Mobile ECG Monitoring Device with Bioimpedance Measurement and Analysis

Maxim Safronov, Andrey Kuzmin, Oleg Bodin, Viktor Baranov, Alexey Trofimov, Alexander Tychkov

Penza State University
Penza, Russia
{safronov.maxim, flickerlight, bodin_o}@inbox.ru, {baranov_va2202, alex.t1978, tychkov-a}@mail.ru

Abstract—**The paper describes the improvement of a portable ECG device, which allows increasing the reliability of cardiovascular disease diagnosis using an electrocardiogram during ambulatory monitoring in conditions of free motion activity. The results of hardware and software development for correction of an ECG form are presented, which minimizes the loss of diagnostic information due to the distortion of the ECG form by the bioimpedance of the tissues and organs of the body that are located between the heart and electrodes of an ECG device. A portable ECG device with a bioimpedance measurement channel between the electrodes is described. The measurement channel includes a programmable computing device. Software provides calculation based on the measurement results of the bioimpedance components of the parameters of the parasitic electric filter, and synthesis of the transfer characteristic of the correction digital filter. The simulation results of the correction procedure of the ECG form in the TINA environment are presented. The simulation results show that the proposed solution can be used in portable heart monitoring systems.**

I. INTRODUCTION

Currently, digital devices of the eHealth segment are gaining wide popularity. Many manufacturers of consumer electronics have already presented their models of smart watches with the function of measuring heart rate. In January 2019, Omron introduced the world's first HeartGuide watch [1], which allows measuring blood pressure at the wrist using the traditional oscillometric method. However, breakthrough technologies in the mHealth segment deservedly bypass the methods of non-invasive recording of the heart electrical activity, but there are good reasons for this. The main reason is high complexity of minimizing noise associated with a patient movement, which leads to the displacement of the sensitive elements of ECG recording devices. An ECG, recorded by an ECG device is one of the main sources of information, on the basis of which heart condition assessment is formed. An ECG device measures a number of temporal and amplitude parameters of electrocardiosignal: frequency range, amplitude and peak-to-peak. A form of QRS-wave, ST-segments and R-R intervals regularity. The detectability of deviations in the functioning of the heart from the norm, and the accuracy of identification of the type of deviation is determined by the accuracy of measurements of these parameters of the ECG.

eMotion Faros Cardiac Monitors [2] – is an instrument for ECG and Heart rate variability (HRV) monitoring and rehab monitor. It operates in pair with a smart-phone that enables data visualization, audible warning of critical condition and Internet connection. After electrodes placement on the body of the patient and activation of the device all control functions are available via smart-phone screen. This system allows monitoring of the existing cardiovascular disease and detecting new cardiovascular diseases both for patients from risk group and for relatively healthy people.

Astrocard – Telemetry [3] – is a complex for long-term (up to 30 days) telemetric wireless ECG monitoring in real-time mode. The monitoring device has a special embedded mobile communication module. It allows transmitting recorded ECG data to the cloud server for storage. This data can be remotely accessed by physicians via smart-phone (iOS or Android) for the following analysis. Free movement in mobile networks coverage area is allowed for patient during the monitoring.

Multi-purpose ECG telemetry system [4] is a solution for telemetric record, transmission and interpretation of ECG signals. The system contains ECG device, cloud analytical service and mobile applications for patients and physicians. The design of the ECG device allows amateur users recording ECG using dry electrodes without any special skills.

Stationary ECG devices have high accuracy, but do not allow organizing monitoring of heart condition outside the hospital. Therefore, portable ECG devices are being actively developed, which monitor the ECG under conditions of free motor activity [5].

II. PROBLEM STATEMENT

In modern portable ECG recording systems, self-adhesive electrodes with a diameter of up to 50 mm are used. Such electrodes with a connector coated with Ag/AgCl provide an acceptable quality of the recorded signal in a stationary position; however they are also shifted from their places in the process of free motor activity. Connecting a portable ECG device with self-adhesive electrodes to a patient's body is shown in Fig.1.

