VALIDATION OF A NOVEL FIBER-OPTIC SENSOR SYSTEM FOR MONITORING CARDIORESPIRATORY ACTIVITIES DURING MRI EXAMINATIONS

Jan NEDOMA[1], *Marcel FAJKUS*[1], *Martin NOVAK*[1],
Nela STRBIKOVA[2], *Vladimir VASINEK*[1], *Homer NAZERAN*[3],
Jan VANUS[2], *Frantisek PERECAR*[1], *Radek MARTINEK*[2]

[1]Department of Telecommunications, Faculty of Electrical Engineering and Computer Science,
VSB–Technical University of Ostrava, 17. listopadu 15, 708 33 Ostrava, Czech Republic
[2]Department of Cybernetics and Biomedical Engineering, Faculty of Electrical Engineering and Computer Science, VSB–Technical University of Ostrava, 17. listopadu 15, 708 33 Ostrava, Czech Republic
[3]Department of Electrical and Computer Engineering, College of Engineering,
University of Texas El Paso, 500 W University Ave, El Paso, TX 79968, United States of America

jan.nedoma@vsb.cz, marcel.fajkus@vsb.cz, martin.novak.st@vsb.cz, nela.strbikova.st@vsb.cz
vladimir.vasinek@vsb.cz, hnazeran@utep.edu, jan.vanus@vsb.cz, frantisek.perecar@vsb.cz,
radek.martinek@vsb.cz

DOI: 10.15598/aeee.v15i3.2194

Abstract. *In this article we report on the validation of a novel fiber-optic sensor system suitable for simultaneous cardiac and respiration activity monitoring during Magnetic Resonance Imaging (MRI) examinations. This MRI-compatible Heart Rate (HR) and Respiration Rate (RR) measurement system is based on the Fiber-optic Bragg Grating (FBG) sensors. Using our system, we performed real measurements on 4 test subjects (2 males and 2 females) after obtaining their written informed consents. The sensor was encapsulated inside a Polydimethylsiloxane polymer (PDMS), as this material does not react with the human skin and is unresponsive to Electromagnetic Interference (EMI). The advantage of our design is that the sensor could be embedded inside a pad which is placed underneath a patient's body while lying in the supine position. The main feature of our system design is to maximize patient's safety and comfort while assisting the clinical staff in predicting and detecting impending patient's hyperventilation and panic attacks. To further validate the efficacy of our system, we used the Bland-Altman statistical analysis test on data acquired from all test subjects to determine the accuracy of cardiac and respiratory rate measurements. Our satisfactory results provide promising means to leverage the advancement of research in the field of noninvasive vital sign monitoring in MRI environments. In addition, our method and system enable the clinical staff to predict and detect patient's hyperventilation and panic attacks while undergoing an MRI examination.*

Keywords

Electromagnetic interference, fiber Bragg grating, fiber-optic sensor, heart rate, magnetic resonance imaging environment, noninvasive, polydimethylsiloxane, respiration rate, vital sign monitoring.

1. Introduction

Hyperventilation and panic attacks in patients undergoing an MRI examination are major concerns for clinicians and MRI machine operators due to their very frequent occurrence [1], [2] and [3]. Hyperventilation is a state of abnormally fast and deep breathing, preceded by a feeling of shortness of breath or "air hunger" (dyspnea). Symptoms of hyperventilation in an anxious patient include faintness or impaired consciousness, sometimes along with a felling of chest tightness, a sensation of smothering, fast heart palpitation, and dizziness. As a result, the patient may exhibit muscle cramps and panic attacks. Therefore, monitoring a patient's respiration and heart rates during an MRI examination can prove very useful and assist the clinical staff in predicting impending hyperventilation and panic attacks.

A possible method to monitor a patient's vital signs during an MRI examination is to use Fiber-Optic Sensors (FOS). These sensors are finding increased applications in many fast developing biomedical areas including performing measurements in MRI environments [4].

Recent advancements in this field can be summarized as follows [5], [6] and [7]. Chethana et al. [5] report interesting results on the design and construction of an FBG-based sensor suitable for heart rate and respiratory rate monitoring. As this sensor is applied to a patient‘s chest, it is very important to pay special attention to the tension developed in the optical fiber to ensure that adequate sensitivity is reached during measurements. It should be mentioned that this sensor has not been tested in an MRI environment. Dziuda et al. [6] report their results obtained from an FBG-based optical strain sensor used for monitoring respiration and cardiac activities during an MRI examination. These authors offer a solution based on Ballistocardiography (BCG), which uses a different measurement principle compared to the sensor described in [5]. In article [7], Dziuda et al. describe the validation of a fiber-optic sensor for monitoring respiratory and cardiac activities under laboratory conditions and report a maximum relative measurement error of 12 %.

