IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received May 7, 2021, accepted June 26, 2021, date of publication July 6, 2021, date of current version July 19, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3095219

Fiber-Optic Bragg System for the Dynamic Weighing of Municipal Waste: A Pilot Study

MARCEL FAJKUS[1], JAN NEDOMA[1], (Member, IEEE), RADEK MARTINEK[2], (Member, IEEE), LUKAS DANYS[2], MICHAEL FRIDRICH[1], PAVEL MEC[3], AND STANISLAV ZABKA[1]

[1]Department of Telecommunications, Faculty of Electrical Engineering and Computer Science, VSB—Technical University of Ostrava, 70833 Ostrava, Czech Republic
[2]Department of Cybernetics and Biomedical Engineering, Faculty of Electrical Engineering and Computer Science, VSB—Technical University of Ostrava, 70833 Ostrava, Czech Republic
[3]Department of Building Materials and Diagnostics of Structures, Faculty of Civil Engineering, VSB—Technical University of Ostrava, 70833 Ostrava, Czech Republic

Corresponding author: Marcel Fajkus (marcel.fajkus@vsb.cz)

This work was supported in part by the European Regional Development Fund in Research Platform focused on Industry 4.0 and Robotics in Ostrava under Project CZ.02.1.01/0.0/0.0/17_049/0008425 within the Operational Programme Research, Development, and Education, and in part by the Ministry of Education of the Czech Republic under Project SP2021/32 and Project SP2021/45.

ABSTRACT The publication focus on a pilot study (design, implementation and verification) of a dynamic weighing system designed for weighing of municipal waste during the dumping of garbage containers. The presented solution is based on fiber Bragg gratings (FBG) and can be additionally implemented into the lifting equipment of commonly employed garbage trucks. The weighing principle is based on the measurement of deformation effect and vibration response of the lifting equipment during the dumping of garbage bins. The measuring system leverages the advantages of power measurement, which use the conversion of the spectral shift of modulated light signal during the measurement to the change in optical power of a pair of spectral overlapping Bragg gratings. Two different methods are presented and discussed: the amplitude method, which analyze the maximum amplitude change of the signal and/or the method, which analyze the time period of the dampened oscillation of the lifting device. Due to the small dimensions, the complete system can be installed together with FBG sensors directly onto the lifting device. The pilot tests of the presented system were carried out for over 4 months, showing an accuracy of up to ±4.04 kg in the range of 10-100 kg for standardized containers used for municipal waste. The system worked in completely standalone mode and the garbage trucks were not modified in any inconvenient way.

INDEX TERMS Fiber Bragg grating, optical sensor, dynamic weighing.

I. INTRODUCTION AND STATE-OF-THE-ART

Dynamic waste weighing offers a solution for tariffication of citizens based on the amount of produced waste. This advantage is overlapping – the detailed overview of garbage containers (including the information regarding their used or free capacity) can be used by smaller cities or municipalities to reduce waste disposal costs and additional fees. The whole waste disposal process can also be optimized internally or externally, based on gathered data and behavior of citizens. These major advantages are behind the increasing deployment of dynamic weighing systems. RFID systems, which use inactive plastic chips placed on waste bins, can be used to transmit the required information [1]–[4]. When the garbage truck is equipped with a weighing system, an information on the commodity and weight of the waste can be directly transmitted, thus identifying, and charging the specific citizen. The data is usually stored in a centralized database and evaluated by a control node.

The conventional approaches for measuring vehicle weight, or dynamic weighing respectively, are nowadays divided into two preferred directions of development: Weigh-In-Motion (WIM) and On-Board Weighing (OBW). WIM systems are independent and external, while the OBW systems are built into the vehicle itself. WIM technology is usually used to measure the axle load of vehicle during its movement in combination with induction loops [5]–[7]. The deployment of fiber optic systems for dynamic weighing while driving based on various principles is further described in publications [8]–[17]. For example, Malla *et al.* [8]

The associate editor coordinating the review of this manuscript and approving it for publication was Salvatore Surdo.

presents interesting experimental results from a measurement on a special optical fiber to measure wheel loads of vehicles. The fiber used has a unique design with two concentric light-guiding regions of different effective optical path lengths, which has the potential to enable direct measurement of magnitudes as well as locations of forces acting at multiple points along a single fiber. In general, these systems are characterized by an error rate of up to ±10 %.

The so-called OBW systems, which are installed directly on the vehicle can be a much more interesting subject. The common goal of the studies mentioned below is to design lightweight sensors and system, with high accuracy that can be easily installed into the existing vehicles (either directly from the factory or retrofitted). The article [18] describes a capacitive flexible sensor, whose dynamic behavior was described using the Maxwell-Kelvin model. The results showed that the measurement error is less than ±10 %. Kheiralla *et al.* [19] dealt with the development of an on-board weighing solution for an industrial wheel loader to provide on-the-go weighing for trucks. Described measuring system consists of the sensing elements (strain gauges), which were based on three locally made load pins transducers replaced the existing pins between the wheel loader arm and the bucket. System accuracy is within acceptable range limit 0.7 % and 1 % of the measured magnitudes under static and dynamic measurements, respectively. Radoiĉić [20] presented a measuring system that is based on a pressure sensor mounted directly within a hydraulic piston, which is used to lift the waste containers. Radoicic and others [21] describe an alternative system for continuous vehicle weighing during waste collection while in motion, which is based on strain gauges. Their deviations in the measured weight values have not exceeded 0.5 %. The collective behind article [22] describes a system where the cargo weight during loading is determined by the gas pressure in the suspension cylinders at the time of the oscillation ending and at the start of the vibration smoothing process. The weighing error is defined by a maximum of 3 %. Article [23] describes a vehicle on-board weighing system based on BP (Back Propagation) neural network. The team carried out an experimental measurements of truck axles deformation, caused by various vehicle loads. The results show that the load measurement error is within 5 %. Based on the previously mentioned studies, it can be clearly declared that a similar approach (the use of fiber-optic sensors) in OBW systems has not yet been published.

Various dynamic waste weighing systems are currently gaining on importance and are often part of a newly manufactured garbage trucks. Since the garbage is often also gathered by older vehicles, a similar system must be retroactively installed into these older vehicles as well. Universal measuring systems can be very expensive, with prices reaching up to units or tens of thousands of dollars, for example On-board vehicle weighing (Hawkley Group Limited, Bordon Hampshire, UK), AE Weighing Systems (AE Van de Vliet, Turnhout Belgium). Complex integration and design changes are also required (for further info refer to mentioned publications). These adjustments are spanning from suspension system adjustments to complete redesigns. These issues were used as a motivation of the author's team to implement a new simple and retrofit friendly system for weighing municipal waste.