In addition to the patient's movements, the state of the skin integument on which the electrodes are located has a significant effect on the ECG form. Changes in the electrical parameters of the skin integument are usually not taken into account during stationary ECG recording, since the surface of the skin is pre-defatting with alcohol-containing compounds. In ambulatory ECG monitoring systems, skin defatting is either very rare (≤ 1 time per day) or is not performed at all, which inevitably leads to distortions of the recorded signal due to perspiration, pollution, etc. [5].
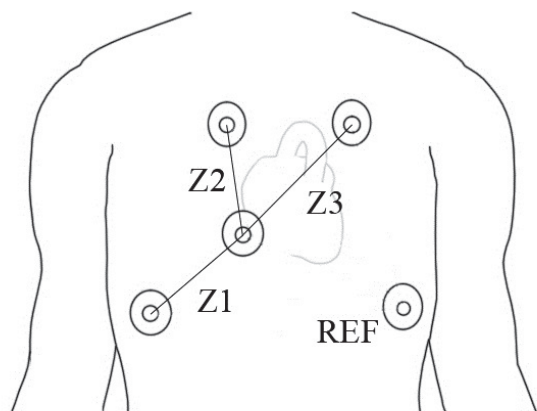
Fig. 1. Connection of a portable ECG device to a patient's body

An ideal voltage source (VG1) is a model of the heart during the formation and registration of the ECG. This voltage source is connected to two electrodes of an ECG device via four-pole network formed by three two-pole networks (RC1-3). Each two-pole network is composed of a resistor (R1-3) and a capacitor (C1-3). Two-pole networks (RC1-2), whose complex resistances are considered to be equal (Z1=Z2), simulate the complex resistance of organs and tissues between the heart and the electrode. A two-pole network (RC3) models the complex resistance between the electrodes attached to the body. A source model of the heart electrical signal connected to the input of the ECG device is shown in Fig. 2.
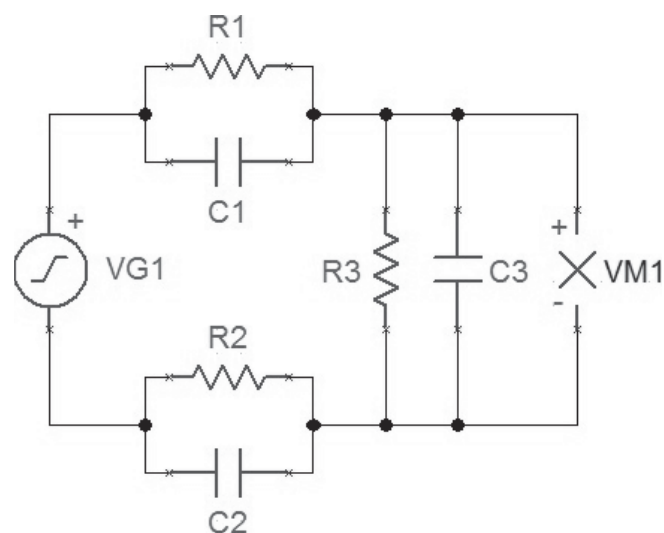

Fig. 2. A source model of the heart electrical signal

Thus, it is not the voltage (VG1) but the voltage (VM1) that is supplied to the ECG device input:

$$VM1 = \frac{Z3}{Z1 + Z2 + Z3} \cdot VG1 = K \cdot VG1 \qquad (1)$$

where Zn is a parallel-connected resistor Rn and a capacitor Cn according to Fig. 2 (n = 1, 2, 3).

The complex coefficient (K) can be considered as a transfer characteristic of a parasitic electric filter that distorts the voltage form (VG1).

Bioimpedance distortions of the form of the electrical signal of the heart adversely affect the detectability of diagnostic signs of cardiovascular diseases. For example, a diagnostic sign of myocardial infarction is a displacement of J-point, etc. [7].

III. SOLUTION VISION

An obvious way to minimize the form distortion of the electrical signal of the heart is to include a correction (reconstruction) filter with a transfer characteristic in the ECG device, which is inverse to the transfer characteristic (K) of the parasitic filter (S=1/K).

