Selected Hardware Solutions Used in the Process of Monitoring Bioparameters

Andrzej Michnik, Zbigniew Szczurek, Barbara Szuster, Bartłomiej Kubik, and Paweł Kowalski

***Abstract*—The paper presents the idea behind the implementation of a system designed to monitor biomedical parameters and the subject's behaviour on the basis of the architecture of measurement modules located on the body. The system was developed as a result of market launch of new generations of electronic devices combining high functionality, small size and low power consumption. The paper presents the elements of the system called BioSip, along with hardware solutions selected for the objectives to be accomplished, i.e. providing communication between system elements that would be efficient and resistant to artefacts, extending the time of operation for battery power supply, as well as ensuring a satisfactory level of reliability and ease of use.**

***Index Terms*—body area network, telemedicine, ultra low power, inductive charging, ECG, GSR, Bluetooth LE, BioSip**

I. Introduction

ALTHOUGH this may appear rather unlikely, dynamic development of sensory elements and microelectronic components, owing to more and more advanced miniaturization and reduction of power consumption, allows for implementing a vision of remote monitoring of several physiological parameters in people performing their everyday activities and professional duties. Importantly enough, the subjects may be monitored without an adverse impact on their comfort of life and professional work. Monitoring is conducted for various reasons, including self-control by overseeing everyday physical activity with a watch or band equipped with an accelerometric sensor which measures the number of steps walked per day. More complex cases involve overseeing the patients' health with the use of wireless sensors placed all over the monitored person's body and measuring, apart from the physical activity, the ECG signal, SpO_2, GSR, the temperature of the skin or even internal body temperature transmitted by radio from a swallowed capsule. In the first example, the obtained results encourage the subject to do more physical activity. The second example may be used for more responsible tasks to protect people's health or life, e.g. for a fast diagnosis of imminent myocardial infarction by analyzing the changes in the ECG curve.

A. Michnik, Z. Szczurek, B. Szuster, B. Kubik and P. Kowalski are with Institute of Medical Technology and Equipment, 118 Roosevelt St., 41-800 Zabrze, Poland (e-mails: andrzej.michnik@itam.zabrze.pl, zbigniew.szczurek@itam.zabrze.pl, barbara.szuster@itam.zabrze.pl, bartlomiej.kubik@itam.zabrze.pl, pawel.kowalski@itam.zabrze.pl,

An important element of contemporary measurement systems is their telemedical capacity which allows for sending measurements collected wherever the subject is staying, to the venue of the analysis, carried out e.g. by a computer with a high computing power or an expert in the monitored field to make a decision about further action. The action can be taken due to base stations of mobile telephone operators and HotSpots, available everywhere. Interestingly enough, universal accessibility and intense competition have resulted in the reduction of data transmission prices to an acceptable level. Wireless medical devices may use built-in modules: GSM, 3G, or LTE, connect via a low-power interface, e.g. Bluetooth, with a mobile telephone in order to transmit data via a mobile network or use Wi-Fi access points.

The paper demonstrates the concept and practical implementation of a system for monitoring human biomedical parameters. The system was developed at the Institute of Medical Technology and Equipment (ITAM) in Zabrze. The Institute has been carrying out research on various methods of monitoring vital parameters for several years, for instance:

- The Revitus system – used for monitoring a patient with cardiac problems at home
- The family of SMP systems – used for monitoring professional drivers or pilots.
- BioSip – a system consisting of a network of measurement sensors used to evaluate spatial orientation, and to measure psychophysiological parameters. It should be pointed out that the sensors may be configured and selected in any way, depending on their purpose. They can make a system for the evaluation of biomechanics, competitive with the motion capture systems, for Holter monitoring or for prevention applications.
- Monitel – this is a system which determines significant parameters, such as the pulse wave velocity specified on the basis of dependencies between two different signals (the pulse and ECG).

II. The Elements Used

One of the key issues of the BioSip project was to select appropriate components for the tasks to be accomplished. The selection centred on reducing power consumption, and on miniaturization. What also mattered was the availability and low price of the selected components without limiting their functionality.

Analogue measurement sections for the presented modules were chiefly created with the Texas Instruments ADS129x family. They are specialized devices used for ECG signal measurement. Versions with the symbol ending with the letter "R" additionally permit the impedance respiration rate measurement. The 24-bit sigma-delta converter converting the analogue signal into a digital format is an important element of the ADS129x structure. The placement of the extremely sensitive analogue part and the C/A converter in one silicone structure results in high resistance to electromagnetic artefacts. Resistance to artefacts is also enhanced by EMI filters located in analogue inputs inside the aforementioned structure.

