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Non-Invasive Fiber-Optic Biomedical Sensor for Basic Vital Sign Monitoring

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Abstract. *This article focuses on the functionality verification of a novel non-invasive fibre-optic sensor monitoring basic vital signs such as Respiratory Rate (RR), Heart Rate (HR) and Body Temperature (BT). The integration of three sensors in one unit is a unique solution patented by our research team. The integrated sensor is based on two Fiber Bragg Gratings (FBGs) encapsulated inside an inert polymer (non-reactive to human skin) called PolyDiMethylSiloxane (PDMS). The PDMS is beginning to find widespread applications in the biomedical field due to its desirable properties, especially its immunity to ElectroMagnetic Interference (EMI). The integrated sensor's functionality was verified by carrying out a series of laboratory experiments in 10 volunteer subjects after giving them a written informed consent. The Bland-Altman statistical analysis produced satisfactory accuracy for the respiratory and heart rate measurements and their respective reference signals in all test subjects. A total relative error of 0.31 % was determined for body temperature measurements. The main contribution of this article is a proof-of-concept of a novel noninvasive fiber-optic sensor which could be used for basic vital sign monitoring. This sensor offers a potential to enhance and improve the comfort level of patients in hospitals and clinics and can even be considered for use in Magnetic Resonance Imaging (MRI) environments.*

Keywords

Basic vital sign monitoring, biomedical instrumentation, body temperature, heart rate, fiber Bragg gratings, fiber-optic sensor, noninvasive, polydimethylsiloxane, respiration rate.

1. Introduction

The emerging trends in biomedical instrumentation development clearly show that the immediate future of vital sign monitoring favors the utilization of sophisticated diagnostic tools and devices which integrate more diagnostic parameters into one universal device. More precisely stated: the integration of a variety of basic sensors into one measurement unit with the purpose to increase safety as well as comfort levels of patients is of great research interest. This article reports our contribution to the field and shares our recent research findings on biomedical applications of fiber-optic sensors. For a review of this emerging field please see articles [1] and [2]. Our research team has developed a patented fiber-optic sensor that allows monitoring of mechanical vibrations of the human body evoked by life activities such as breathing and cardiac rhythms as well as body temperature [3].

A number of research articles which used one or more FBGs, have presented results of measurements of respiration rate, heart rate or both simultaneously [4], [5], [6], [7], [8] and [9]. For example, Chethana et al. have presented very interesting results based on the design and construction of an FBG-based sensor attached to the patient's chest that enables respiratory and heart rate monitoring [4]. In this design, it is essential to pay special attention to the tension of the optical fiber so that adequate sensitivity is achieved. The detailed design of this FBG-based sensor for monitoring respiratory and heart rates in human subjects is presented in [5]. In this work, the sensor consists of an FBG embedded inside a single-mode optical fiber that operates with the wavelength of approximately 1550 nm with a maximum relative measurement error of 12 %. The experimental results reported in article [6] describe an FBG-based sensor prototype designed for monitoring the respiratory rate. In this work, the FBG sensor is encapsulated inside a PDMS enclosure. The sensor assembly is mounted on an elastic contact strap that encircles the patient's chest. The tension in the chest caused by breathing leads to a spectral shift of the reflected light from the FBG. In [7], Dziuda et al. present results obtained from monitoring the respiration and heart rates of a patient in a Magnetic Resonance Imaging (MRI) environment using a fiber-optic FBG-based sensor. This sensor was proposed by its developers to specifically acquire BallistoCardioGraphic (BCG) signals from a patient positioned inside a dynamic magnetic field. The authors in [8] report a fiber-optic-based smart textile sensor for respiratory rate monitoring capable of operating in MRI environments. In this work, two FBGs placed on the thorax enable the conversion of chest wall movements during respiration to measurable signals. Interestingly, article [9] focuses on an MRI-friendly fiber-optic sensor for monitoring the heart and respiration rates simultaneously. In this design, the sensor employs a Plexiglas springboard to which an FBG is attached to convert the patient's body movements to mechanical strain while lying on the springboard.

Current research by our team substantiates that our novel sensor based on Mach-Zehnder interferometers along with adaptive signal processing methods can find applications in a variety of fields including noninvasive monitoring of basic vital signs in obstetrics and gynecology (uterine contractions, fetal heart rate monitoring and others) [10], [11], [12] and [13].