An analysis of the source model of the heart electrical signal has led to the following conclusions. Complex resistances (Z1) and (Z2) can be considered identical in all patients, and unchanged in the process of forming an ECG. Typical resistance values of resistors (R1,3) are in the range from 10^2 to 10^4 Ohms, and capacitance values of the capacitors (C1,3) are in the range of 5 – 500 pF [8]. On the contrary, the complex resistance (Z2) is individual for each patient, and significantly changes in the process of monitoring. Thus, it is necessary to measure periodically the parameters of a two-pole network (RC2) to determine the current values of the coefficient (K).

The variability of the coefficient (K) in the process of mobile monitoring virtually eliminates the possibility of hardware implementation of the reconstruction filter. The reconstruction filter should be implemented by software as a digital filter.

The authors propose to use a portable ECG device for mobile monitoring of the heart with a bioimpedance measurement channel of the patient's tissues, and digital filtering of the electrical signal of the heart.

A structural diagram of an ECG device is shown in Fig. 3. This scheme contains 2 independent channels combined in one device: an ECG recording channel (ECG part) and a bioimpedance measurement channel (Bioimpedance part). The ECG recording channel is a series-connected differential amplifier and a delta-sigma ADC. ADC is connected to a microcontroller via a digital interface (SPI, for example). Parallel to the ECG channel, the bioimpedance measurement channel is also connected to the microcontroller, which represents a collection of a whole set of components, such as sine wave generator, phase meter and voltmeter. These nodes can be made individually or as part of specialized microcircuits. The microcontroller collects the current ECG and bio-impedance data and, with the help of Digital Signal Processing (DSP), performs the subsequent ECG recovery. Further, the received signal is packaged for transmission over a wireless communication channel (Ex. Bluetooth, Zigbee) to the server for information storage and processing

The device has a two-channel structure: an ECG forming channel and a bioimpedance measurement channel. The hardware part of the ECG forming channel is designed

according to the traditional diagram and consists of an amplifier, an analog-to-digital converter (ADC), and a microprocessor. The bioimpedance measurement channel contains a reference element with a complex resistance (Z0), a sine wave generator (VG1), a digital voltmeter of effective value, and a digital phase meter.
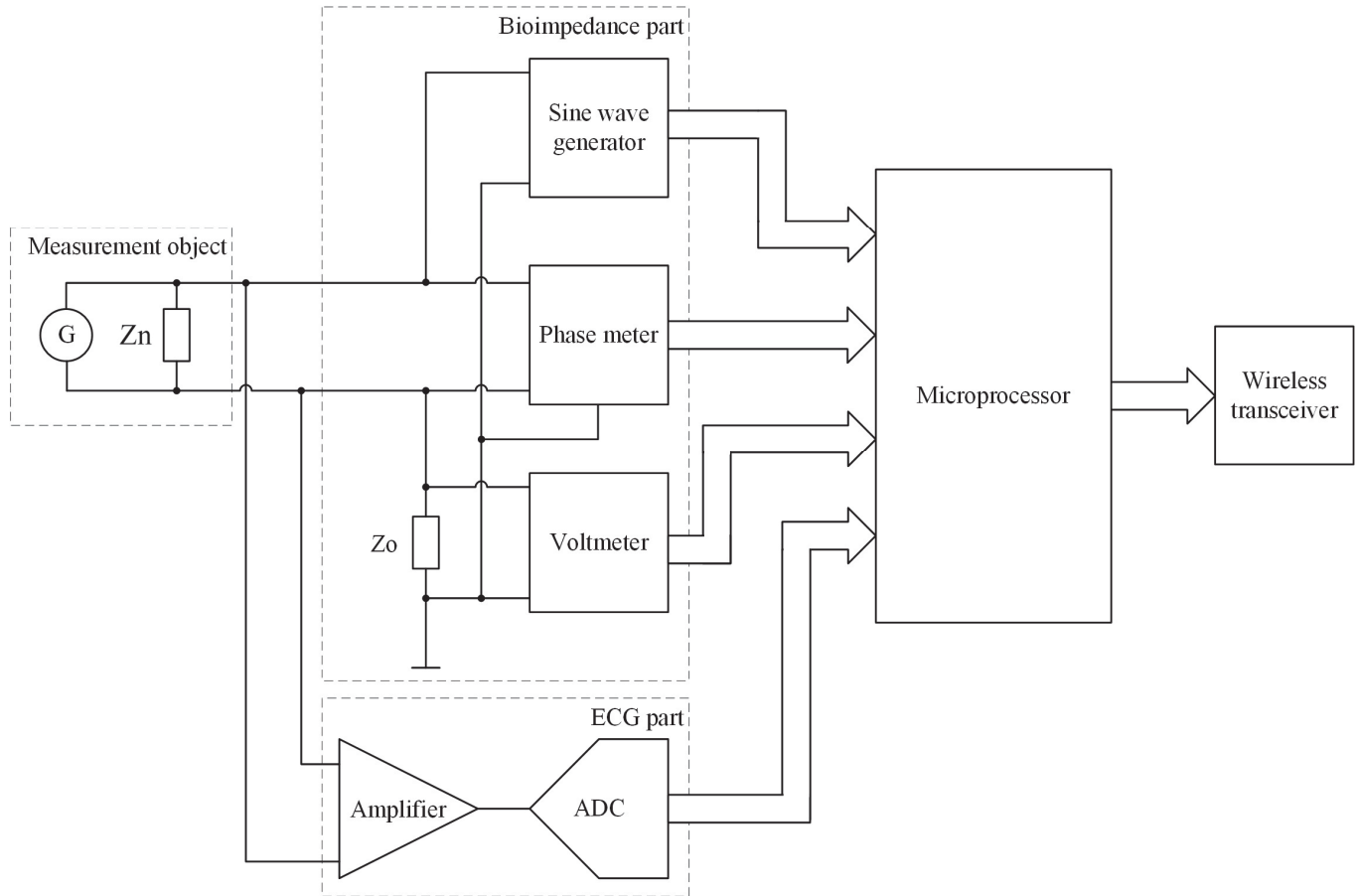