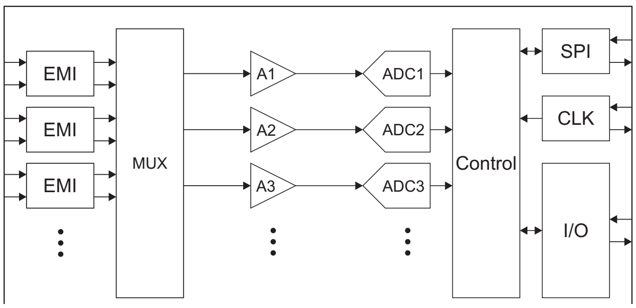

Fig. 1. A simplified block diagram of the ADS129x family.

Most elements of the BioSip system, apart from the Integrator, are controlled by the Nordic Semiconductor SOC nRF51422 or nRF51822 chip which has an embedded microcontroller. This element integrates two blocks in its structure, the energy efficient ARM Cortex-M0 core processor block and the 2.4 GHz radio block. Hence, the designed equipment solutions can be highly miniaturized, and the software control of the radio block via a processor is simplified. Another useful functionality of the processor is that internal peripherials (e.g. UART, I2C, PWM) can be connected freely to any pins of the processor, which optimizes the connectivity topography on a PCB, and allows for optimization of the polygon topology (better EMC parameters) or for reduction of the number of PCB layers (lower costs). A great advantage of the processor is that it is fine-tuned for power consumption. The processor, and the radio block allow for operation lasting several years without battery replacement provided that the parameter does not require very frequent measurements. For slowly changing parameters, such as the temperature, humidity, position of the body or skin resistance, the device will remain in operation for months or years without battery replacement or charging. Self-discharge is a significant factor which decreases the shelf-life of a battery already after a few months' operation. For Li-Po batteries the self-discharge process may be ca 5% per month, therefore mainly lithium batteries are used in sensors to be used for a year or longer.

Special attention should be paid to the nRF51x22 radio block which operates in the 2.4GHz bandwidth, and enables wireless connection in popular standards: Bluetooth 4.0 LE, ANT+ (only nRF51422), as well as the use of other protocols adapted to the required needs. The 2.4GHz bandwidth permits the use of low-power protocols due to shorter time of operation of the radio block required for sending a specified amount of data compared with solutions based on ISM bandwidths with lower frequencies. There is an advantage to the high frequency: small-sized antenna can be used, which plays a role in miniaturization.

The BioSip integrator module requires a processor with a higher computing capacity as it is expected to handle a larger amount of tasks, such as the algorithms for initial data processing. While the project was being initiated, a processor with the ARM Cortex-M3 core by STMicroelectronics STM32L162 was selected owing to its low power consumption and a large quantity of communication interfaces. Within the scope of other projects, performance tests were carried out for the analytical libraries developed on evaluation PCBs, containing a processor with the ARM Cortex-M4 core. Processors with this core make it possible to significantly increase the computing capacity of the device, especially because of the availability of the Floating Point Coprocessor, and at the same time they offer low power consumption. An ARM Cortex-M4 core processor would be an optimal choice for the integrator module these days.

BioSip system modules processing large amounts of data, e.g. ECG, consume more energy. They are powered with Li-Po batteries. CR2032 alkaline batteries are used for measurements taken less often. Inductive charging in the popular Qi standard has been used for charging batteries in some modules; inductive charging is frequently used to charge smartphone batteries. The Texas Instruments BQ51050 charger is used for the inductive charging process. The design uses the receiver coil made by TDK and a regular Nokia charger (Fig. 2).

Fig. 2. The receiver coil and Nokia inductive charger.

A. *BioSip system modules*

The focus of the research team at ITAM was on the development of a configurable set of measurement elements that can interoperate in a system or can be used individually. The basic system design is made up of one primary integrator and additional modules transmitting measurement results to the primary module. The integrator module is equipped with a set of wireless interfaces enabling global communication via Wi-Fi or Bluetooth 2.0 with the operator's workstation or a network terminal, as well as communication in a personal area network for the exchange of data with the other BioSip modules. The operator's workstation that the integrator communicates with was not covered by the design and is only an ancillary element used to check the effectiveness of Biosip operation.

The primary module – the integrator – is also equipped with measurement systems and sensory elements, which makes it possible to omit certain additional modules and build less complex monitoring systems. Until now, six elements have been developed in the BioSip module set designed for the monitoring of various ranges of biomedical and environmental parameters (Fig. 3).