From the brief review above, it is evident that noninvasive vital sign monitoring in MRI environments still faces some challenges and there is more room for research and improvement in this field. Recognizing this demand, our research team has developed a novel sensor system that allows monitoring the mechanical vibrations in the human body which are evoked by living activities such as breathing and cardiac rhythms [8], [9] and [10]. Our main aim here is to report the evaluation results of our small size, low-cost fiber-optic sensor solution with minimal weight in the form of a pad, which could be placed underneath a patient's body while lying in a supine position, thereby enabling simultaneous monitoring of cardiac and respiratory activities with an accuracy exceeding 95 %. The relative error level of approximately 5 % in our sensor system is clinically acceptable as our system is designed for cardiorespiratory activity monitoring rather than for performing accurate diagnosis of cardiopulmonary conditions. In addition, our sensor offers the advantage of enabling the clinical staff to detect and predict impending hyperventilation and panic attacks during MRI examinations.

2. Methods

Our novel measurement probe (weight: 150 g, dimensions: first layer - 75 × 75 × 4 mm, second layer - 10 × 10 × 1 mm) is based on a FBG encapsulated inside a PDMS polymer. A FBG is formed by a periodic change of refractive index in the core of optical fiber (n_1, n_3) and n_2 represents the refractive index of the fiber cladding, see Fig. 1.

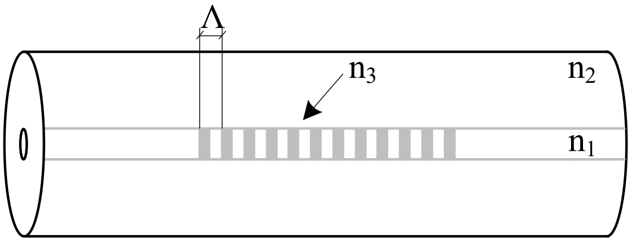


Fig. 1: Structure of fiber Bragg grating.

Dependent on the grating period, the light of a specific wavelength called the Bragg wavelength λ_B is reflected, and the other wavelengths are transmitted. FBG is one of the most widely used types of the fiber-optic sensors [4], [11], [12] and [13]. The Bragg wavelength is given by:

$$\lambda_B = 2 n_{eff} \Lambda, \tag{1}$$

where n_{eff} is the effective refractive index of the used optical fiber with Bragg grating and Λ is the period of changes in the refractive index of the core of the used optical fiber.

The primary use of FBG is based on the deformational and temperature sensitivities. According to dependencies on the mechanical stress and temperature, size of Bragg wavelength change $\Delta\lambda_B$ can be defined by:

$$\frac{\Delta\lambda_B}{\lambda_B} = k\varepsilon + (\alpha_\Lambda + \alpha_n)\Delta T, \tag{2}$$

where k is the deformational coefficient, α_n the optical temperature coefficient, α_Λ the coefficient of thermal expansion, ΔT the temperature change, and ε the applied deformation. Deformational and temperature dependence are determined both by the parameter values and the central Bragg wavelength. Normalized deformational and temperature coefficients are determined based upon their individual sensitivities [14], [15] and [16].

The normalized FBG strain response at constant temperature is:

$$\frac{1}{\lambda_B}\frac{\Delta\lambda_B}{\Delta\varepsilon} = 0.78 \cdot 10^{-6}\ \mu\varepsilon^{-1}, \tag{3}$$

where $\Delta\varepsilon$ is the applied deformation change and the normalized temperature sensitivity at constant strain is:

$$\frac{1}{\lambda_B}\frac{\Delta\lambda_B}{\Delta T} = 6.678 \cdot 10^{-6}\ ^{\circ}\mathrm{C}^{-1}. \tag{4}$$

The Polydimethylsiloxane polymer does not react with the human skin and is resistant to EMI. The cumulative results presented in our published works [17], [18], [19], [20] and [21] indicate that this type of encapsulation does not affect the structure of the FBG or interferometer. Figure 2 shows the experimental setup and the positioning of our sensor system to acquire data from a test subject.