Fig 3. Structural diagram of an impedance measurement channel

The maximum peak-to-peak voltage (VM1) is 10 mV, and it is amplified by the differential voltage amplifier to the level of 500 mV. The voltage at the output of the amplifier is subjected to analog-to-digital conversion. The ADC must have at least a 12-bit resolution, and the integral nonlinearity of no more than 1 unit of the lower order. The results of the analog-to-digital conversion are recorded in the memory of the microprocessor.

Simultaneously with recording the values of the electrical signal of the heart, the device periodically measures the impedance (Zn) of the signal source.

IV. IMPLEMENTATION

The process of measuring bioimpedance is carried out using the measuring circuit shown in Fig. 4. A harmonic signal with amplitude of 1 V and a frequency of 1 kHz is fed via certain electrodes from a functional generator VG2, which is a digital-to-analog converter (DAC), to the patient's skin Zn. This signal is then recorded by the remaining electrodes in accordance with the table of leads preset in the device. After that, the above process is repeated at a frequency of 500 Hz.
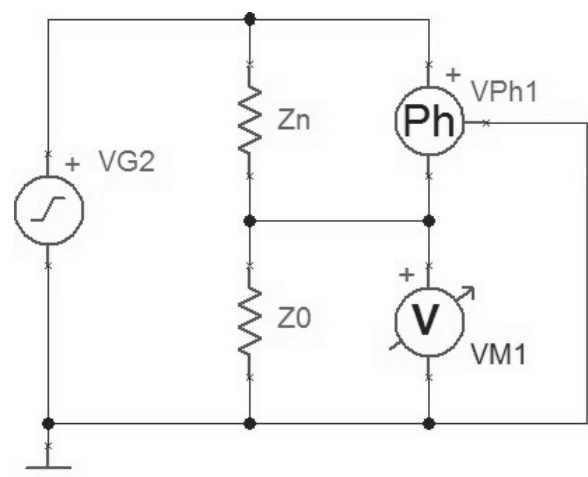

Fig 4. Structural diagram of a bioimpedance measurement channel

Then, the recorded signals are digitally subtracted from the modulated signal, whose parameters are known in advance. The resulting values of the difference function for both

frequencies are laid out in the spectra, thereby determining the parameters of rejection of the useful signal by the patient's skin.

Bioimpedance measurement is carried out on the base exponential form of a complex number. Generator (VG1, see Fig. 2) is designed on the base of DAC controlled by microprocessor. It generates harmonic voltage with effective value Us=1 V and frequency of 1 kHz. Measurement scheme is a voltage divider which consists of measurable impedance and reference resistive element (Z0).