The main parameters of currently used weighing systems are summarized in Table 1, covering the error rates, whether the system can be retrofitted and whether it is an external (standalone) or internal (installed directly into the vehicle) system.

TABLE 1. The summary of researched municipal waste weighing systems.

Type	Error rate (%)	Retrofittable	External / Internal System	References
WIM	5-15	No	External	5-18
OBW	0.3-5	Yes	Internal	19-24

Our original weighing solution is based on fiber optic sensors, specifically fiber Bragg gratings. The entire system can be retrofitted into a garbage truck and, due to its small size and weight, can be installed together with FBG sensors directly on the garbage trucks lifting equipment, without any additional modifications of the vehicle. Thanks to the use of power measurements for information evaluation, the light source in the form of Light-Emitting Diode (LED), and conventional low-cost FBG sensors the price of the whole system is approx. $2000 (counting only the necessary material). The applicability, usability and accuracy of the presented system is determined by an initial study (4 months) on a real testing garbage truck and standard 0-100 kg containers.

II. ANALYSIS OF SUITABLE PLACES FOR INSTALLATION OF FIBER BRAGG GRATINGS

The designed weighing system based on fiber Bragg gratings technology was tested on a selected commonly used garbage truck (MAN TGS 28.360 6 × 2-4 BL). The lifting system of a garbage truck is generally formed by a steel rectangular solid profiles, which are connected by pins and driven by a hydraulic piston. The weighing system is based on the mechanical stress of these profiles during the emptying of garbage bins. This mechanical stress causes measurable deformations of the profiles.

The introductory part of the research was mainly focused on the selection of suitable locations of Bragg gratings and understanding of the dynamic behavior of deformation forces on individual parts of the lifting system during the dumping of garbage bins.

The resistance foil strain gauges were chosen as a suitable technology. Resistance strain gauges are used as a sensing element of various deformation forces and are a standardized solution for deformation sensing. The iNET-555-EU measuring control panel (GW Instruments, Charlestown, USA) and SGD-3/350-LY11 (Omega Engineering, Norwalk, USA) resistance foil strain gauges were selected for the measurements.

Foil strain gauges were installed in preselected locations, where the largest loads were presumed. These locations were predetermined by an earlier simulation of lifting system. Six foil strain gauges were fitted directly to the profiles of the lifting system (Fig. 1) – the positions are marked as P1 to P6. Three foil strain gauges were mounted on the upper arm of the lifting system, while three other were mounted on the lower arm.

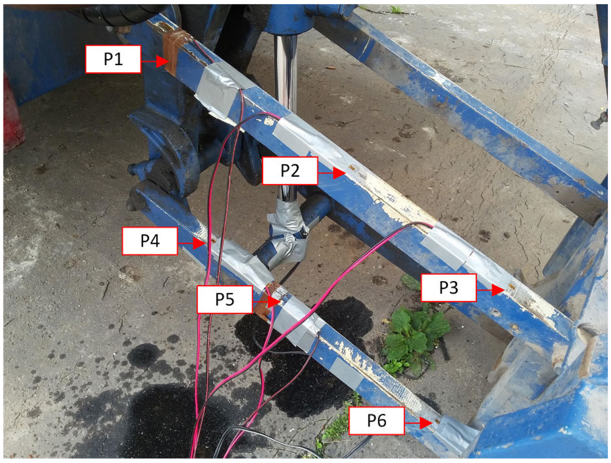


FIGURE 1. Garbage truck lifting system with predetermined foil strain gauges locations.

Based on an initial study, a set of repeated "emptying cycles" was performed on two types of plastic garbage bins (garbage bin A: volume 120 liters, container weight 10 kg; garbage bin B: volume 240 liters, container weight 15kg). Data gathered during these initial test were used as a basis for further analysis. In the initial study, the "emptying cycle" was carried out with both empty bins and bins with predetermined weights (10-100 kg, 10 kg step). The output was used to predetermine the most suitable location of the Bragg grating sensors on the lifting system. Based on the analysis of the gathered data - where the magnitude of the response to deformation, the dependence on the weight of the garbage bin contents and the stability during the "emptying" process were monitored - position P5 was selected as the most suitable spot for mounting of the fiber Bragg grating sensor.

A typical waveform captured by the foil strain gauge located at the selected position (P5) can be seen in Fig. 2. The example represents the specific "emptying cycle" of 240 l garbage bin weighing 30 kg. Phase 1 is a "warming up" 4 second long interval, where the whole lifting mechanism is resting. This phase is followed by Phase 2, which represents the lifting and emptying processes and can be further divided into three parts. Part 2a represents the beginning of the lift. This section is characterized by oscillation of the lifting system, with subsequent slow attenuation in a time interval of about 0.7 s. Part 2b represents the lifting process, where the deformation of the lifting arm at position P5 is at its maximum, followed by a significant impact caused by connection of the two main moving parts of the lifting arm.

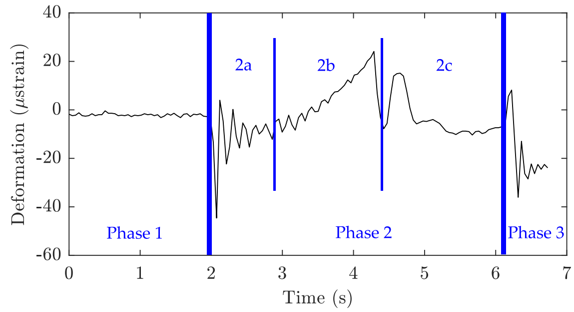


FIGURE 2. A typical waveform captured from the strain gauge during emptying cycle.

Part 2c represents the last impact of the arm on the structure of the vehicle, which again causes the lifting system to oscillate.

The analyzed data showed that the detected deformation at the P5 location is in the measurable range ±100 μstrain and are therefore also measurable by fiber Bragg gratings.

III. BRAGG GRATING SENSORS, BASIC PRINCIPLE AND INSTALLATION OF THE DESIGNED SYSTEM

A. FIBER BRAGG GRATING (FBG)

Fiber Bragg grating (FBG) is formed by a structure with periodic variation in the index of the fiber core. In this structure, the refractive index of the core n_1 alternates with an increased refractive index $n_3 = n_1 + \delta_n$, where δ_n is the induced refractive index which results from exposure of the photosensitive optical fiber to UV light. Figure 3 shows the structure and the functional principle of the Bragg grating.

