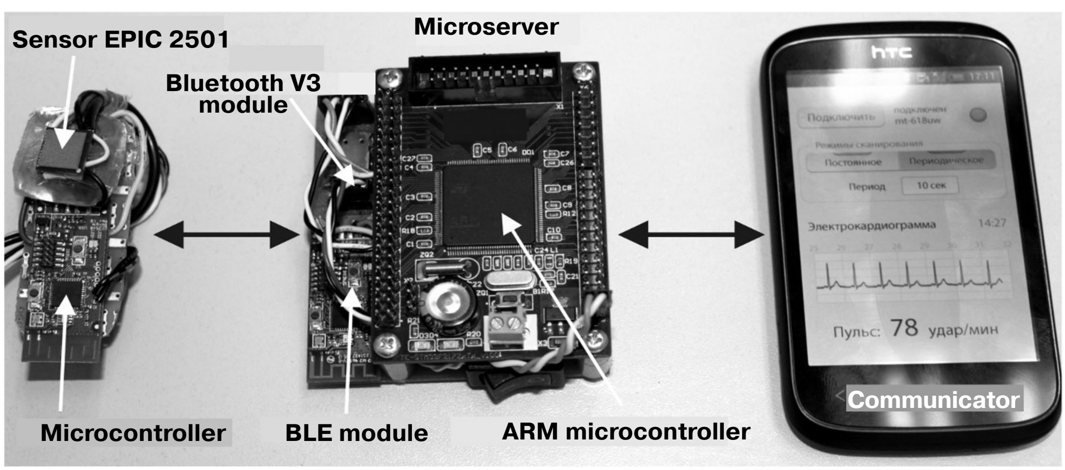

Fig. 4. Monitoring system hardware.

the contact is restored. In this case, ECG sensors switch from the signal registration mode to the standby mode until the contact is restored while reducing sampling frequency of the signal, terminating transmission of data not bearing diagnostic information, thus reducing the power consumption of the sensor.

Description of Application of the Mobile Device

The application is based on the open platform Android, enabling its use on any Android-powered device regardless of the manufacturer. Additionally, Android-powered devices with the necessary characteristics are more common and much more accessible than similar devices on other platforms. The application was implemented in Java under the ADT (Android Development Toolkit by Google). This approach has several advantages, such as GUI (Graphical User Interface) adaptability to screens of different devices, the possibility of implementing a background operation of the application, and full integration with Android API resources [9]. The software architecture of the mobile application is shown in Fig. 3a. On a preset time slot, the control module sends through the communication module a request to transfer an ECG "frame" and heart rate value to the microserver. After receiving the data, they are transferred to the processing and storage module, where, taking into account preset threshold characteristics of the patient (user), an alarm degree is calculated, and the data are stored in the memory of the SQLite device. When the application is active, the data are transferred to the display module to form charts and graphs on the screen of the device. For a given time interval or on the estimated alarm degree of the ECG data, the control module generates data for transmission to the medical server (MS) through the communication module. For coordination of the microserver and mobile application, a communication standard was developed that includes the following types of messages: request for data/status of microserver and sensors; installation of system configuration; transmission of status/data (ECG, heart rate, etc.), error status.

To provide flexible development of the project for implementation of the server application, the Python-based Django framework was selected, which fully realizes the MVC (Module – View – Controller) programming concept [10]. The general server architecture is shown in Fig. 3b. Nginx plays the role of http-server with an option of interacting with FastCGI-processes that are launched for the Django-realized website. After the data from the patient's mobile applications are received, they are saved in the database of the medical server. The doctor can remotely view the patient's data after authorization on the MS site from any computer on the Internet.

Conclusion

The system based on Android-communicator, microserver, and contactless ECG and heart rate sensors enables creation of a mobile wearable system for continuous monitoring of a patient's cardiac activity (electrocardiography, heart rate, temperature) by remote medical service using sensors that do not prevent patients from performing their daily functions. Using the microserver based on ARM-microprocessor as an intermediary between the sensors and the device minimizes demand for computing resources of the communicator, and in the absence of connection with the device provides storage for the data within the internal memory of the microserver, and ensures reliable communication with sensors and long-term operation through independence of data collection processes from device usage mode and operations performed by it.

Experimental studies using the prototype of the miniature autonomous wearable complex, constructed in accordance with the structure shown in Fig. 1 (hardware without cases is shown in Fig. 4) revealed that the main elements determining the quality and reliability of the system are the modern ECG sensors. Input signal filtering and identifying artifacts significantly improve data accuracy; however, the best commercially available ECG sensors do not fully meet the requirements of mobile continuous monitoring systems. Thus, the developed device can be suggested as a prototype of an effective system for monitoring basic parameters of the cardiovascular activity of a person for early detection of potentially fatal health disorders, early treatment, and prevention of cardiovascular diseases.

REFERENCES

1. Makarov L.M., Holter Monitoring [in Russian], 2nd Edn., Medpraktika-M, Moscow (2003).
2. Borromeo S., Rodriguez-Sanchez C., Machado F., Hernandez-Tamames J.A., de la Prieta R., Proc. 29th Ann. Int. Conf. of the IEEE EMBS Cité Internationale, Lyon, France, August 23-26 (2007).
3. Lee D.H., Rabbi A., Choi J., Fazel-Rezai R., Int. J. Adv. Computer Sci. Appl., **3**, No. 3 (2012).
4. Morozov V.V., Seriapin Y.V., Kravchenko Yu.L., Tarkov S.M., Bessmeltsev V.P., Katasonov D.N., Sluev V.A., Fundament. Issled., No. 7 (Pt. 3), 589-593 (2013).
5. Bessmeltsev V.P., Katasonov D.N., Morozov V.V., Sluev V.A., Proc. XXI Int. Conf. "Laser information technologies in medicine, biology and geoecology", Abrau-Durso, Novorossiisk, September 10-14 (2013).
6. Bekmachev A., Komponenty Tekhnol., No. 1, 21-24 (2013).
7. http://www.mioglobal.com.
8. Johnston P., Luo S., J. Electrocardiol., **43**, 486-496 (2010).
9. Google, Android Development Toolkit (https://developer.android.com/reference/packages.html).
10. Django Software Foundation, Django framework (https://docs.djangoproject.com).