Recent literature in the field of noninvasive maternal and fetal vital sign monitoring provides ample evidence that the integration of several diagnostic measures in one all-purpose instrument or sensor, although an appealing concept, is facing many challenges; consequently, there is a vast need for improvement and research in this area. Our sensor, which allows the measurement of body temperature in addition to monitoring the heart and/or respirations rates as described in the articles above, offers an innovative solution in noninvasive, basic vital sign monitoring and is thus a step forward.

2. Methods

FBGs are currently the most frequently used single-point fiber-optic sensors due to their desirable properties such as: small size with high tensile strength, immunity to electromagnetic interference, and minimal aging effect with regard to the components from which they are assembled [14], [15] and [16]. Basically, FBGs function by means of the periodical change of the refractive index in their optical core, selectively filtering certain wavelengths that are reflected back, while allowing the remaining part of the spectrum to pass through. All the reflected light signals combine coherently to form one large reflection at a particular wavelength when the grating period is approximately $1/2$ of the input light's wavelength. This is referred to as the Bragg Condition, and the wavelength at which this reflection occurs is called the Bragg Wavelength. An example of the FBG structure and its working principle is shown in Fig. 1. As FBGs are sensitive to strain and temperature changes, they are suitable for many biomedical measurements. Single-point FBG sensors can be connected together in cascade, thereby producing a multi-point sensor within one optical fiber. The easiest method for enhancing the resolution of individual sensors is to use wavelength-division multiplexing. We can integrate tens of sensors within the wavelength-division multiplex, whose capacity is given by the type of a measured value, the size of measuring ranges and the size of the protection zone, see [17] and [18].

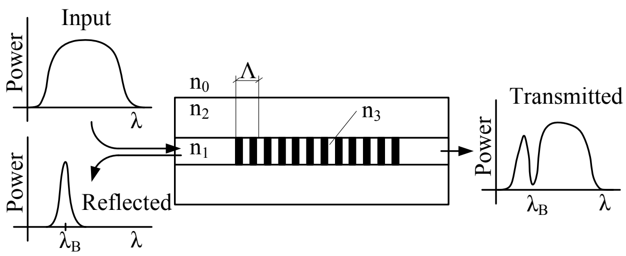


Fig. 1: An example of FBGs structure and working principle.

The size of Fiber Bragg wavelength is given by the following relationship:

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

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. Deformation and temperature dependence are given by the central Fiber Bragg Wavelength and parameter values (where λ_B is the Bragg wavelength, $\Delta\lambda_B$ is the shift of the Bragg wavelength, $\Delta\varepsilon$ is the change of deformation and ΔT represents a change in temperature). To determine individual sensitivities, normalized deformation and temperature coefficients are used [19]. The normalized deformation coefficient is given by the following relationship:

$$\frac{1}{\lambda_B}\frac{\Delta\lambda_B}{\Delta\varepsilon} = 0.78 \cdot 10^{-6}\ \mu\text{strain}^{-1}, \tag{2}$$

and the normalized temperature coefficient is given by the following relationship:

$$\frac{1}{\lambda_B}\frac{\Delta\lambda_B}{\Delta T} = 6.678 \cdot 10^{-6}\ {}^{\circ}\text{C}^{-1}. \tag{3}$$

3. Results

Our sensor with the following dimensions: 70 mm (length) × 40 mm (width) × 4 mm (thickness), and the weight of 50 grams, is used for measuring the respiratory rate, heart rate and body temperature in the human body. It is based on two FBGs which are encapsulated inside a polydimethylsiloxane polymer [20] and [21], see (Fig. 2). Our results reported elsewhere [22] indicate that this type of encapsulation does not affect the structure of the FBG.

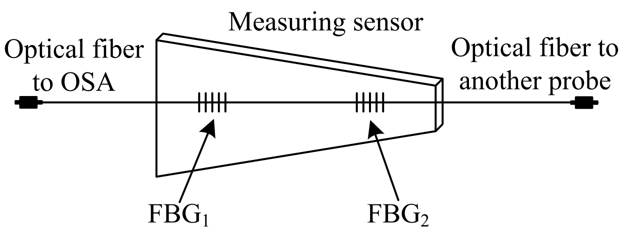


Fig. 2: The design of our noninvasive basic vital sign sensor.

Measurements were carried out in ten volunteer subjects of both sexes (5 men: M1–M5, and 5 women: F1–F5), after obtaining their written informed consents, in a research laboratory with the temperature of 24 °C. The subjects were between 21 and 47 years of age, their heights were between 156 and 197 cm, and their weights were between 47 and 108 kg. No significant differences were found in the quality of the recorded data based on the subjects' age, height, and weight. The sensor probe was placed on the chest (around the pulmonic area) and fixed by a contact elastic strap, see Fig. 3. The subjects were tested in the supine position in a relaxed state.