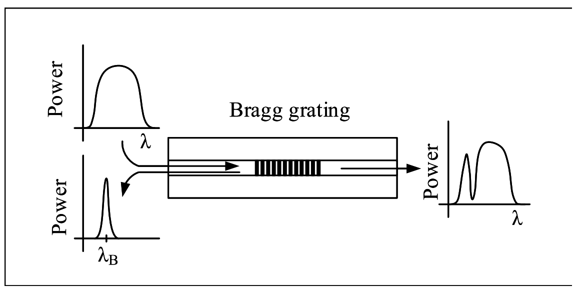


FIGURE 3. Structure and operational principle of the Bragg grating.

The structure of the Bragg grating reflects a narrow frequency band of the broadband light and transmits the others. The central part of the reflected spectrum is called the Bragg wavelength λ_B and is given by relation (1):

$$\lambda_B = 2n_{eff}\Lambda, \quad (1)$$

where n_{eff} is the effective refractive index of the grating in the fiber core, Λ is the grating period. Other wavelengths are transmitted without attenuation.

The Bragg wavelength is the geometric and optical properties that change under the influence of mechanical and/or thermal stresses. It is important to mention the equation (2), where the Bragg wavelength change, the relative deformation and temperature change is expressed by:

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

where $\Delta\lambda_B$ represents Bragg wavelength shift, k is deformation coefficient, ε is deformation, α_Λ is the coefficient of thermal expansion, α_n is the thermo–optic coefficient and ΔT is change of temperature. [24]

B. MEASURING POWER OF THE DEFORMATION BY A PAIR OF BRAGG GRATINGS

In multipoint sensor applications, the wavelength-division multiplexing is one of the most widely used and simplest methods. This multiplexing method is based on the fact that individual Bragg sensors are made with different Bragg wavelengths. The optical signal reflected from series of FBG sensor sis formed by the sum of partially non-overlapping reflection spectra. Monitoring the precise shift of Bragg spectra requires the employment of costly evaluation unit, which is often based on a wide-spectral source, a diffraction grating and a fast CCD linear detector. [25]

Therefore, in case of single-purpose applications with a limited number of FBG sensors, it is often advised to transition to simple power measurements. This measurement uses the conversion of the Bragg wavelength shift to change of the optical power. The most commonly used methods are the deployment of the wavelength-dependent filter [1], [2], a wavelength-dependent coupler [4], [5] or a system with two Chirped Bragg gratings with overlapping spectra [6], [7]. In this article, the previously mentioned method of two Bragg gratings with overlapping spectra, was used to weigh the waste and reduce the long-term costs.

The scheme of proposed measuring system (please see Fig.4) used wide-spectrum LED (light-emitting diode), type SLD1550S-A1 1 mW (Thorlabs, Newton, New Jersey, USA), optical circulator 1550 nm (Guilin GLsun Science and Tech Group, Guilin, Guangxi, China), pair of Bragg gratings with partially overlapping reflection spectra with parameters mentioned below. The reflected light is fed to a photodetector (InGaAs APD G10899-01K 1.55 μm, Hamamatsu Photonics K.K, Japan), digitized by an A/D converter, and processed by a micro processing unit that evaluates the weight of the waste.

The sensor part of the proposed system consists of a measuring sensor (FBGM) and a reference sensor (FBGR). The measuring sensor is directly attached (by glue) to the previously mentioned position (P5) of the lifting system, so the deformations from the structure were transmitted to the grating structure of the measuring FBGM sensor. The reference sensor is installed with respect to deformation insensitivity (by appropriate encapsulation as defined below) on the lifting system of the garbage truck. The advantage of this approach is automatic temperature impact compensation, because both used sensors are affected by the temperature equally.

Figure 5 shows the spectra of both FBGM and FBGR sensors, where the red color of the spectrum corresponds to the FBGR reference sensor and the blue color corresponds to the FBGM measuring sensor. Figure 5(a) describes the state of the spectra when the FBGM measuring sensor is not influenced by the measured deformation (due to the weight of the waste bin during the dumping process). In this case, the reflected power P_1 consists of both reflected spectra, this power enters the evaluation unit (Interrogator part). Figure 5(b) shows the spectra with the loaded FBGM sensor (due to the weight of the trash in the trash bin), which directly corresponds to the increased distance between both spectra and the consequent increase of the area under both spectra curves. The power P_2 ($P_2 > P_1$) is used for evaluation.

For the purpose of this specific measurement scenario, a linear working area is used, which is located at the beginning of the conversion characteristic (for details see Fig. 6).

The determination of a suitable spectral configuration of a pair of Bragg gratings was based on our previous research [26] in the OptiSystem environment. Different spectral widths of the Bragg gratings, their spectral separation and reflectance were chosen to achieve the conversion characteristic approaching the linear course with high steepness and sufficient measuring range. The following Fig. 7 shows the characteristics for the spectrum widths of 300 pm, with a reflectance of 95%. This characteristic (for a spectrum width

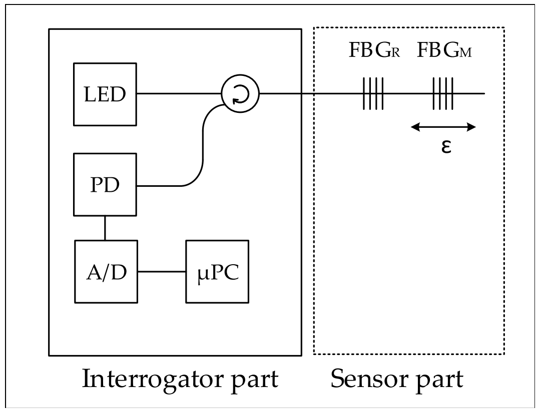


FIGURE 4. Scheme of fiber-optic system with a pair of Bragg gratings.

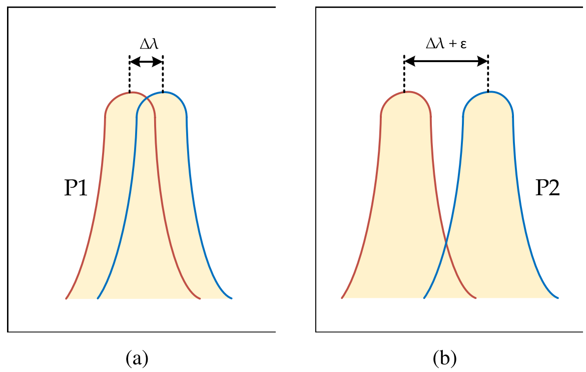


FIGURE 5. Basic principle of a system with a pair of grating sensors whose spectra partially overlap: (a) a measuring sensor in the unloaded state; (b) measuring sensor in loaded state.

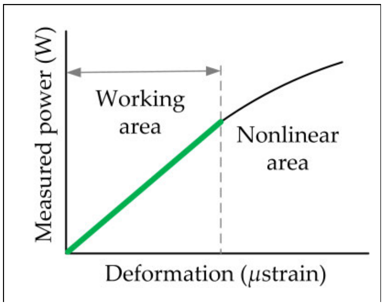


FIGURE 6. Conversion characteristic of the mentioned measuring principle with a linear dependence of the measured power on the deformation.