During bioimpedance measurement digital voltmeter measures effective voltage value U0 on reference element Z0. The result of voltage measurement (U0) is used by microprocessor for the estimation of the effective voltage value (Un) on measurable impedance (Zn) and for estimation of impedance (Zn):

$$Zn = \frac{(Us - U0)Z0}{U0} \qquad (2)$$

Simultaneously digital phase meter measures a phase shift (PH) between the output of voltage generator (VG1) and the voltage on reference element (Z0) that is the voltage on the middle point of measuring circuit. On the base of measured effective voltage on the object (that is in direct proportion to modulus of measurable impedance zn) and voltage phase shift exponential impedance form is synthesized:

$$Zn = zn \cdot e^{jPH} \qquad (3)$$

where e = 2,718…, j – imaginary unit.

The algorithm of the portable ECG recording system excluding bioimpedance influence of its form is shown in Fig. 5.
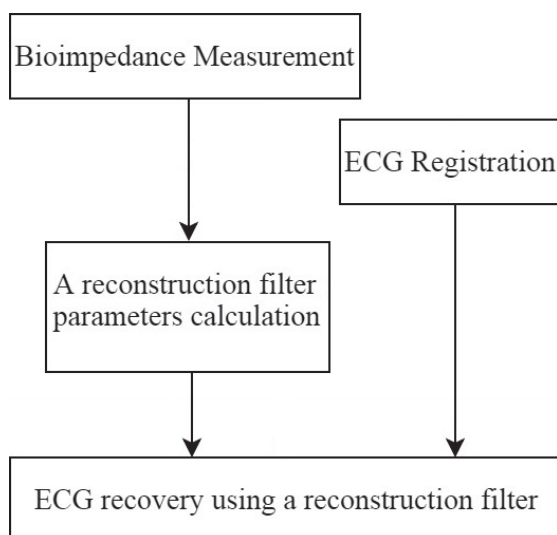

Fig 5. Algorithm of the portable ECG recording with bioimpedance measurement

An impedance (Z1) is related to the components of the parasitic filter by the dependence:

$$Zn = \frac{2Z1Z2}{2Z1 + Z2} = 2Z1K \qquad (4)$$

Consequently, the transfer characteristic S of the reconstruction filter can be defined as

$$S = 1/K = 2Z1/Zn \qquad (5)$$

The reconstruction of the form of the heart electrical signal is carried out by the microprocessor by multiplying the recorded signal values by the transfer characteristic S. The corrected numerical sequence describing the undistorted signal form of the patient's body by bioimpedance is transmitted to the workstation of a cardiologist for presentation in the ECG form.

V. EXPERIMENTAL INVESTIGATION

A. Investigation scheme

Experimental study of the effect of the parasitic impedance on the detected ECG signals from the electrodes is carried out in the Texas Instruments TINA environment [9]. The experimental scheme is shown in Fig. 6. The VM2 node was added to simultaneously display the reference and filtered signals.
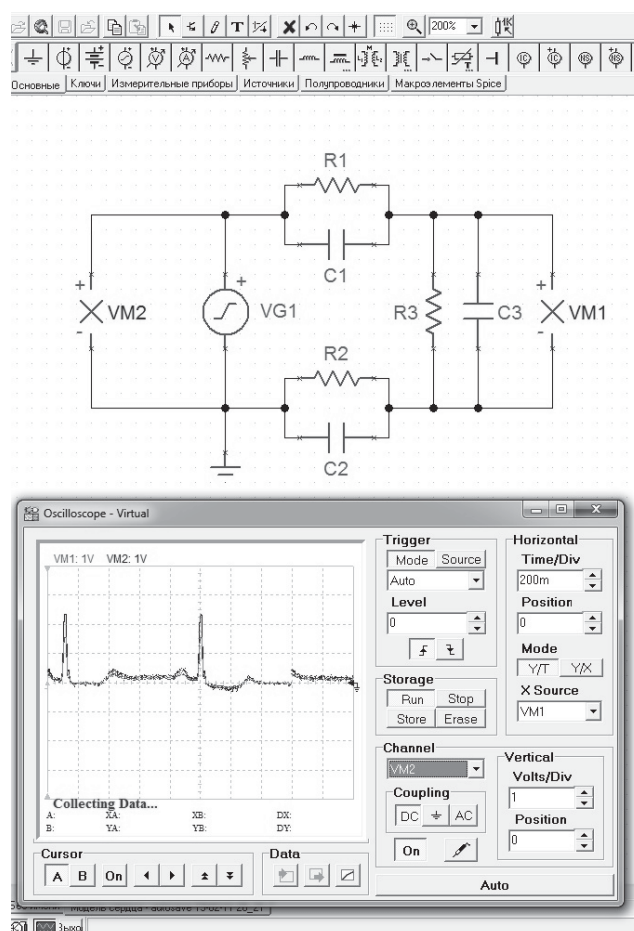

