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Polymer optical fiber-based sensor for simultaneous measurement of breath and heart rate under dynamic movements

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HIGHLIGHTS

- POF-embedded smart textile for breath and heart rates monitoring.
- Analytical approach for the sensor operation principle.
- Technique for detecting heart and breath rates even when the subject is moving.
- Signal processing to mitigate the influence of gait frequency in the sensor response.

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ABSTRACT

In this paper, we present the development of a polymer optical fiber (POF) sensor for simultaneous measurement of breath (BR) and heart rates (HR). The sensor is embedded as a smart textile solution that can be used within the user's clothes. In addition, a signal processing technique is proposed for obtaining the HR and BR without the influence of body movements and in different positions of the user's chest. Sensor signal processing and analysis are made in the frequency domain and different filters are applied. Results show errors below 4 beats per minute and 2 breaths per minute for the HR and BR, respectively, even when the user is performing periodic body movements such as the ones induced by the gait. Thus, the proposed POF-based smart textile is a low-cost solution with good accuracy that can be readily applied in the remote monitoring of patients at home without disturbing their daily activities.

1. Introduction

Sensor technology, wireless communications and data analysis have experienced significant advances. In this way, the health condition assessment is not limited to the clinical environments [1]. Thus, it is possible to monitor different physiological parameters for patients at home, which is especially desirable for the elderly population and people with locomotor disabilities [2]. Among many important physiological parameters, abnormalities on the heart rate (HR) and breathing rate (BR) are important indicators of some cardiovascular diseases [3], fatigue [4], apnea [4] and respiratory abnormalities [5].

To that extent, several electronic sensors based in different approaches such as piezo-electric films, dry textile electrodes, flexible capacitive electrodes (among others) have been proposed throughout the years, which such technologies are summarized in the following review works [2,6]. However, in general, electronic sensors are sensitive to electromagnetic interferences, which inhibit their application in magnetic resonance imaging (MRI) [7].

In order to overcome this limitation, optical fiber sensors have been proposed may be used and present the advantage of immunity to electromagnetic field. In addition, optical fiber sensors also are compact, lightweight, present chemical stability and multiplexing capabilities [8]. Such advantages have been exploited in the embedment of the fiber in different structures such as exoskeletons for human-robot interaction forces assessment [9], in insoles for plantar pressure [10] and ground reaction force estimation [11] and in a pen for arterial pulse waveform monitoring [12,13]. Furthermore, there is also the development of smart textiles with optical fibers for monitoring parameters

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such as oxygen saturation [14], HR [15], BR [16] and body temperature [17].

Regarding the application of optical fiber sensors in heart and BRs assessment, Dziuda et al. [18] proposed a fiber Bragg grating (FBG) sensor for MRI environment. Similar approaches based on FBG sensors were also proposed in [19]. A wearable sensor with smart textile for respiration monitoring was also proposed in [20] and for HR in [21]. FBG-embedded smart textiles were also proposed for thoracic respiration pattern monitoring in [22]. However, FBG sensors require costly specialized equipment for the gratings inscription and additional high cost equipment for the sensor interrogation [23]. For these reasons, low-cost approaches for breath and heart rate sensors were also developed. These low-cost optical fiber sensors are generally based on the intensity variation principle, where the optical power attenuation measured in the fiber is directly related to the body motions (mostly the chest) during the respiration [4,15,16,24]. In addition, sensors configurations based on light reflectivity were also proposed [25,26], but with the important disadvantage of less compactness, since there is the need of additional optical component such as light couplers or circulators and are perpendicularly positioned in the subjects, which inhibit their application in smart textiles.

As a general application for the optical fiber-based HR and BR sensors presented in the literature, they are used in the physiological monitoring in MRI environments and during the sleep [4,15,18,27]. Although these applications take advantage of optical fiber's electromagnetic immunity and compactness, in such applications the user is in static position or, at least, with reduced movement. Since these sensors generally detect body movement (especially torso movements) and correlate it with the respiration and heartbeat, if the user makes additional movements, the sensor will present errors in the measurements [27].

Such errors may also happen in some low-cost electronic sensors in which the user needs to stop moving during the HR or BR measurement. In order to tackle this undesired feature, Nishyama et al [4] proposed an array with 8 sensors, where each sensor response is compared to reduce the influence of the body movement in the BR assessment. However, the proposed configuration requires 8 photodetectors, which makes it less suitable for wearable applications.

Another approach is presented in [15], where there is a filter for noise reduction that removes some of the non-periodic movements and the signal is only processed when it is stable, i.e., without movements. Although these strategies were able to reduce the influence of the body movement, it was still reported measurement errors due to the body non-periodic movement.