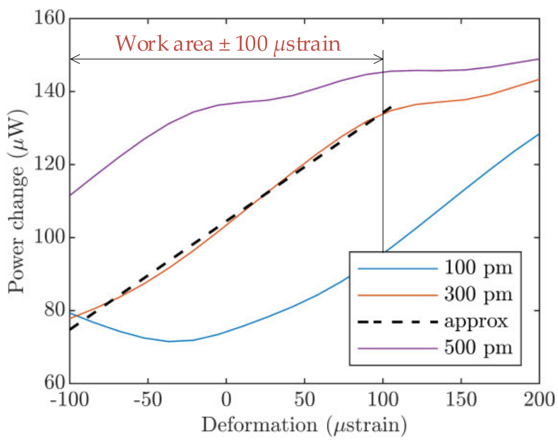


FIGURE 7. Analysis of a suitable spectral spacing of a pair of Bragg gratings usable to achieve the best possible linearity of the conversion characteristic in the range from -100 to 100 μstrain.

of 300 pm) can be written by a linear relationship $p_1\varepsilon + p_2$ with the R-square parameter $R^2 = 0.9946$, where ε is deformation, $p_1 = 0.2973$, and $p_2 = 104.5$. It is a combination of parameters that exhibits acceptable properties.

With regard to the linearity and steepness of the conversion characteristic and the required measuring range of 200 μstrain (see Chapter II), a variant with a spectral spacing of both Bragg gratings of 300 pm was chosen. The selected conversion characteristic shows (in the range from -100 μstrain to $+100$ μstrain) a steepness of 0.3 μW/μstrain with R-Squared parameter of 0.994. The actual parameters of the Bragg gratings affected by the production method can be seen in Table 2.

TABLE 2. Parameters of used Bragg gratings.

Parameter	FBGM	FBGR
Bragg wavelength (nm)	1540.126	1540.410
FWHM (pm)	302	308
Reflectivity (%)	95.1	94.8

C. INSTALLATION OF FBG SENSORS

Bragg gratings in polyimide protection (SM fiber, G.652.D. standard) on one fiber with a spacing of 25 cm were used for the installation. Polyimide recoating of Bragg gratings was chosen due to the stronger tightness of the primary protection and the optical fiber and thus ensuring the better transmission of deformation effects to the optical fiber with the FBG structure. The location of the measuring sensor (FBGM) and the reference sensor (FBGR) on the lifting system is shown in Fig. 8 and Fig. 9. The FBGM sensor is installed by a fixed joint (Loctite EA 3430, Düsseldorf, Germany) at position P5 as mentioned in previous simulations.

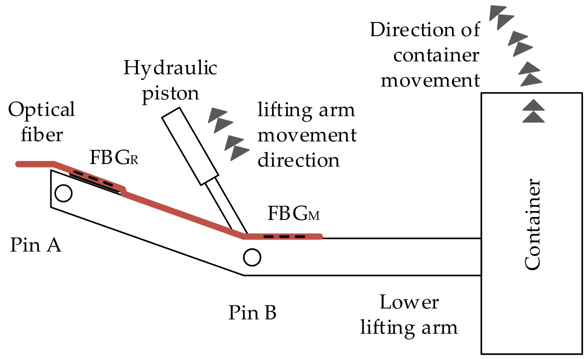


FIGURE 8. Diagram of the garbage truck lifting arm with locations of FBG sensors (the red line represents the optical fiber, in which the dashed lines at both pin A and B represent Bragg grating).

A simplified diagram of the lifting device can be seen in Fig. 8. The lifting system is attached to the truck by a connecting pin A. Another pin – Pin B – is fitted at the bending point of the arm. A hydraulic piston used to lift the whole arm is attached directly to the pin B. When the arm is lifted by the piston, the garbage bin (or container) is raised to maximal height and the container is emptied. A FBGR reference Bragg grating is located near pin A. This specific location was picked, since there are only very small deformations, corresponding to two orders of magnitude lower values than in the place behind the pin B, where the measuring Bragg grating FBGM is located.

The reference FBGR sensor was located in the place with the smallest deformation, as was determined by the previous measurements, which employed foil strain gauges. The reference grating was also not attached directly to the surface of the structure. It was separated by a several millimeter layer of foamed polymeric material. Due to this location and specific attachment, the transmission of deformations and vibrations from the structure to the reference grating was prevented. Due to the relatively small distance of both sensors and the employment of the previously mentioned thermally conductive sealant, a comparable thermal stress of both FBG gratings is achieved.

During the static experimental measurements, there were only very small temperature differences in both deployed locations. According to the measurements, the oscillation of temperature led to a change in the spectral separation (between FBG_R and FBG_M) by a maximum of 20 pm. Due to the sufficiently large working area of the transfer characteristic (see Fig. 7), these changes do not affect the principle and

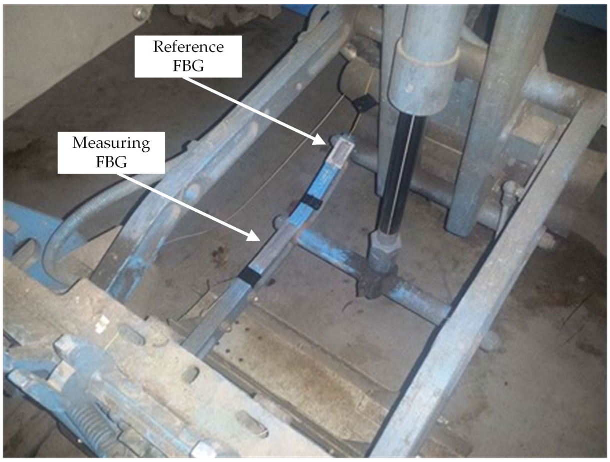


FIGURE 9. **Installation of a pair of FBG on the lifting system of the garbage truck.**

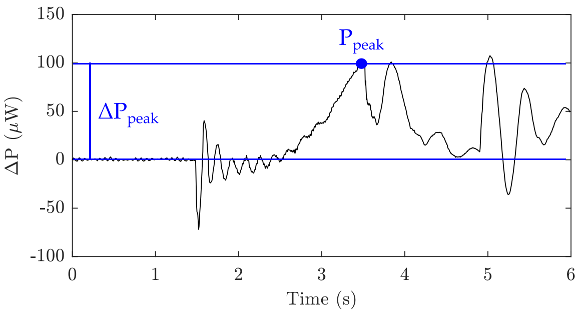


FIGURE 10. **The process of emptying an empty bin - marking (blue colour) the change in power ΔP_{peak} for amplitude method.**