Fig 6. Diagram of a simulation model in TINA environment

B. Experimental results

The authors suppose that the parasitic impedance of the skin leads to change in the shape of the recorded ECG signal. For testing purposes, computer simulation of the processes of the equivalent scheme of skin bioimpedance was carried out. The record 100.dat from the open database of physiological signals PhysioNet (section MIT-BH Arrhythmia Database) was adopted as a reference signal [10].

This record was then converted to WAV format using the MATLAB environment, the resulting WAV file was used to generate signal via VG1 DAC (see Fig. 2). This signal was passed through an equivalent bioimpedance scheme of the skin with average values of permissible ranges of all elements and registered using the VM1 node. Fig. 7 represents the curves of the reference and filtered signals.
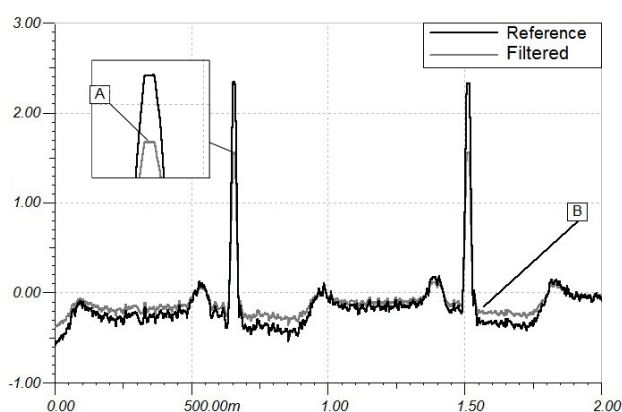

Fig. 7. Reference and filtered ECG curves

As shown in Fig.6, there are two sharp distinctions between reference and filtered curves marked by the letters «A» and «B»:

- «A», a decrease in the R-wave amplitude was found, which can lead to a wrong diagnosis of such diseases as exudative pericarditis, myocardiofibrosis, myxedema and cachexia [11];
- «B», a change (in this case, a rise) of J-point, which is the beginning of the ST-segment, is detected. The displacement of the J-point relative to the isoelectric line more than 2 mm is one of the signs of myocardial infarction [12].

So, from the simulation results it can be seen that the parasitic bioimpedance of the skin can be the reason of a wrong diagnosis.

VI. HARDWARE DESIGN

The hardware implementation of the device under development, which implements the method proposed by the authors, is based on a specialized microcircuit (ECG Analog Front End) of Texas Instruments - ADS1298R [13]. The "R" index in the title means that this line of microcircuits supports the function of registering human breathing, based on continuous measurement of skin impedance. The authors propose to use data from the respiration measurement channel

ADS1298R to compensate for ECG losses caused by the previously described bioimpedance of the skin at the points electrode contacts. This feature of the ADS1298R allows the use of circuitry offered by Texas Instruments without any changes and additional microcircuits. This is an important issue when developing portable medical devices, as an increase in the number of energy consumers has a negative effect on the battery life of the device as a whole.

The well-proven microcontroller with an integrated support for Bluetooth Low Energy (BLE) technology of Nordic Semiconductor NRF52832, whose characteristics are presented in Table I, was selected as the central unit of the system.