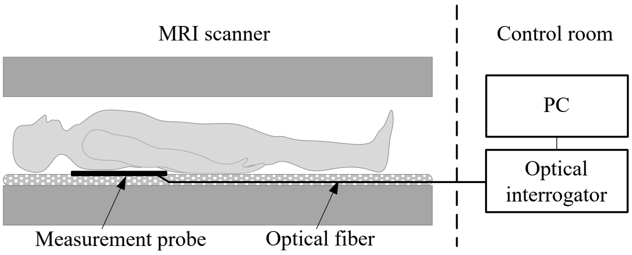


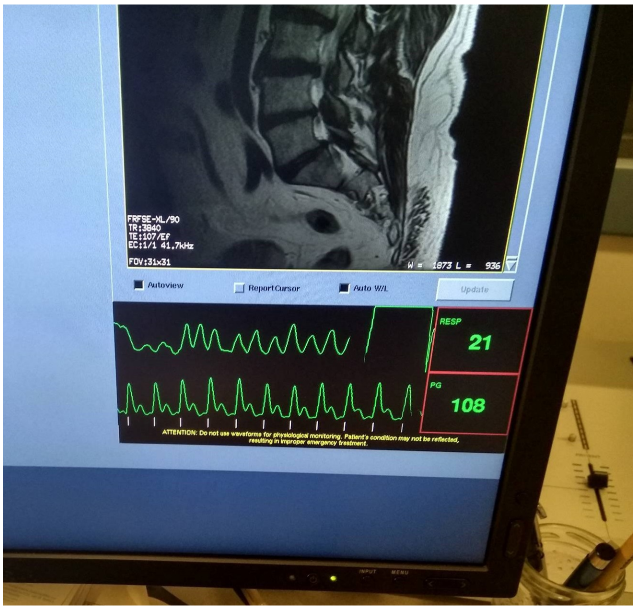
Fig. 2: Positioning of the sensor system and the experimental setup.

Data obtained from our FBG-based sensor were transferred to a control room by using an optical fiber based on the G.652.D Standard. The Optical Interrogator is composed of a wideband spectral light source from a Light-Emitting Diode (LED) with a central wavelength of 1550 nm, a spectral width of 40 nm and an output power of 1.5 mW. Furthermore, our data collection system is composed of an Optical Circulator, an Optical Spectrum Analyzer (OSA) using a sampling frequency of 100 Hz, in addition to a Digital Signal Processing (DSP) as well as an Electronic Control Unit (ECU) for each individual optical element. The cardiac and respiratory signals sensed by our sensor were further processed by our data acquisition system and finally displayed on a PC screen in a graphical user interface as part of an application created in LabVIEW (2015, National Instruments, Austin, Texas, USA).

To obtain the Heart Rate (HR) and Respiratory Rate (RR) in our tested subjects, we first performed a spectral evaluation of the measured signals and then implemented peak detection to calculate the time intervals between these peaks. The RR values were expressed in respiration per minute (rpm) and the HR values were expressed in beat per minute (bpm). These were calculated as the inverse of the detected time intervals in these signals and were then multiplied by 60.

3. Results

Data collection was carried out in a clinical setup (Private Clinic Prostejov) on 4 test subjects (2 males: age: 26 and 28 year, height: 174 and 179 cm, weight: 78 and 84 kg; and 2 females: age: 21 and 26 year, height: 162 and 167 cm, and weight: 52 and 58 kg) after obtaining their written informed consents. A Signa HDxt 1.5T MRI Scanner [22] was used in our experiments (Please see Fig. 4). To obtain reference heart and respiratory rate information we made use of the Scanner's built-in features (Please see the lower part of Fig. 3). The total data acquisition time for all of the four test subjects was 87 minutes and 43 seconds.



ATTENTION: Do not use waveforms for physiological monitoring. Patient's condition may not be reflected, resulting in improper emergency treatment.

Fig. 3: Estimated reference heart and respiratory signals and their rates displayed by the Signa HDxt 1.5T MRI Scanner (Please see lower part of this figure).

For better visualization of the experimental setup and positioning of the cardiorespiratory sensor within the MRI Scanner's bed, Fig. 4 shows a photo with the sensor pad encircled with red color.