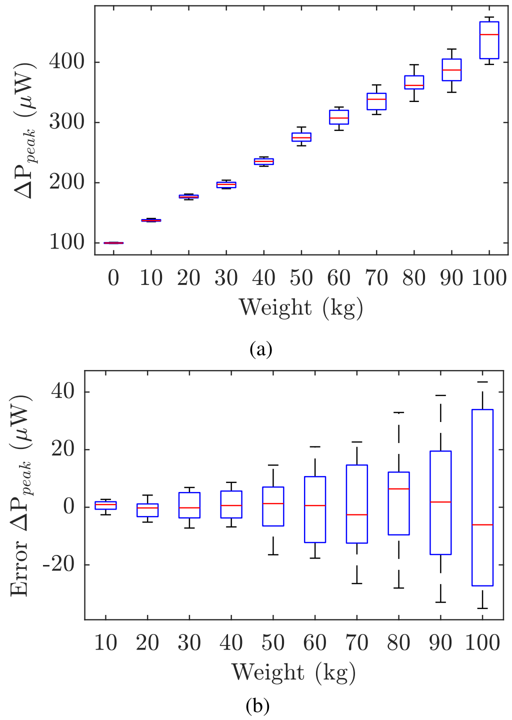


FIGURE 11. **Amplitude method for waste weight estimation: (a) box plot for changes in emptying process; (b) the deviation of the power change from the averaged value for different weights.**

accuracy of the weighing principle. In addition, the accuracy of weighing is not affected, as the measurements of fast dynamic phenomena are not affected by the slowly changing temperature.

IV. EVALUATION PRINCIPLES

Based on the obtained data, two possible methods of signal processing were defined to find the optimal conversion characteristic of the garbage bin weight. The first one is an amplitude method that monitors the increase in amplitude during emptying (Fig. 10), while the second one examines the oscillation period of the lifting system (Fig. 12).

A. AMPLITUDE METHOD

Amplitude method is based on the increase in signal amplitude during the emptying process. The monitored value is the difference in power amplitude ΔP_{peak} between the averaged value shifted to zero in phase 1 and the maximum value of P_{peak} in phase 2 (or part 2b) – for further info refer to Fig. 2 and Fig. 10.

This method was used to perform a series of test measurements during the "emptying process" with different weights spanning from 0 to 100 kg in steps of 10 kg. Figure 11 shows the variance of power change ΔP_{peak} and the deviations from the averaged value of the power change using a box plots for all measurements (a total of 220 cycles of emptying cycles, 20 for each weight).

The dependence of the average value of the change in power on weight is linear with the reliability of $R^2 = 0.9935$. Based on the value of reliability, it is clear that the average values of performance changes are linearly dependent of the weight of the waste bin contents. The method of content mass calculation can be expressed by the following equation (3):

$$w = 0.31\Delta P_{peak} - 33.03. \qquad (3)$$

Based on the equation (3) and the calculated characteristics, the relative error of the garbage bin weight was estimated as 14 %. The mentioned solution and the method of weight calculation is only approaching the real values – therefore it is not sufficient for waste collection optimalization. For this reason, a second method based on the vibration response of the lifting system was proposed.

B. TIME METHOD

At the beginning of the "lift", the course of deformation is characterized by the oscillation of the lifting system, which is dampened quickly, see Fig. 2 (phase 2a). In terms of mechanical vibration, the frequency of these vibrations depends on the magnitude of the rigidity of the lifting system and the weight of the garbage bin. The basic principle of the signal processing can be seen in Fig. 12. The beginning of the waveform is cut, so that a section of 40 ms before the first oscillation is still present. Subsequently, an offset shift is applied on the y-axis to the value of 0. Then the rear part of the signal is cut off, so that only an interval of 0.7 s is left. In the next phase, local maxima (positive peaks) are identified, time intervals between adjacent maxima are calculated and these intervals are averaged. The same process is carried out with local minima (negative peaks).

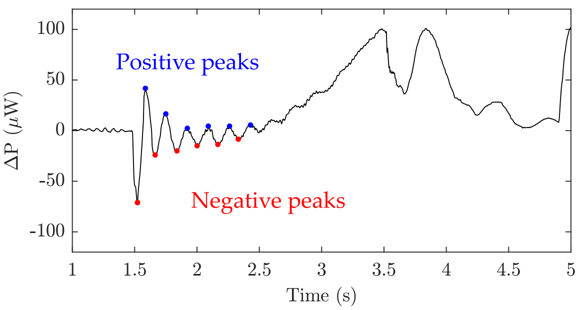


FIGURE 12. Basic principle of time method with local positive/negative peaks, which are used for determination of the oscillation time period of lifting system.

This method was also used in similar scenario as in the previously mentioned amplitude method (emptying garbage bins weighing from 0 to 100 kg with step of 10 kg). Gathered dataset was used to determine the dependence of the oscillation time period on the weight of the waste. Figure 13 shows the variances of the oscillation period and the deviation from the averaged value. The oscillation period is calculated as the arithmetic mean between the periods obtained from positive local maxima and the negative local maxima.

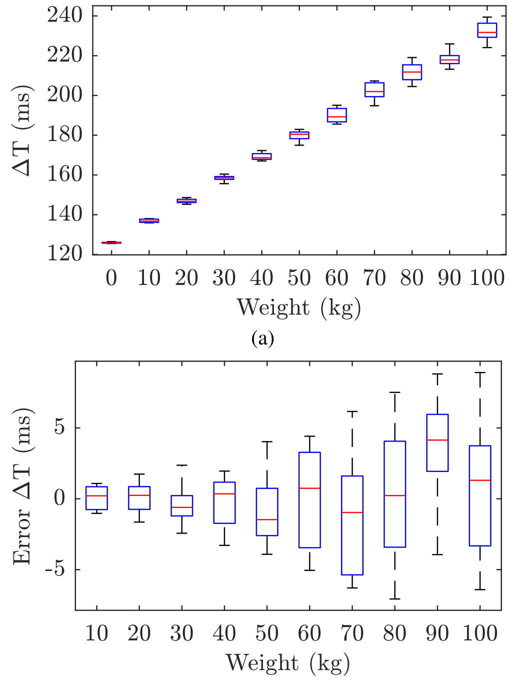
The dependence of the average value of the change in power on weight is linear with the reliability of $R^2 = 0.996$. Based on the value of reliability, it is clear that the average values of performance changes are linearly dependent of the weight of the waste bin contents. The method of content mass calculation can be expressed by the following equation (4):

$$w = 0.92\Delta T - 116.15. \quad (4)$$

Based on the equation (4) and the calculated characteristics, the relative error of the garbage bin weight was estimated as ±6 %. The presented solution of municipal waste weighing is comparable to commercially available solutions and shows a promising solution for waste collection optimalization, while also offering significant advantages such as simple installation and much lower price.