TABLE I. SPECIFICATIONS OF NRF52832

Parameter	Value
Data Rate (Phy)	2Mbps
Output Power	4dBm
Sensitivity	-96dBm
Memory Size	256kB Flash, 32kB RAM
Serial Interfaces	I²C, SPI, UART
Supply Voltage	1.7 V ~ 3.6 V
Current Rx, Tx (max)	6.5mA, 7.1mA

The choice of this microcontroller is due to the presence of a powerful computing core of the Cortex M3 line, on the basis of which the work with AFE ADS1298R will be conducted according to SPI protocol in Direct Memory Access mode, as well as digital processing of the received information, hardware data encryption and their transfer to the receiving device for further processing, as well as hardware support for widespread BLE technology supported by most modern mobile devices. One should noted low power consumption of the chip: in the maximum transmitter power mode, the current limit is 7.1 mA [14]. These factors, along with an affordable price, make the use of the NRF52832 microcontroller justified in developing devices of this level.
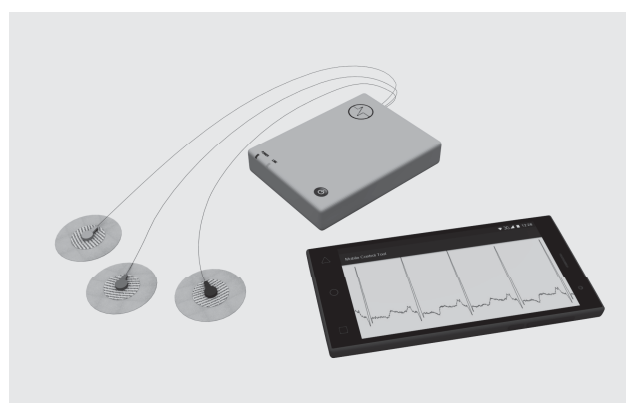

Fig. 8. Developed ECG device

Fig. 8 shows the general view of the device developed by the authors. Technical characteristics of the device are shown in Table II.

The device is a parallelepiped, with dimensions of less than 75x60x30 mm, equipped with a connector for attaching an ECG recording cable with «banana» plugs at one end and a

DB-9 plug at the other end. On the front panel, there are 2 separate LEDs and a multi-functional control button.

TABLE II. SPECIFICATION OF THE DEVICE

Parameter	Value
Overall dimensions	Less than 75x60x30 mm
Resolution	24 bits
Channels	3 (up to 8)
A/D Sampling Rate	Variable, 500 Sps and 1000 Sps
Wireless protocol type	Bluetooth Low Energy
Power source	LIR2450, 3.6 V, 110 mAh
Battery lifetime	More than 24 hours

VII. FUTURE WORK

One of the future research directions is the refinement of the electrical model of the measurement object, which includes taking into account the influence not only of the impedance of the skin itself, but also the influence of such a skin condition as moisture, caused not only by natural processes of hidropoiesis, or by any external factors (blood, dirt, etc.) [15]. This will allow using such systems in emergency situations, when the accuracy of ECG recording directly affects the actions taken by specialists.

The ultimate goal of the work is to create a mobile device for recording and processing electrocardiographic information in conditions of free motion activity, as accurate as possible. This device can be an essential element of medical sensor networks as well as smart spaces and environments in general [16], [17].

VIII. CONCLUSION

The results of the show that bioimpedance can affect the form of ECG especially in case of mobile monitoring systems with free motion. These deformations can lead to wrong diagnosis. Thus mobile ECG device should have an ability to correct the form of ECG.

General scheme and algorithm of ECG recording with bioimpedance measurement are proposed. Bioimpedance measurement channel and special filter are designed. Proposed scheme is experimentally tested in TINA environment. ECG device with bioimpedance measurement solution is designed on the base of AFE ADS1298R and NRF52832 microcontroller.

