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Simultaneous cardiac and respiratory frequency measurement based on a single fiber Bragg grating sensor

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Abstract
A respiratory and cardiac-frequency sensor has been designed and manufactured to monitor both components with a single fiber Bragg grating (FBG) sensor. The main innovation of the explored system is the structure in which the FBG sensor is embedded. A specially developed polymeric foil allowed the simultaneous detection of heart rate and respiration cycles. The PVC has been designed to enhance the sensor sensitivity. In order to retrieve both components individually, a signal processing system was implemented for filtering out the respiratory and cardiac frequencies. The developed solution was tested along with a commercial device for referencing, from which the proposed system reliability is concluded. This optical-fiber system type has found an application niche in magnetic resonance imaging (MRI) exam rooms, where no other types of sensors than optical ones are advised to enter due to the electromagnetic interference.

Keywords: optical fiber sensor, fiber Bragg grating, healthcare monitoring, integration

1. Introduction

The ability to monitor patients requiring medical assistance is a crucial issue. An example of such concern is the need to monitor the patient's vital signals [1]. These signals are of high interest, including (among others) the respiratory and the cardiac frequencies [2]. Up to now, research on healthcare monitoring systems has focused on electronic sensors and on wireless configurations [3]. However, in a few specific situations (e.g. magnetic resonance imaging or MRI) their implementation is unsuitable. Thermal or electrical burns associated with oximeter sensors and cables, temperature probes and MRI surface coils can be induced during a MRI exam [4, 5]. As documented by Wehrle *et al* [6], a similar situation can occur when the patient is subject to cardiothoracic surgery. Consequently, it is necessary to provide means for acquiring the vital signals in an effective and safe manner. An alternative and safer approach can be implemented with optical-fiber-based systems. Due to their nature, the optical fibers do not contain conductive parts and, therefore, are insensitive to external electromagnetic fields.

The main contribution of this paper is the development of a sensing solution able to measure the cardio-pulmonary components with a single sensor and entirely compatible with healthcare environments. The proposed solution uses fiber Bragg grating (FBG) sensors to monitor both the respiratory and cardiac frequencies, rather than using the macro-bending loss effect of a single optical fiber (of other type) [7, 8]. Although Gurkan *et al* [9] had developed a FBG-based solution, it was based on an approach that enabled only the heartbeat measurement. Additionally, the developed system must be compatible with different people. In order to comply with these requirements, the proposed solution is based on a small flexible structure that can be attached and removed from the chest site via Velcro, or even be worn by the subject (figure 1).

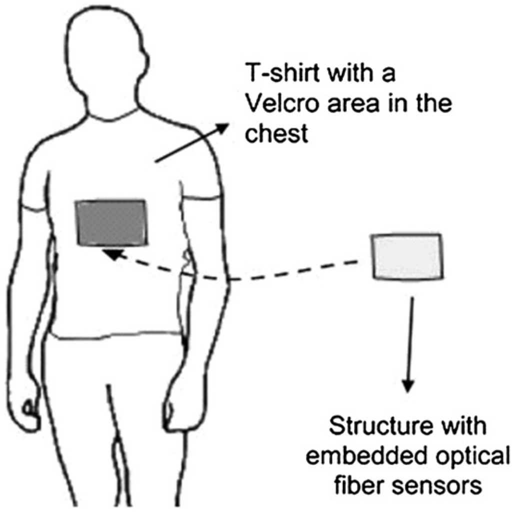

Figure 1. An illustration of the proposed approach.

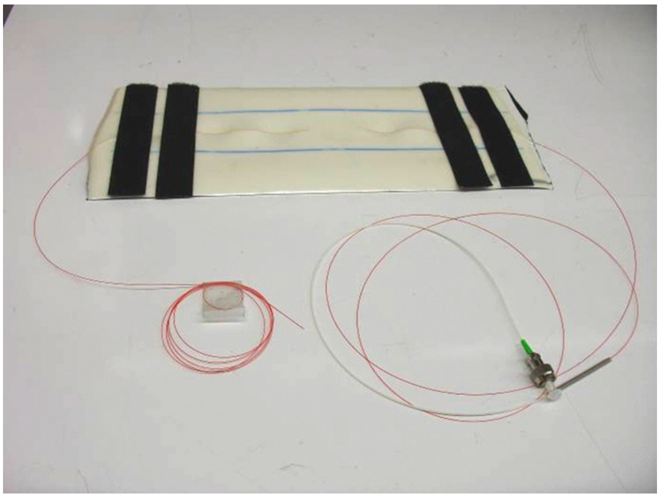

Figure 2. A photograph of a sensing prototype.
(This figure is in colour only in the electronic version)