V. LONG-TERM TESTING

The verification of the functionality and its accuracy was carried out during a 4-month pilot study, in which the system was subjected to a total of 2589 emptying cycles with a previously known weight of waste in garbage bins. This long-term measurement was not carried out in real conditions, since it was necessary to know the exact weight of the waste to determine the quality parameters related to the accuracy and



(b)

FIGURE 13. Time method for waste weight estimation: (a) box plot representing changes in time periods during emptying process; (b) the deviation of the period change from the averaged value for different weights.

reproducibility of the weighing. The long-term measurement was carried out in the background of the company that provides waste collection.

The experimental setup was the same as in the analysis of the weighing principle in the previous Chapter. A garbage truck (MAN TGS 29.360 6 × 2-4 BL) with a pair of Bragg gratings installed on the lifting device was used for the measurement (see Fig. 9). The signal from the Bragg gratings was routed via an optical cable to the evaluation unit located in the rear of the vehicle. The optical signal is then converted to an electrical digital signal using a conventional photodetector and an A/D converter with sampling frequency of 500 Sps. This discrete signal is processed in the μPC unit and the estimated weight of waste in the container is stored in the internal memory (Fig. 4). A 120 l waste collection container with various test weights from 10 to 100 kg was used to test the system.

The results of the 4-month pilot study can be seen in Fig. 14. Fig 14(a) shows all measurements, where each point represents one garbage dump process. The dependence of the estimated weight and the actual weight corresponds to a linear dependence with the R parameter of 0.9937. Fig. 14(b) shows the variance of the weighed weights, where the x-axis shows the average value of the estimated and actual weights, while the y-axis shows the difference between the estimated weight and the actual weight. The figure shows the confidence band ±1.96 SD (Standard Deviation) with a width of 8.09 kg and its mean systematic error of −0.24kg.

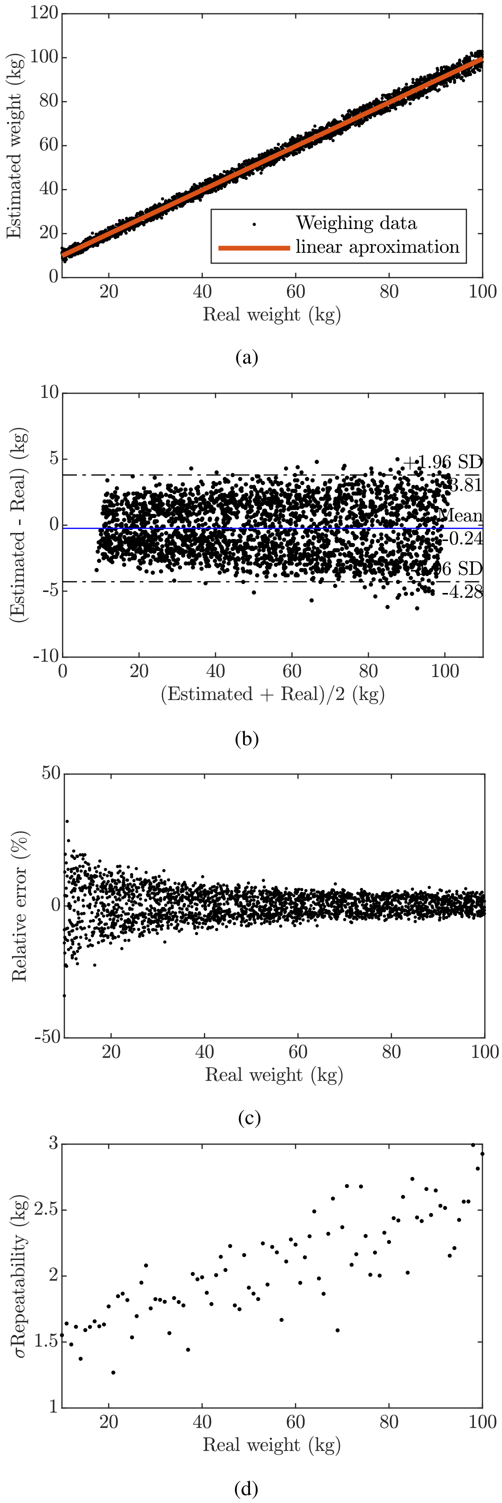


FIGURE 14. Results of waste weighing from a 4-month long-term measurement. (a) dependence of the measured weights of the waste on the actual dump weight; (b) absolute weighing error; (c) relative weighing error; (d) reproducibility of the weighing system scenario, determined by the variability of the data set out lied by a standard deviation.

The results show that 97.91% of the measurements lie in the confidence band of random errors. Only in case of 54 dumps out of a total of 2589 is the error greater than the band defined by twice the standard deviation. Fig. 14(c) shows the relative weighing error relative to the actual weight of the dumped waste. Weighing accuracy for weights up to 20 kg shows a relative average error of approx. 16%, while the weights of up to 50 kg reached approx. 7%, and weights over 80% reached approx. 5%. Due to the lon-term measurement, which was spread over a period of 4 months (September to December), it is not possible to specify the repeatability of the measurement, but the reproducibility of the measurement, which indicates the variability of the weighing, can still be repeated. Fig. 14(d) shows the weighing variability by the standard deviation. The standard deviation was calculated for all weighed weights rounded to the nearest kilogram. The repetitions for each weight of waste were different and ranged from 13 for weight of 100 kg to 47 repetitions for a weight of 59 kg. The smallest standard deviation of 1.268 occurs at a weight of 21 kg, while the largest standard deviation of 2.993 us at a weight of 98 kg.

The presented weighing system shows a weighing accuracy of ±4.04 kg with a mean value of -0.24 kg in 97.91% of waste dumping processes. Based on a 4-month experiment, a total of 140 682 kg of waste was dumped in repeated test cycles. In terms of absolute values, a total of 140 062 kg was measured by the installed fiber optic weighing system. The difference was therefore only 620 kg, which represents a difference of 0.44% compared to the real testing weight of the waste.

The evaluation system was during long-term measurements located in the rear of the vehicle, where the storage space for the vehicle operator is defined. This minimized the necessary distance of the interconnecting optical fiber situated between the sensor part and the evaluation part (this distance was approx. 2m). The encapsulation of the used optical cable (G.657.D) into a polymer tube with Kevlar with an outer diameter of 3mm guarantees that the system is resistant to external influences (weather) and mechanical damage. The 2m optical fiber ensures that the attenuation of the fiber is a negligible value.