REFERENCES

[1] Omron official website, HeartGuide. Wearable blood pressure monitor. Web: https://omronhealthcare.com/products/heartguide-wearable-blood-pressure-monitor-bp8000m/

[2] Biomation official website, eMotion mobile FAROS sensor for ECG, HRV. Web: http://ecg.biomation.com/faros.htm

[3] Astrocard official website, System for telemetry ECG recording and analyzing "Astrocard® - Telemetry". Web: https://www.astrocard-meditek.php?page=prod_06

[4] M. Marouf, G. Vukomanovic, L. Saranovac, M. Bozic. "Multi-purpose ECG telemetry system", *BioMedical Engineering OnLine,* vol 16, 2017, pp. 80. DOI: 10.1186/s12938-017-0371-6

[5] J.S. Steinberg, N. Varma, I. Cygankiewicz, P. Aziz, et al, 2017 "ISHNE-HRS expert consensus statement on ambulatory ECG and external cardiac monitoring/telemetry", *Annals of Noninvasive Electrocardiology*, vol. 22, Issue 3, 2017, pp. 1-40, DOI: 10.1111/anec.12447

[6] S. Rossi, C. Mancarella, C. Mocenni, L. Della Torre, "Bioimpedance sensing in wearable systems: From hardware integration to model development," *IEEE 3rd International Forum on Research and Technologies for Society and Industry (RTSI)*, Publisher: IEEE, 2017, pp. 1-6 DOI: 10.1109/RTSI.2017.8065956

[7] G. Clifford, F. Azuaje, P. McSharry, "Advanced Methods and Tools for ECG Data Analysis". ArtechHouse, 2006. 384 p.

[8] J. McIntyre, K. M. Ellyett, E. A. Mitchell, G. M Quill, J. Thompson, A. W Stewart, R. N Doughty, P. R Stone, "Validation of thoracic impedance cardiography by echocardiography in healthy late pregnancy", *BMC Pregnancy and Childbirth*, 2015, 15:70 DOI: 10.1186/s12884-015-0504-5

[9] Designsoft official website, TINA Circuit Simulator for Analog, RF, Digital, MCU, HDL, Symbolic & Mixed Circuit Simulation with Integrated PCB Design, Web: https://www.tina.com

[10] A. Goldberger, L. Amaral, L. Glass, J. Hausdorff, P. Ivanov, R. Mark, J. Mietus, G. Moody, C.-K. Peng, H. Stanley. "PhysioBank, PhysioToolkit, and PhysioNet: Components of a New Research Resource for Complex Physiologic Signals", *Circulation*, vol. 101(23), 2000, p. 215-220.

[11] Y.-S. Shin, J.-K. Wee, I. Song, S. Lee, "Small-area low-power heart condition monitoring system using dual-mode SAR-ADC for low-cost wearable healthcare systems", *3rd International Conference on Biomedical Engineering and Technology (iCBEB 2014)*, Beijing, China, 2014, pp. S277-S284.

[12] A. Kuzmin, M. Safronov, O. Bodin, M. Petrovsky, A. Sergeenkov, "Mobile Heart Monitoring System Prototype Based on the Texas Instruments Hardware: Energy Efficiency and J-point Detection", *International Journal of Embedded and Real-Time Communication Systems*, vol. 7(1), 2016, pp. 64-84 DOI:10.4018/IJERTCS.2016010104

[13] Texas Instruments official website, ADS129xR Low Power, 8-Channel, 24-Bit Analog Front-End for Biopotential Measurments. Web: https://www.ti.com/product/ADS1298r

[14] Nordic Semiconductor official website, NRF52832 Flexible, efficient Bluetooth 5 and Bluetooth mesh multiprotocol SoC. Web: https://www.nordicsemi.com/Products/Low-power-short-range-wireless/nRF52832

[15] Yongkang Zhou, Xiaoqiong Li, "Multifrequency time difference EIT imaging of cardiac activities", *Biomedical Signal Processing and Control*, vol. 38, 2017 pp. 128-135 DOI: 10.1016/J.BSPC.2017.05.012

[16] D.G. Korzun, A.V.Borodin, I.V. Paramonov, A.M. Vasilyev, S.I. Balandin, "Smart Spaces Enabled Mobile Healthcare Services in Internet of Things Environments", *International Journal of Embedded and Real-Time Communication Systems*, vol. 6 (1), 2015, p.1-27.

[17] Y.V. Zavyalova, D.G. Korzun, A.Yu. Meigal, A.V. Borodin, "Towards the Development of Smart Spaces-Based Socio-Cyber-Medicine Systems", *International Journal of Embedded and Real-Time Communication Systems*, vol. 8 (1), 2017, pp. 45-63.