To compare the differences between the HRs and RRs estimated from the cardiac and respiratory signals acquired from our sensor pad with their corresponding reference values (HRs and RRs) determined from the Signa HDxt 1.5T MRI Scanner, the Bland-Altman Plots were used [23]. In these plots, the differences between the sensor and the reference data (reference - sensor), are plotted against their average, (reference + sensor)/2 values. The reproducibility is considered to be good if 95 % of the results lie within a ±1.96 SD (Standard Deviation) range. Please see Fig. 6.

Figure 5 shows an example of a 60-second recording of the respiratory activity in a male subject (MAN2) sensed by our FBG-based sensor.

Fig. 4: A photo of the sensor pad positioned within the MRI Scanner's bed (encircled with red color).

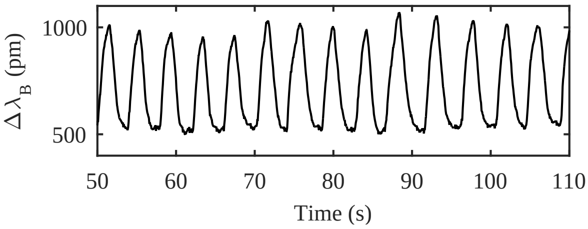
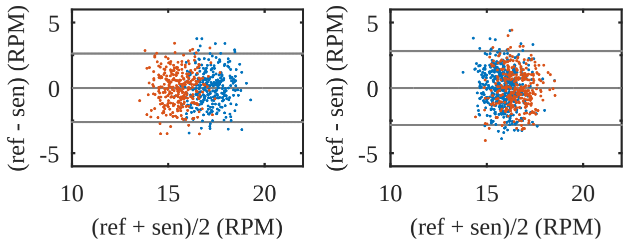


Fig. 5: The recording from our FBG sensor representing the time course of the respiratory activity in a male test subject (MAN2).

The key results of the respiratory rate measurements are summarized in Tab. 1. Recording time represents the subject's total data acquisition time and NoS sensor represents the number of measured samples from the FBG sensor. The maximum relative error was 4.41 %. For the entire data set, 96.10 % (96.29 % for males and 95.91 % for females) of the values lied within the ±1.96 SD range for the respiratory rate accuracy determination. Figure 6 shows the Bland-Altman Plot of respiratory rate measurements for two male (left) and for two female (right) subjects.



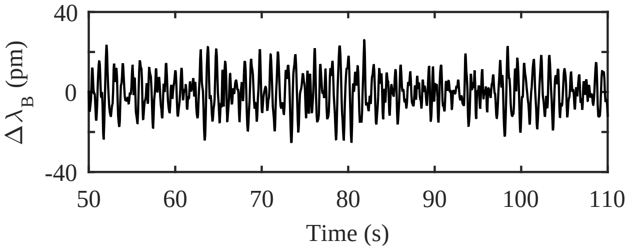
(a) Two male subjects. (b) Two female subjects.

Fig. 6: Statistical analysis using the Bland-Altman Plots for respiratory rate measurements.

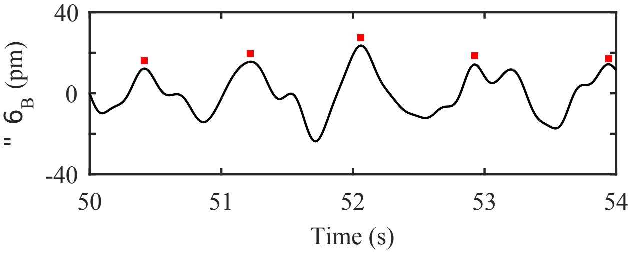
Figure 7(a) shows an example of a 60-second recording of cardiac activity in a female subject (F1) sensed by our FBG-based sensor. Figure 7(b) shows a 4-second expanded version of the recording shown in part Fig. 7(a).

Tab. 1: Statistical data for respiratory rate measurements in 4 test subjects.

Subject	**Rec. time (s)**	**Respiratory Rate (RR)**	
		NoS sensor	**Samples in ±1.96 SD (%)**
MAN1	1032	295	96.27
MAN2	1157	298	96.31
FEMALE1	1876	497	95.77
FEMALE2	1198	329	96.05



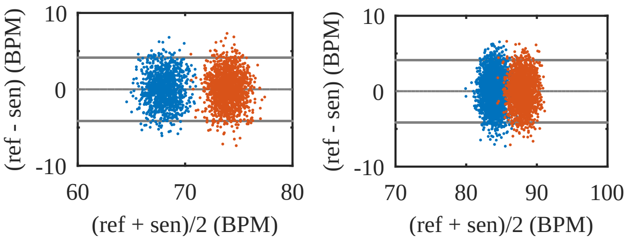
(a) 60-second recording.