VI. DISCUSSION

This publication describes an introductory study verifying primarily the principle of functionality and a possible new direction in the development of a fiber optic system for weighing municipal waste when emptying garbage bins. The mentioned solution can be additionally implemented on the lifting system of any commercial garbage truck without any additional structural modifications of the vehicle, which is a significant advantage. However, it should be noted that due to the complex issues of this proposed solution, the research and long-term testing was carried out on a selected (commonly used) type of garbage truck. In case of other types of lifting equipment, it might be necessary to specify more suitable places for the installation of FBG sensors and to calibrate the system again. The author's team is now focusing on this specific area.

Long-term testing was performed within the test polygon and the results were presented to local companies dealing with the collection of municipal waste. Discussions on the deployment of this solution on a pilot test car in real operation are currently underway. The system will be supplemented with a GPS module and an identification code reader in order to create a comprehensive solution for monitoring the amount of municipal waste in order to reduce costs and streamline waste collection.

The price of the whole system, including measuring sensors, is approx. $ 2000, counting only the necessary material. The author's team is aware of the fact that a system for dynamic weighing of waste is nowadays a part of newly manufactured garbage trucks. Nevertheless, it should be noted that the majority of companies still employ cars with an older production date, which in the case of deployment of dynamic weighing system require additional installation of customized equipment. Universal measuring systems can be expensive, with prices reaching up to tens of thousands of dollars, for example On-board vehicle weighing (Hawkley Group Limited, Bordon Hampshire, UK), AE WEIGHING SYSTEMS (Turnhout Belgium).

Two weigh evaluation approaches are discussed - the amplitude method analyzing the maximum change in signal amplitude and the method analyzing the time periods of damped oscillations in the signal. In both cases, the HW configuration was the same, only the evaluation algorithm behind the A/D converter was changed. The results from the amplitude approach of signal processing show that the amount of deformation of the arm of the lifting device increases with increasing weight of the waste. However, from the point of view of weighing accuracy, the author's team recommends using the time approach of data processing, in which a higher accuracy was achieved and maintained.

VII. CONCLUSION

This publication summarizes the results of an initial pilot study describing the design, implementation and verification of a new fiber optic system based on fiber Bragg grating for weighing municipal waste. The presented system can be additionally implemented on the lifting system of commonly used garbage trucks. The principle of weighing is based on the measurement of deformation effects and vibration response of the lifting equipment of garbage trucks during the dumping of garbage bins.

Two weigh evaluation approaches are discussed - the amplitude method analyzing the maximum change in signal amplitude and the method analyzing the time periods of damped oscillations in the signal.

The presented weighing system was pilot tested for 4 months within the test polygon on a real garbage truck. The results of the pilot study show a relative accuracy of ± 6 % in the range of 0–100 kg for standard containers intended for the collection of municipal waste.

REFERENCES

[1] B. Chowdhury and M. U. Chowdhury, "RFID-based real-time smart waste management system," in *Proc. Australas. Telecommun. Netw. Appl. Conf.*, Dec. 2007, pp. 175–180.

[2] A. Meixedo, A. Gonçalves, R. Calçada, J. Gabriel, H. Fonseca, and R. Martins, "On-line monitoring system for tracks," in *Proc. 3rd Exp. Int. Conf.*, Jun. 2015, pp. 133–134.

[3] S. Abdoli, "RFID application in municipal solid waste management system," *Int. J. Environ. Res.*, vol. 3, no. 3, pp. 447–454, 2009.

[4] M. Safdar, "A mobile vehicle weight sensor and its application in transportation," *Int. J. Sci. Res. Develop.*, pp. 1021–1049, 2017.

[5] J. Gajda, P. Burnos, and R. Sroka, "Accuracy assessment of weigh-in-motion systems for vehicle's direct enforcement," *IEEE Intell. Transp. Syst. Mag.*, vol. 10, no. 1, pp. 88–94, Jan. 2018.

[6] P. Li and X. Li, "Study of intelligent measurement for vehicle dynamic weighing," *Chin. J. Sens. Actuators*, p. 6, 2017.

[7] S.-T. Jeng and L. Chu, "Tracking heavy vehicles based on weigh-in-motion and inductive loop signature technologies," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 2, pp. 632–641, Apr. 2015.

[8] R. Malla, A. Sen, and N. Garrick, "A special fiber optic sensor for measuring wheel loads of vehicles on highways," *Sensors*, vol. 8, no. 4, pp. 2551–2568, Apr. 2008.

[9] M. Lydon, S. E. Taylor, C. Doherty, D. Robinson, E. J. O'Brien, and A. Žnidarič, "Bridge weigh-in-motion using fibre optic sensors," *Proc. Inst. Civil Eng. Bridge Eng.*, vol. 170, no. 3, pp. 219–231, Sep. 2017.

[10] A. Grakovski and A. Pilipovecs, "Multi-purpose fibre optic system for automated vehicle's weighting-in-motion and classification in applications of intelligent transport systems," in *Proc. 5th IEEE Int. Conf. Models Technol. Intell. Transp. Syst. (MT-ITS)*, Jun. 2017, pp. 610–615.

[11] M. Lydon, D. Robinson, S. E. Taylor, G. Amato, E. J. O. Brien, and N. Uddin, "Improved axle detection for bridge weigh-in-motion systems using fiber optic sensors," *J. Civil Struct. Health Monitor.*, vol. 7, no. 3, pp. 325–332, Jul. 2017.

[12] S. Gupta and V. Upadhyaya, "Automated vehicle detection using optical fiber communication," in *Proc. IEEE SENSORS*, Oct. 2016, pp. 1–3.

[13] L. L. Feng, Y. T. Wang, C. Ruan, and S. Tao, "Road vehicle information collection system based on distributed fiber optics sensor," in *Advanced Materials Research*, vol. 1030. Trans Tech Publ, 2014, pp. 2105–2109.

[14] A. A. Syukron, A. Marzuki, and A. Setyawan, "Fabrication and analysis signal optical fiber sensor based on bend loss for weight in motion applications," *J. Phys., Conf.*, vol. 909, Nov. 2017, Art. no. 012033.

[15] S. Yang, C. Ruan, and Y. Wang, "Pressure sensor for weight-in-motion measurement based on fiber loop ring-down spectroscopy," *Proc. SPIE*, vol. 10158, Oct. 2016, Art. no. 101580U.

[16] M. Al-Tarawneh and Y. Huang, "Glass fiber-reinforced polymer packaged fiber Bragg grating sensors for low-speed weigh-in-motion measurements," *Opt. Eng.*, vol. 55, no. 8, Aug. 2016, Art. no. 086107.