2. System design

2.1. Approach

The respiratory and the cardiac physiological systems are significantly complex. The lung's expansion and the heartbeats have more than one degree of freedom in the organ dynamics, leading to thoracic movements. While the inflation and deflation of the lungs implies thoracic movement of high amplitude, the cardiac movement is precisely the opposite. The chest displacement due to breathing ranges from 4 to 12 mm [10, 11]. In contrast, the heartbeat movement traditionally implies an average chest displacement in the range from 0.2 to 0.5 mm [10, 12]. Furthermore, studies have shown a linear response between the volume and the chest wall movement [10]. In order to separate the two components, it is necessary to acquire a signal where both components are present. As a consequence, the sensor must provide means to record movements from 0.2 up to 12 mm, which is a significantly wide range. Thus, a high-sensitivity sensor and a monitoring system of high resolution are required. As both respiratory and cardiac signals have different spectral components, they can be isolated via signal processing filters [10].

FBGs were selected as sensing elements due to their high performance in terms of sensitivity and linear response. These sensors differ from other optical fiber sensor approaches because their optical signal is not based on power amplitude but instead on spectral changes. This factor is important for embodiment techniques since bends in the optical fiber introduce intensity changes, which do not represent any concern for this purpose [13].

2.2. The flexible sensing structure and the FBG sensor

Although previous works already considered the use of a FBG for acquiring the respiratory component, the ability to measure both the cardiac and respiratory frequencies with a single sensor is still missing [6]. Another important issue is the sensor positioning; as the chest has a quite large area, it would be crucial to place the sensor where the cardiac-induced chest displacement is maximum. In this sequence of strategy, a carrier structure large enough to cover the greatest possible portion of the chest must be provided. This would maximize the transmission of the chest movements (due to the respiratory component, but especially due to the cardiac element) into the FBG. Consequently, a carrier structure with an embedded FBG sensor was manufactured. Details about the full manufacturing process can be found in [14]. Moreover, the FBG used contains gratings with lengths of 8 mm with a resonance wavelength of 1547.65 nm, corresponding to a refractive index modulation period of the core in the half-micrometre range [14, 15].

2.3. Methodology

A functional prototype (figure 2) was tested on a group of 12 healthy subjects with ages between 20 and 30 years. The measurements were carried out with the subjects standing up and maintaining the full body resting. The sensing foil was placed on the chest because this is the position of the human body where the effects of the heartbeats are most significant.

In the tests performed, the subjects were asked to breathe naturally and also to stop breathing. In order to have a reference signal, a commercial device able to measure both the respiratory and cardiac components (e.g. the commercial device Zephyr BioHarness) was employed in the tests.

Figure 3 shows a block diagram of the complete FBG acquisition system prototype, where a filtering system was implemented for separating the respiratory and cardiac frequencies from the acquired FBG raw signals. A band-pass filter tuned in the range 0.1–0.4 Hz allows the measurement of the respiratory frequency, while a second band-pass filter with a band pass in the range 0.5–1.3 Hz was used to retrieve the cardiac frequency. This second band-pass filter was used to discriminate the frequency set of interest around 1 Hz, by cutting the respiratory components below 0.5 Hz, and likewise, the high frequencies (the high-frequency noise) above 1.3 Hz.

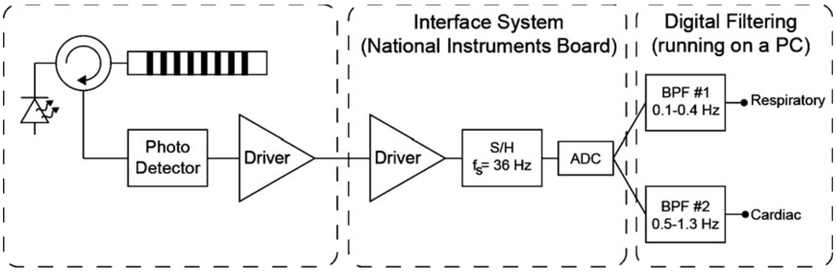

Figure 3. The block diagram of the FBG acquisition system.