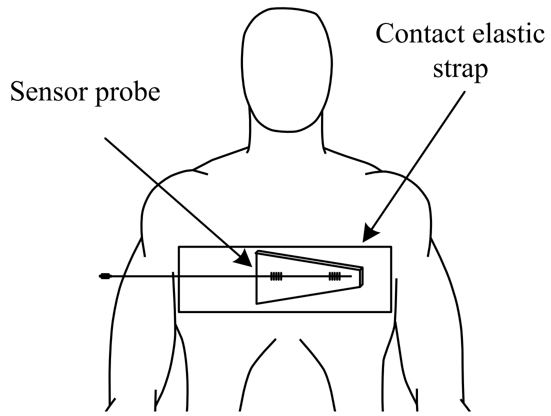


Fig. 3: Implementation sensor with contact elastic strap on human body.

An Optical Interrogator (OI) system developed by our team was used to further process the sensed vital signs acquired by the sensor [3]. The OI system is composed of a wideband spectral light source from a Light Emitting Diode (LED) with the central wavelength of 1550 nm and the output power of 1 mW. Furthermore, it is composed of an Optical Spectrum Analyzer (OSA) unit using the sampling frequency of 250 Hz, an optical circulator, a Digital Signal Processing (DSP) Unit, and an Electronic Control Unit (ECU) for each individual optical element. The vital sign information (comprised of heart rate, respiratory rate, and body temperature) was displayed in a graphical user interface in an application created in LabVieW (2015, National Instruments, Austin, Texas, USA) by our research team.

The heart rate (expressed in beats per minute BPM) and respiratory rate (expressed in respiration per minute RPM) were obtained by a spectral evaluation of the measured signals. Based on signal peak detection and the calculation of time intervals between these peaks, the heart and respiratory rates were determined. The reference ECG and respiratory signals were acquired by using a real-time monitoring system with standard bioelectrodes, a respiratory sensing module fixed to a subject's chest along with a real-time ECG and respiratory signal monitoring system based on a virtual instrumentation system (NI ELVIS, II Series, National Instruments, Austin, TX, USA). The body temperature (expressed in degrees Celsius °C) was obtained by the mathematical relationships shown in Eq. (4). A digital thermometer (Greisinger, Prague, Czech Republic) was used to acquire the reference temperature signal and recordings.

To determine the body temperature, we used two FBGs with different temperature and deformation sensitivities. Different sensitivities were within the proposed sensor range given by a specific form and shape of encapsulation. It is established that if the sensor is affected by deformation or temperature, the size of both of these impacts could be determined by using the following relationship [23]:

$$\begin{pmatrix} \Delta T \\ \Delta\varepsilon \end{pmatrix} = \frac{1}{K_{1T}K_{2\varepsilon} + K_{2T}K_{1\varepsilon}} \cdots \\ \cdots \begin{pmatrix} K_{2\varepsilon} & -K_{1\varepsilon} \\ -K_{2T} & K_{1T} \end{pmatrix} \begin{pmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{pmatrix}, \tag{4}$$

where $\Delta\varepsilon$ is deformation, ΔT is the temperature change, $K_{n\varepsilon}$ is the deformation coefficient, and K_{nT} is the temperature coefficient belonging to the first or second FBG. $\Delta\lambda_{B1}$ and $\Delta\lambda_{B2}$ represent the shift of the Bragg Wavelength for the first FBG$_1$ and the second FBG$_2$, respectively.

Figure 4 shows a 30-second long record of changes in Fiber Bragg Wavelength during the measurement of breathing activity in test subject M1 as an example.

For comparison, Fig. 5 shows a 10-second long record of changes in the Fiber Bragg Wavelength during the measurement of heartbeat activity in a female test subject (F4).

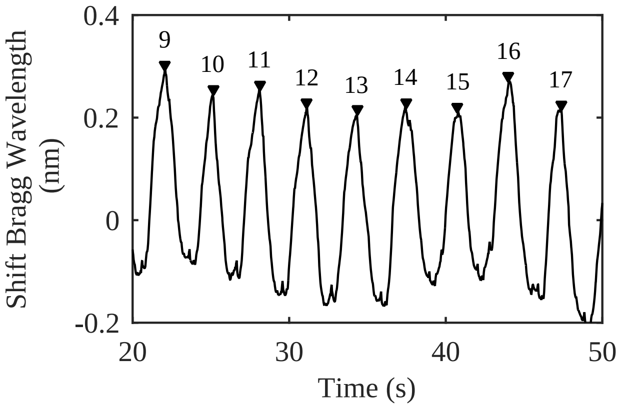


Fig. 4: A 30-second record of changes in the Fiber Bragg Wavelength during the measurement of breathing activity in a male test subject (M1).