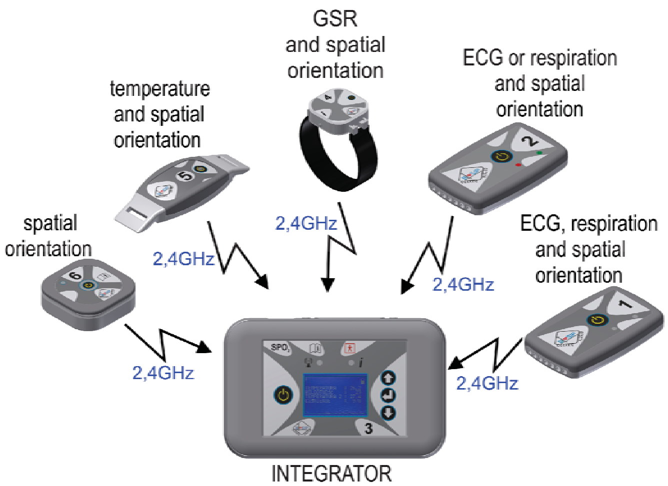

Fig. 3. BioSip system elements.

B. *ECG modules*

Two dual-channel ECG modules which differ by the respiration measurement function were the first measurement modules to be created within the BioSip system.

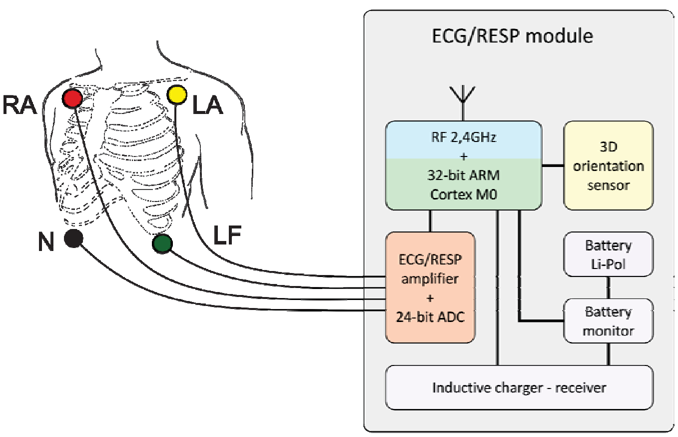

Fig. 4. Block diagram of the ECG modules.

The purpose of the project was to create a miniaturized device for long-term monitoring of basic parameters, indicative of the cardiac and respiratory condition (Fig. 4). Measurement of the ECG signal was the module's main task. The ECG measurement chain which integrates the analogue elements and the 24-bit sigma-delta converter has been built with the use of a dedicated Texas Instruments device ADS1292 or ADS1294R (in the version with the integrated respiration impedance measurement). The module is also responsible for monitoring the movement activity and quality of sleep via an embedded STMicroelectronics LIS3DH accelerometric sensor. Interestingly enough, inductive charging in the Qi standard is used in the device; this is currently a popular standard for charging batteries in smartphones. The battery is charged with the Texas Instruments BQ51050 device.

Fig. 5. The ECG module with the respiration impedance measurement.

The charging status of the Li-pol battery is monitored by the dedicated Texas Instruments charge measurement device BQ27421; this enables precise estimation of the life of the device, and simultaneously offers information about the need to replace the battery depending on the discharge level.

The operation of the module is controlled by the Nordic Semiconductor nRF51x22 device. This is a 32-bit ARM Cortex M0 microcontroller which also consists of a radio block for communication in a personal area network. Moreover, the nRF51x22 SoC enables direct wireless connection with mobile devices, such as a smartphone or tablet, equipped with Bluetooth LE or ANT connections, after providing the nRF51x22 with a software stack handling communication in this standard.

C. *The Integrator Module*

The Integrator (Fig. 6) mainly receives data from wireless BioSip modules placed on the patient's body or from other measurement devices located in close vicinity, such as the sphygmomanometer, glucometer or scales. The Integrator uses a Wi-Fi interface or Bluetooth 2.0 in order to communicate with the “external world” (e.g. the operator's monitoring workstation or network access terminal).