(b) 4-second expanded version (red dots show the local maxima of the recordings or the detected peaks).

Fig. 7: The recording of cardiac beat activity by using our FBG sensor in a female test subject (F1).

The key results of the heart rate measurements are summarized in Tab. 2. Recording time represents the subject's total data acquisition time and NoS sensor represents the number of measured samples from the FBG sensor. The maximum relative error was 5.86 %. For the entire data set, 95.49 % (95.61 % for males and 95.37 % for females) of the values lied within the ±1.96 SD range for the heart rate determination. Figure 8 shows the Bland-Altman Plots of the heart rate measurements for two male (left) and for two female (right) subjects. Based on Bland-Altman statistical analysis, we can state with confidence that no basic systematic errors occurred in our measurements. The sensor showed satisfactory results in measuring both the respiratory and the heart rates with acceptable accuracy without systematic errors.



(a) Two male subjects.

(b) Two female subjects.

Fig. 8: Statistical analysis using the Bland-Altman Plots for heart rate measurements.

Tab. 2: Statistical data for heart rate measurements in 4 test subjects.

Subject	**Rec. time (s)**	**Heart Rate (RR)**	
		NoS sensor	**Samples in ±1.96 SD (%)**
MAN1	1032	1118	95.64
MAN2	1157	1363	95.58
FEMALE1	1876	2542	95.13
FEMALE2	1198	1680	95.61

4. Conclusion

Here we reported on the validation of a novel fiber-optic sensor system suitable for simultaneous cardiac and respiration monitoring during Magnetic Resonance Imaging (MRI) examinations. The sensor's functionality was verified by performing a series of real measurements carried out in a clinical setup (Prostejov Private Clinic) on four test subjects after obtaining their written informed consents. During data collection, the subjects were asked to express their personal feeling of comfort level. None of the subjects experienced any feeling of discomfort. The Bland-Altman statistical analysis of the acquired data demonstrated that there were no basic systematic errors in the measurement data. The sensor showed satisfactory results in accurately measuring both respiratory and heart rates. For the entire data set 95.49 % of the values lied within the ±1.96 SD range for the heart rate determination and 96.10 % for the respiratory rate determination. The results of heart rate measurements were characterized by a maximum relative error of 5.86 % while the respiratory rate measurements were characterized by a maximum relative error of 4.41 %.

Our satisfactory results provide promising means to leverage the advancement of research in the field of noninvasive vital sign monitoring in MRI environments. Furthermore, our method and system enable the clinical staff to predict and detect impending hyperventilation and panic attacks in patients while undergoing an MRI examination.

For our future research, we are very excited to report that the clinicians at the Prostejov Private Clinic in the Czech Republic have agreed to deploy our novel sensor system to investigate its utility and evaluate its efficacy in predicting and detecting impending hyperventilation and panic attacks in their patients during MRI examinations.

Acknowledgment

This article was supported by the project of the Technology Agency of the Czech Republic TA04021263 and by Ministry of Education of the Czech Republic within the projects Nos. SP2017/128 and SP2017/79. The research has been partially supported by the Ministry of Education, Youth and Sports of the Czech Republic through the grant project no. CZ.1.07/2.3.00/20.0217 within the frame of the operation programme Education for competitiveness financed by the European Structural Funds and from the state budget of the Czech Republic. This article was also supported by the Ministry of the Interior of the Czech Republic within the project No. VI20152020008.

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About Authors

Jan NEDOMA was born in 1988 in Prostejov. In 2012 he received a Bachelor's degree from VSB–Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science, Department of Telecommunications. Two years later, he received his Master's degree in the field of Telecommunications in the same workplace. He is currently employee and a Ph.D. student of Department of Telecommunications at VSB–Technical University of Ostrava. He works in the field of fiber-optic sensor systems.

Marcel FAJKUS was born in 1987 in Ostrava. In 2009 he received a Bachelor's degree from VSB–Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science, Department of Telecommunications. Two years later, he received a Master's degree in the field of Telecommunications in the same workplace. He is currently employee and a Ph.D. student of Department of Telecommunications at VSB–Technical University of Ostrava. He works in the field of optical communications and fiber-optic sensor systems.