Thus, the optical fiber-based sensors for HR and BR assessment reported in the literature are not able to perform under dynamic movements of the user.

In this paper, we propose a sensor and algorithm for simultaneous measurement of HR and BR based on polymer optical fiber (POF), which presents advantages over silica optical fiber related to its higher flexibility, non-brittle behavior, resistance to impact loads, among others [8]. Additionally, POFs are more rugged, which result in a device safer for the user than the ones made of silica fibers [15]. In order to eliminate the influence of the body movement on the sensor response, we apply signal-processing techniques and, differently than the works presented in the literature, the analysis is made in the frequency domain to further eliminate such effects. Thus, the contribution of this work is a POF-based sensor for simultaneous measurement of HR and BR that can be used in dynamic activities. For this reason, different from the previously presented sensors, the proposed approach can be applied not only in MRI environments and patient monitoring during sleep, but also as an e-health solution for continuous monitoring of the patients during their daily activities.

The remainder of the paper is divided as follows. Sensor design and theoretical background are presented in Section 2. Section 3 depicts the sensor operation principle by means of simulation. The experimental protocol for the sensor validation is presented in Section 4. Section 5 addresses the sensor's validation results. Finally, conclusions and future works are depicted in Section 6.

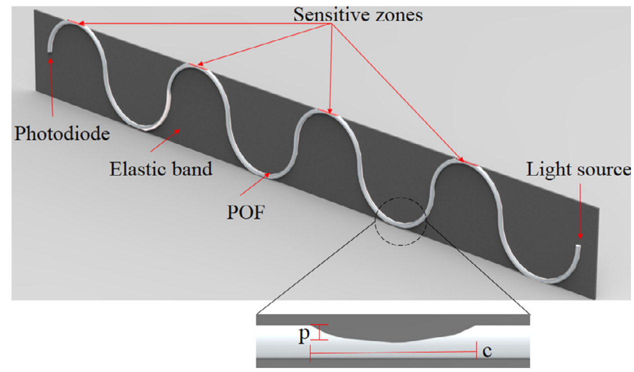

Fig. 1. Overview of the proposed POF-based smart textile for HR and BR monitoring. Inset shows the magnified view of the fiber lateral section, where the sensitive zone depth (p) and length (c) are presented.

2. Sensor design and theoretical background

The proposed sensor is based on the optical power attenuation created by the curvature difference during the breathing.

Therefore, the proposed approach is a curvature sensor that correlates the rate of the curvature differences with the breathing and heart rate. In order to increase the sensor sensitivity, lateral sections are made by removing the fiber cladding and part of its core with a sandpaper with controlled grit size [28]. This procedure is performed in the places with high curvature grade. Thus, we made 8 lateral sections on the fiber to obtain an uniform and more sensitive response of the sensor with respect to the chest circumference variation during the breathing.

The sensor is embedded in an elastic band as shown in Fig. 1. Even though similar configurations have been already explored in the literature [16,24], the sensor presented in [16] does not have polished lateral sections, which results in lower sensitivity. On the other hand, the sensor presented in [21] has 60 lateral sections, which not only makes the sensor fabrication a cumbersome and time consuming process, but also increases the sensor cross-sensitivity with respect to the body movements [21]. In addition, we use the lateral section length and depth that results in the highest sensor sensitivity as reported in [28]. For this reason, we obtain similar (slightly lower) sensitivity in our sensor when compared to the one presented [21] with a lot less lateral sections, resulting in a better configuration/sensitivity compromise.

As also shown in Fig. 1, the sensor works in the transmission mode, where the light source is a LED IF-E97 (Industrial Fiber Optics, USA) with central wavelength at 660 nm and a photodiode IF-D91 makes the optical power variation acquisition. A polymethyl methacrylate (PMMA) POF (HFBR-EUS100Z, Broadcom Limited) with a core diameter of 980 µm, a cladding of fluorinated polymer with 20 µm thickness and a polyethylene coating was employed in this work. In addition, the inset of Fig. 1 shows the magnified view of the POF lateral section aforementioned.

The elastic band presented in Fig. 1 is fixed on the user's chest and, as the respiration occurs, the band stretches, which leads to the curvature variation on the POF. In addition, the body vibrations induced by the heartbeat are also detected with this setup. The sensor power attenuation can be estimated through geometric optics approach as discussed in [29]. In this case, the ration between the input (P_i) and POF output power (P_o) is obtained through Eq. (1).

$$\frac{P_o}{P_i} = \frac{(S_C - S_o)\sin^2(\theta_b)}{S_C \sin^2(\theta_c)}, \tag{1}$$

where S_c is the cross-sectional area of the fiber core, S_o is the area of