[17] A. Grakovski and A. Pilipovecs, "Dynamics of interaction between the road surface and vehicle's wheel in fibre-optic system for automatic weighing in motion of transport," *Procedia Eng.*, vol. 178, pp. 5–12, Jan. 2017.

[18] L. Cheng, H. Zhang, and Q. Li, "Design of a capacitive flexible weighing sensor for vehicle WIM system," *Sensors*, vol. 7, no. 8, pp. 1530–1544, Aug. 2007.

[19] A. Kheiralla, M. M. A. Eltigani, A. O. Elzaki, and M. Hamed, "Design and development and calibration ofan on-board weighing system for an industrial wheel loader," in *Proc. Int. Conf. Trends Ind. Mech. Eng. (ICTIME)*, 2012, pp. 1–7.

[20] G. Radoičić, M. Jovanović, L. Ilić, and B. Blagojević, "Expert shell for on-line dynamic control of a transportation process," *Int. J. Innov. Tech. Exp. Eng.*, vol. 3, no. 9, pp. 37–45, 2014.

[21] G. Radoičić, M. Jovanović, and M. Arsić, "Experience with an on-board weighing system solution for heavy vehicles," *ETRI J.*, vol. 38, no. 4, pp. 787–797, 2016.

[22] M. A. Semenov, O. M. Bolshunova, A. A. Korzhev, and A. M. Kamyshyan, "Modernization of dump truck onboard system," *IOP Conf. Earth Environ. Sci.*, vol. 87, Oct. 2017, Art. no. 022017.

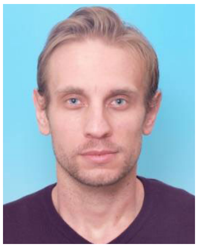
[23] Q. Wei, X. Guoyan, and Y. Guizhen, "A research on vehicle on-board weighing system based on BP neural network," *Automot. Eng.*, p. 5, 2017.

[24] A. Othonos, K. Kalli, D. Pureur, and A. Mugnier, "Fibre Bragg gratings," in *Wavelength Filters in Fibre Optics*. Springer, 2006, pp. 189–269.

[25] W. W. Morey, J. R. Dunphy, and G. Meltz, "Multiplexing fiber Bragg grating sensors," *Fiber Integr. Opt.*, vol. 10, no. 4, pp. 351–360, 1991.

[26] M. Fajkus, M. Novák, J. Nedoma, E. Hrubesova, P. Mec, and R. Martinek, "Parameter analysis of a pair of Bragg gratings with overlapping spectra for power measurement of small deformations," *Optoelectron. Adv. Mater. Rapid Commun.*, vol. 13, pp. 168–174, Mar./Apr. 2019.

MARCEL FAJKUS was born in Czech Republic, in 1987. In 2017, he successfully defended his dissertation thesis and works as an Assistant Professor at the VSB—Technical University of Ostrava. His current research interests include fiber Bragg sensors and distributed systems in traffic, civil engineering, and biomedical applications. He has more than 137 journal articles and conference papers (Author H-index: 9 without self-citations) in his research areas and three valid patents.

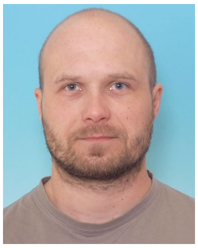


JAN NEDOMA (Member, IEEE) was born in Czech Republic, in 1988. He received the master's degree in information and communication technology from the Technical University of Ostrava, in 2014. Since 2014, he has been working with the Technical University of Ostrava as a Research Fellow. In 2018, he successfully defended his dissertation thesis and worked as an Assistant Professor at the Technical University of Ostrava. He has become an Associate Professor in communication technologies, in 2021, after defending the habilitation thesis titled "Fiber-optic sensors in biomedicine: Monitoring of vital functions of the human body in Magnetic Resonance (MR) environment." He has more than 150 journal articles and conference papers in his research areas and nine valid patents. His research interests include optical communications, optical atmospheric communications, optoelectronics, optical measurements, measurements in telecommunication technology, fiber-optic sensory systems, data processing from fiber-optic sensors, the use of fiber-optic sensors within the SMART technological concepts (smart home, smart home care, intelligent building, smart grids, smart metering, and smart cities), and for the needs of industry 4.0.

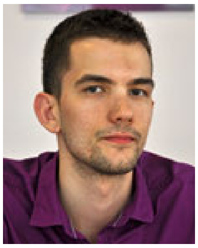
RADEK MARTINEK (Member, IEEE) was born in Czech Republic, in 1984. He received the master's degree in information and communication technology from the VSB—Technical University of Ostrava, in 2009. Since 2012, he has been working with the VSB—Technical University of Ostrava as a Research Fellow. In 2014, 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 has become an Associate Professor in Technical Cybernetics, in 2017, after defending the habilitation thesis titled "Design and Optimization of Adaptive Systems for Applications of Technical Cybernetics and Biomedical Engineering Based on Virtual Instrumentation." He has been working as an Associate Professor at the VSB—Technical University of Ostrava, since 2017. His current research interests include digital signal processing (linear and adaptive filtering, soft computing - artificial intelligence and adaptive fuzzy systems, non-adaptive methods, biological signal processing, digital processing of speech signals), wireless communications (software - defined radio), and power quality improvement. He has more than 200 journal articles and conference papers in his research areas.

LUKAS DANYS was born in Bilovec, Czech Republic, in 1994. He received the master's degree from the Faculty of Electrical Engineering and Computer Science, VSB—Technical University of Ostrava, in 2018. He is currently pursuing the Ph.D. degree in technical cybernetics. His research interests include visible light communication systems and wireless communication platforms.

MICHAEL FRIDRICH was born in Trutnov, Czech Republic, in 1995. He received the bachelor's and master's degrees in information and communication technology from the VSB—Technical University of Ostrava, in 2017 and 2019, respectively, where he is currently pursuing the Ph.D. degree with a focus on fiber Bragg sensors and distributed systems in transportation, construction, and biomedical applications.



PAVEL MEC was born in Ostrava, in 1985. He received the degree in civil engineering from the Secondary School. He is currently pursuing the degree in civil engineering with VŠB—TU Ostrava, with a focus on building materials and diagnostic of building and also building structures. For three years, he also studied the computational mathematics. He specializes in material research, both in terms of material engineering and mechanics.



STANISLAV ZABKA was born in Myjava, Slovakia, in 1988. He received the bachelor's degree and the master's degree in information technologies from the Department of Information and Communications Technologies, Faculty of Electrical Engineering and Computer Science, VSB—Technical University of Ostrava, in 2010 and in 2013, respectively. He is currently pursuing the Ph.D. degree. He is currently working as a software developer with an international IT company in the area of energy utilities, distribution processes, and communication.