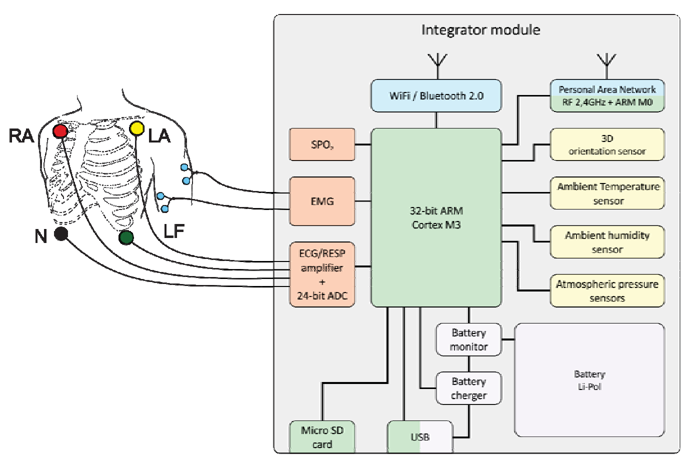

Fig. 6. Block diagram of the BioSip system integrator.

Along with communication functions, the Integrator has the following measurement functions: 5-channel ECG including the respiration rate measurement, 2-channel EMG, an SpO_2 sensor, a spatial orientation sensor, as well as sensors for monitoring environmental parameters (temperature, humidity, air pressure).

The Texas Instruments ADS1294R device was used to process the 2-channel ECG and measure the respiration rate. The module also includes the processing function of a 2-channel EMG signal made with the use of mainly Texas Instruments INA333 instrumentation amplifiers, and a 12-bit approximation converter of the main microcontroller. The integrator also permits the connection of a Nonin SpO_2 sensor, and the measurement of saturation, pulse, and monitoring of the plethysmographic signal.

Additional measurement functions of the module's spatial orientation are provided by the orientation sensor InvenSense MPU-9150 which integrates the following elements: the accelerometer, gyroscope, magnetometer as well as the Digital Motion Processor permitting the use of algorithms responsible for spatial orientation. The integrator also permits the measurements of the parameters of the environment in which the subject is staying, such as temperature, humidity and air pressure. Temperature and humidity are measured with a Sensirion SHT25 sensor. Air pressure is measured with a Bosch BMP085 sensor.

Wireless communication with extra sensors is handled with the Nordic Semiconductor nRF518*x*22 device as described above. The integrator is equipped with a monochromatic 128x64 LCD display module. As a result, it is possible to configure the device and view the measured parameters.

The integrator has been equipped with a relatively large 3.7V, 1950mAh Li-Po battery charged from a USB port. The battery is charged with the Intersil ISL6292 charger.

Fig. 7 demonstrates a visualization of the integrator's enclosure.

Fig. 7. Visualization of the BioSip integrator enclosure.

D. The GSR module

The GSR module is responsible for measuring resistance of the hand's skin. This parameter is of particular importance for the assessment of the subject's stress level. The module presented in Fig. 8 has been constructed in the form of a "watch" attached to the subject's wrist. GSR measurements are taken by means of an operational amplifier and a source of electric current. The Microchip MCP6H02 operational amplifier was used owing to good Rail-to-Rail parameters permitting measurements in a broad resistance range, at present from 10kΩ to 10MΩ.

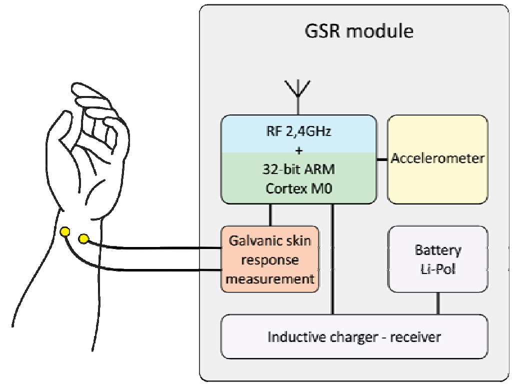

Fig. 8 Block diagram of the GSR module.

Apart from the GSR measurement, the module provides acceleration measurements in three axes with the STMicroelectronics LIS3DH accelerometer.

The operation of the GSR module and radio connection are handled by the Nordic Semiconductor nRF518*x*22 microcontroller. The module also uses a 10-bit A/D converter of a microcontroller for GSR measurements. The microcontroller may select amplification from three measurement ranges in order to obtain the aforementioned measurement range.

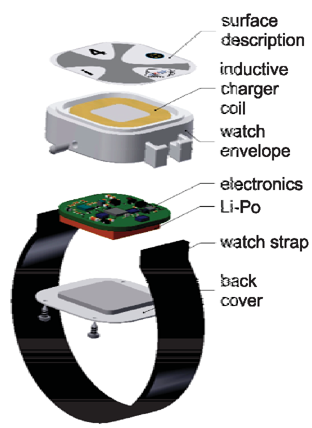

Fig. 9. Visualization of the GSR module elements.