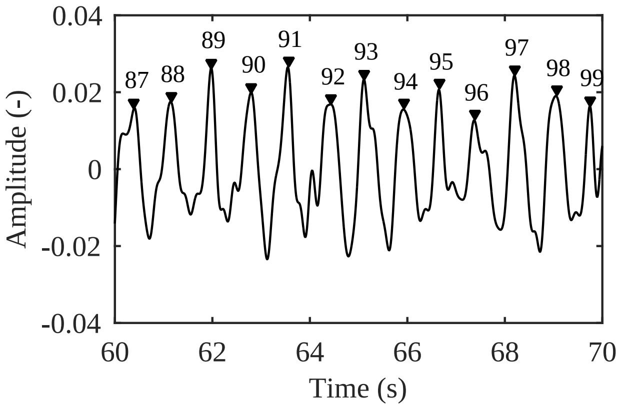


Fig. 5: A 10-second record of changes in the Fiber Bragg Wavelength during the measurement of heartbeat activity in a female subject (F4).

Figure 6 shows a 60-second-long record of temperature measurement in test subject M1.

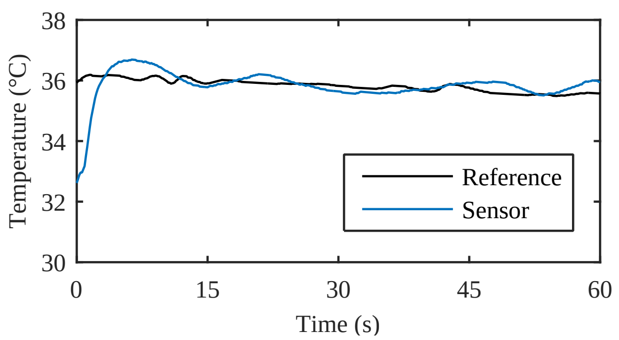


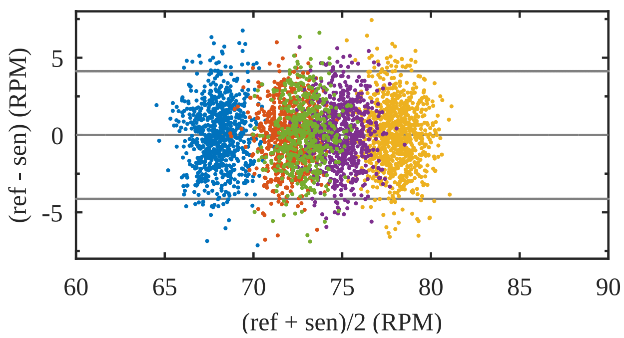
Fig. 6: A 60-second-long record of measurement and determination of temperature in test subject M1.

To compare the differences between the reference signals and those acquired from our novel sensor, the Bland-Altman plot was utilized [24]. The differences between the sensor and the reference traces, $x_1 - x_2$, are plotted against the average, $(x_1 + x_2)/2$. The reproducibility is considered to be good if 95 % of the results lie within the ± 1.96 SD (Standard Deviation) range.

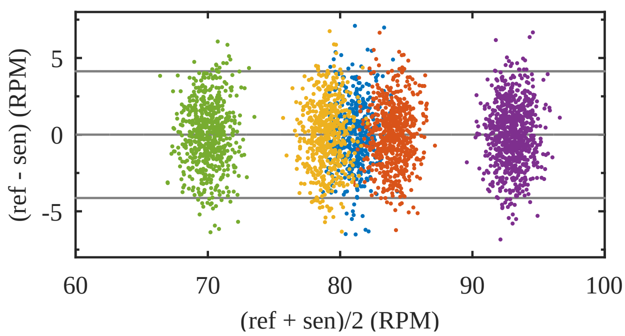
The key experimental results for the heart and respiratory rate measurements are summarized in Tab. 1. In the case of heart rate measurements for the entire data set, 95.34 % (95.45 % for men and 95.24 % for women) of the values lie within the ± 1.96 SD range for the HR determination and no significant differences were found between observed individuals (Fig. 7).

Tab. 1: Summary of respiratory and heart rates measurements.