Martin NOVAK was born in 1989 in Prostejov. In 2012 he received a Bachelor's degree from VSB–Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science, Department of Telecommunications. Three years later, he received his Master's degree in the field of Telecommunications in the same workplace. He is currently Ph.D. student of Department of Telecommunications at VSB–Technical University of Ostrava. He works in the field of optical communications and fiber-optic sensor systems.

Nela STRBIKOVA was born in 1993 in Sumperk. In 2017 she received a Master's degree from VSB–Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science, Department of Cybernetics and Biomedical Engineering. She wants to continue with her studies in Ph.D. program in Department of Technical Cybernetics.

Vladimir VASINEK was born in Ostrava. In 1980 he graduated in Physics, specialization in Optoelectronics, from the Science Faculty of Palacky University. He was awarded the title of RNDr at the Science Faculty of Palacky University in the field of Applied Electronics. The scientific degree of Ph.D. was conferred upon him in the branch of Quantum Electronics and Optics in 1989. He became an associate professor in 1994 in the branch of Applied Physics. He has been a professor of Electronics and Communication Science since 2007. He pursues this branch at the Department of Telecommunications at VSB–Technical University of Ostrava. His research work is dedicated to optical communications, optical fibers, optoelectronics, optical measurements, optical networks projecting, fiber-optic sensors, MW access networks. He is a member of many societies: OSA, SPIE, EOS, Czech Photonics Society; he is a chairman of the Ph.D. board at the VSB-Technical University of Ostrava. He is also a member of habitation boards and the boards appointing to professorship.

Homer NAZERAN holds B.Sc., M.Sc. and Ph.D. degrees in Electrical (Honors), Clinical and Biomedical Engineering from UT Austin, Case Western Reserve and University of Texas Southwestern Medical Center (UTSWM) at Dallas/UTA, respectively. He has close to 3 decades of experience in industry and academia and has practiced and taught biomedical engineering in the Middle East, Europe, Australia and USA. In Australia, with Professor Andrew Downing he co-founded the School of Engineering at the Flinders University of South Australia, introduced and established the electrical and electronics and biomedical engineering degree programs (1991 to 2001). He returned to the University of Texas at Arlington as a visiting professor in 1997 and 2001. He joined UTEP in 2002 to create and establish biomedical engineering degree programs at the Department of Electrical and Computer Engineering. His research interests are in the areas of computer modeling of physiological systems, intelligent biomedical instrumentation and biomedical signal processing as applied to chronic health conditions and telemedicine. He has more than 150 journal and conference articles in his research areas published in IEEE Engineering in Medicine and Biology Society (EMBS) and other flagship international conference proceedings. He is a reviewer for several national and international journals in his related fields including IEEE Transactions on Biomedical Engineering, Medical and Biological Engineering and Computing, Biomedical Engineering Online and others. His teaching interests are in electronics, biomedical instrumentation, physiological systems, and biomedical signal processing. He is also interested in development of novel teaching methods, lifelong learning and critical thinking habits in the classroom and interdisciplinary education based on application of nonlinear dynamics systems (complexity) theory. His research, teaching and professional activities have been supported by NIH, NSF, and DOE among others.

Jan VANUS was born in 1972 in Czech Republic. He is currently Academic Staff Member, Department of Cybernetics and Biomedical Engineering of the Faculty of Electrical Engineering and Computer Science, VSB–Technical University of Ostrava. The research title is "Design and application Intelligent Buildings Control Systems". His research interests include Smart Home and Smart Home Care (remote comfort control, visualization, Data Mining, Big Data processing, energy management, optimization, recognition, classification, prediction), speech signal processing, adaptive filters, voice communication with control system.

Frantisek PERECAR was born in 1989 in Presov. In 2011 he received a Bachelor's degree from University of Zilina. Two years later, he received his Master's degree in the field of Telecommunications in the same workplace. He is currently a Ph.D. student of Department of Telecommunications at VSB–Technical University of Ostrava. He works in the field of fiber-optic sensor systems.

Radek MARTINEK was born in 1984 in Czech Republic. In 2009 he received Master's degree in Information and Communication Technology from VSB–Technical University of Ostrava. Since 2012 he worked here as a research fellow. In 2014 he successfully defended his dissertation thesis titled "The use of complex adaptive methods of signal processing for refining the diagnostic quality of the abdominal fetal electrocardiogram". He works as an associate professor at VSB–Technical University of Ostrava since 2017.