The GSR module is powered by a 3.6V, 105mAh Li-Po battery. Inductive charging is applied (Fig. 9).

E. The skin temperature module

A miniature module has been used to take skin temperature measurements. The module may be stuck to the body with an adhesive plaster or placed in a strap on the chest (Fig. 10).

Fig. 10. Visualization of the skin temperature module enclosures from the left: the plaster, strap.

The body temperature measurement is taken with the Measurement Specialties TSYS01 sensor of high precision (±0.1°C) obtained due to sensor calibration at the production stage. The measurement of accelerations with the STMicroelectronics LIS3DH device is an additional function of this module. The indications of this sensor may be used for the measurement of the body position, for example during sleep. The Nordic Semiconductor nRF51x22 device is responsible for module control and radio connection (Fig. 11).

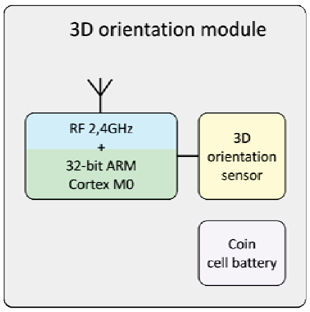

Fig. 11. Block diagram of the skin temperature module.

Owing to the fact that temperature is rarely measured, and ultra low power components are used, the module is powered by one battery CR2032 (Fig. 12).

Fig. 12. Photo of the skin temperature module.

F. *The spatial orientation module*

The spatial orientation module is the last component of the BioSip module. It analyzes motion, and movements of the sensor (Fig. 13).

The applied measurement element is the orientation sensor InvenSense MPU-9150 integrating the following elements: the accelerometer, gyroscope, magnetometer as well as the IMU processor which permits the use of algorithms responsible for the calculation of spatial orientation. Like in the aforementioned measurement module, the Nordic Semiconductor nRF51x22 is responsible for module control and radio connection. The device is powered by the CR2032 battery.

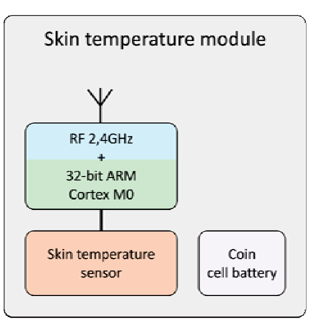

Fig. 13. Block diagram of the spatial orientation module.

G. *Pulse measurement module*

The last developed system element is the pulse measurement module created as a comprehensive extension of the GSR module concept. The device has the form of a watch worn on the wrist. The functional capacity of the module has been significantly extended compared with the GSR module. The module will additionally measure the pulse transit time (PTT) and the pulse wave velocity (PWV). Just like the GSR module, the pulse measurement module can measure GSR and define spatial orientation with the use of an accelerometer. The pulse measurement module is additionally equipped with a precise skin temperature sensor, similar to the BioSip-5 module which measures the temperature on the wrist. What is new about the module is the patient's pulse recording function.

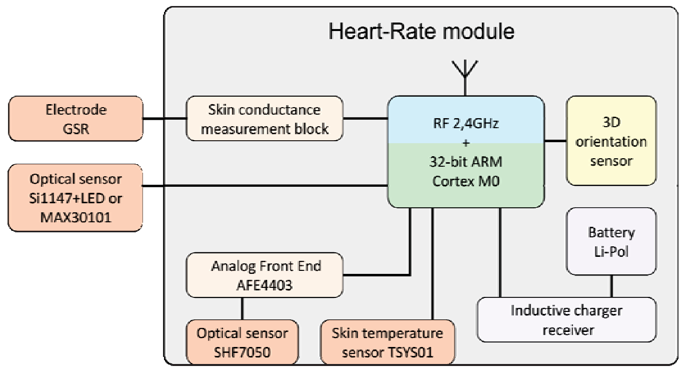

Fig. 14. Block diagram of the pulse measurement module

Several interesting solutions are currently available on the market when it comes to optical sensors for pulse and SpO_2 measurements with the reflection method. Specialized modules by Silicon Labs, Si1147 as well as MAX30101 by Maxim Integrated attracted our attention during the works. In its structure, the first module integrates input amplifiers, the logic that automates the process of sampling the plethysmographic wave as well as the receiving photodiodes. Only the transmitting LED diodes should be connected as external elements. The second solution is the Maxim Integrated module which, in its structure, integrates all elements of the sensor, i.e. the control logic, input amplifiers, the receiving photodiode, and three transmitting diodes: green, red and infrared.