Sub.	Rec. time (s)	RR NoS sensor	RR Samples in ± 1.96 SD (%)	HR NoS sensor	HR Samples in ± 1.96 SD (%)
M1	720	204	94.61	816	95.47
M2	530	133	94.38	636	95.60
M3	680	197	95.53	884	94.57
M4	540	141	93.80	675	95.56
M5	440	122	95.18	535	96.07
F1	340	71	94.57	459	96.08
F2	450	135	95.56	630	95.71
F3	420	106	96.33	553	94.39
F4	490	139	94.54	760	96.05
F5	530	133	95.59	616	93.99



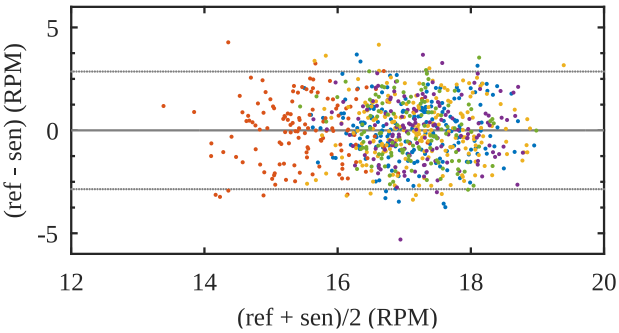
(a) Five tested men.



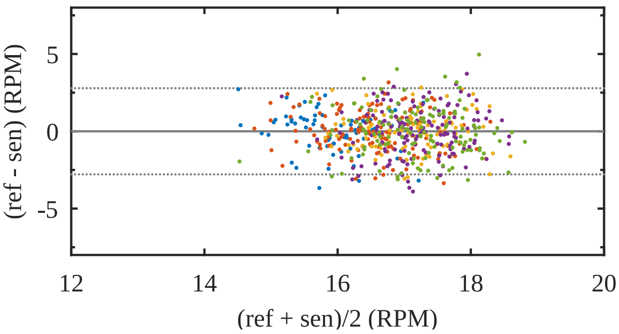
(b) Five tested women.

Fig. 7: Statistical analysis of heart rate using the Bland-Altman plot.

In the case of respiratory rate measurements for the entire data set, 95.01 % (94.71 % for men and 95.31 % for women) of the values lie within the ± 1.96 SD range (Fig. 8).



(a) Five tested men.



(b) Five tested women.

Fig. 8: Statistical analysis of the respiratory rate using the Bland-Altman plot.

The key experimental results of body temperature measurements are summarized in Tab. 2. This table shows temperature values obtained after a measurement time interval of 60 seconds. The maximum relative error of temperature measurement was 0.55 %.

Tab. 2: Summary of body temperature measurements.

Subject	Rec. time (s)	60	Relative error (%)
M1	ref. (° C)	35.7	0.28
	sensor (° C)	35.8	
M2	ref. (° C)	35.6	0.28
	sensor (° C)	35.7	
M3	ref. (° C)	36.3	0.55
	sensor (° C)	36.5	
M4	ref. (° C)	36.8	0.27
	sensor (° C)	36.7	
M5	ref. (° C)	36.9	0.27
	sensor (° C)	37.0	
F1	ref. (° C)	36.7	0.27
	sensor (° C)	36.8	
F2	ref. (° C)	36.6	0.27
	sensor (° C)	36.5	
F3	ref. (° C)	36.3	0.28
	sensor (° C)	36.4	
F4	ref. (° C)	36.6	0.27
	sensor (° C)	36.7	
F5	ref. (° C)	37.1	0.27
	sensor (° C)	37.2	

4. Conclusion

Here we described the functionality verification of a novel non-invasive fiber-optic sensor for the monitoring of human basic vital signs: Respiratory Rate (RR), Heart Rate (HR), Body Temperature (BT). Experiments were carried out in a research laboratory condition on 10 volunteer test subjects after obtaining their written informed consents. At the completion of the experiments all test subjects were asked whether they had sensed or encountered any feelings of discomfort, especially at the moment of fixing the measurement sensor into a contact strap. None of the test subjects expressed any sense of discomfort. The total time for carrying out all experiments was 85 minutes 39 seconds. The Bland-Altman Statistical Analysis for the respiratory rate (95.01 %) and heart rate (95.34 %) measurements showed satisfactory accuracy for all data acquired from the test subjects. The maximum relative error for temperature measurement was 0.55 %. The outcomes of these experiments have unambiguously proved the functionality of our novel sensor. We are hoping that our contribution reported here paves the way for researchers in this fast developing and emerging field and facilitates their efforts in expanding the applications of fiber-optic sensors and devices in sophisticated medical diagnostic instrumentation in the near future.

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