The third solution deployed in the presented device is the specialized module AFE4403 by Texas Instruments, and sensor SHF7050 containing lighting LED diodes: green, red and infrared, and the receiving photodiode. The sensor can also record the pulse wave on the wrist with the reflection method. The module can be adjusted to record pulse only with the green LED diode, or to measure oxygen saturation and pulse with red and infrared LED diodes. The green colour makes it possible to obtain signals with a much higher amplitude than red or infrared; this results in higher resilience of the measurement module to limb movements. Unfortunately, if oxygen saturation (SpO_2) is to be measured, light wavelengths that are less resilient to movement must be applied.

The module also provides for the option to record pulse on the patient's finger with electrodes. An additional electrode which measures GSR only in the basic configuration has been used in this method. The conductive bottom part of the module enclosure is the second electrode.

Fig. 15. BioSiP pulse module

III. SUMMARY

The presented equipment solutions are the result of project works preceded by gathering extensive experience during various projects dedicated to monitoring systems at the Institute of Medical Technology and Equipment (ITAM) in Zabrze. The proposed solutions have also been created in response to global trends in this field, supported by the analysis of options used in the equipment available on the market. This paper describes the current status of the works. The tests of ready-made modules will provide an answer to the question if all the assumptions have been satisfactorily achieved. Future papers will offer an answer whether all the system potential, measurement parameters, times of operation without battery charging or battery replacement, as well as ease of use may be regarded as a practical solution for latest-generation systems designed to monitor an individual's biomedical parameters and behaviour.

ACKNOWLEDGMENTS

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Andrzej Michnik was born in Bytom, Poland, in 1976. He received the M.Sc degrees from the Silesian University of Technology in Electronic and Telecommunication (specialization: electronic equipment) in 2001.
Currently employed at the Institute of Medical Technology and Equipment ITAM as a constructor electronic and assistant. He is a member of telemedical systems department. He has been working on electronic design and programming embedded systems.
His main field of study are medical electronic, mechatronics in rehabilitation and wireless communications.

Zbigniew Szczurek received the M.Sc. degrees from Silesian University of Technology of Gliwice Poland in 1976. Since 1976 till now he is employed in Institute of Medical Technology and Equipment ITAM in Zabrze. He is designer of modern equipment for diagnostics, therapy and medical rehabilitation. He is interested in designing systems for remote monitoring of vital parameters and telemedical care.

Barbara Szuster was born in Mikołów, Poland, in 1989. She received the B.Sc degrees from the Silesian University of Technology in Biomedical Engineering in 2012 and M.Sc in Electronic and Telecommunication (specialization biomedical electronics) in 2013.
Currently employed at the Institute of Medical Technology and Equipment ITAM as a constructor electronics and assistant. She is a member of telemedical systems department. She has been working on electronic design and programming embedded systems and test benches.
She main field of study are medical electronic, processing and analysis of bioelectric signals used for the create the systems based on a personal body area network.

Batłomiej Kubik received the M.Sc degrees from the Silesian University of Technology in automatics and electrical metrology in 2011. From to 2010-2016 he was a constructor and programmer electronics in the department of telemedical systems in the Institute of Medical Technology and Equipment ITAM in Zabrze. He has been working on electronic design and programming embedded systems and test benches and oversee a lot of projects e.g. *BIO-SIP, MICROS, Revitus-T, Monitel-HF, Rengo, IR-Diagnostics*. His main field of study are medical electronic, systems based on a personal body area network, system to monitor the treatment of burn wounds and systems for the special applications.

Paweł Kowalski received the M.Sc degrees from the Silesian University of Technology in Automatics and Robotics in 2003. He is currently pursuing the Ph.D. degree in mechanics at the Silesian University of Technology. From to 2004-2012 he was a constructor electronics and assistant in the department of telemedical systems in the Institute of Medical Technology and Equipment ITAM in Zabrze. Currently employed as a manager in department of telemedical systems. He has been working on electronic design and programming embedded systems and test benches and oversee a lot of projects realized in Institute. His main field of study are medical electronic, processing and analysis of bioelectric signals used for the create the systems based on a personal body area network, system to monitor the treatment of burn wounds and systems for the cardiac rehabilitation and special applications.