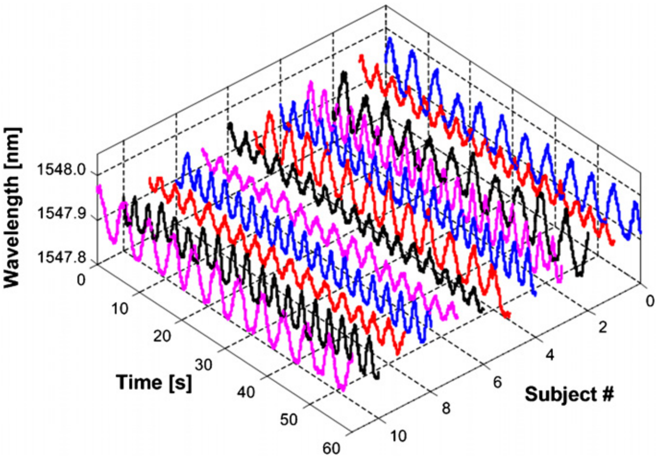

Figure 4. The sensor response to a normal breath (raw data), obtained for a group of 12 healthy subjects (#0 to #11).

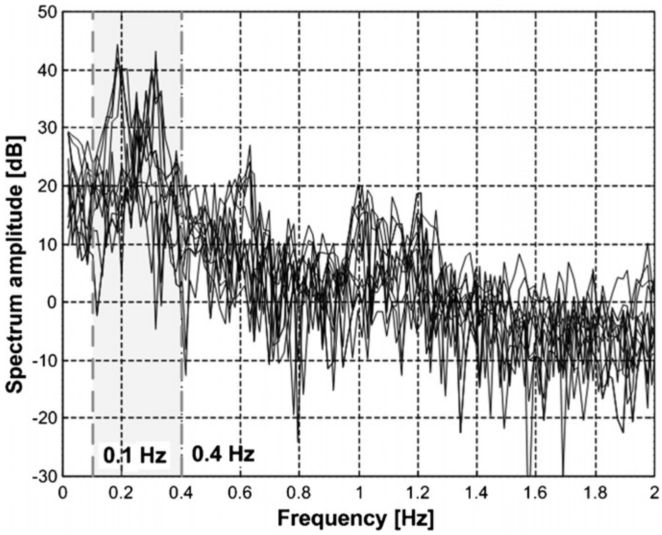

Figure 5. The frequency spectrum of normal breath also obtained for a group of 12 healthy subjects (#0 to #11). This plot shows a superposition of all frequency spectra for achieving a better visualization of the breathing peaks.

Both band-pass filters were implemented in the digital domain using the bilinear technique with the sampling frequency of 36 Hz for approximating their analog transfer function [16].

3. Results

3.1. Experimental results: respiratory frequency

Figure 4 shows the raw data obtained from the FBG sensor with the subjects breathing naturally. External interferences do not appear to degrade the quality of the acquired signals. The main perturbations are detected at the transition between the inhale and the exhale.

The ability to establish a relation between the wavelength deviation and the other measurands (e.g. the displacement and force) is an advantage of these sensors due to their linear response to strain. As the FBG spectral signature deviates 8 nm per 1% of elongation [14], it is possible to retrieve how much the chest expanded. Consequently, the air volume that is inhaled and exhaled can also be estimated as well as the force that is being applied to breathe [17]. A similar approach can be used for determining the applied load to inhale since there is also a linear relationship between the elongation and the necessary load [18].

The corresponding frequency spectra (figure 5) reveal the main frequency peak between 0.1 and 0.4 Hz. It is also possible to observe the group of high-frequency components superimposed on the normal respiratory signal that may originate from involuntary body movements.

By applying the band-pass filter in the 0.1–0.4 Hz range, the detected exterior perturbations in the signal were removed with a low noise–signal ratio. Figure 6 shows for a single subject the signals that were acquired with the commercial device and with the FBG sensor after the filtering stage. The signals' variations have the same behavior, and the few observed differences may be due to the signal processing stage of the commercial device to which there was no access. Nevertheless, the same respiratory frequency (e.g. 24 inhales per minute) was determined in both signals, validating the measurements of the proposed solution.

3.2. Experimental results: cardiac frequency

Figure 7 shows an example of an obtained optical response when the subject was asked to halt his or her breath. A higher frequency response was observed when compared with the respiratory frequency. This new signal led to the assumption that it was related to the heartbeat frequency.

In order to retrieve the cardiac frequency, the processing stage stated in figure 3 was implemented, resulting in the signals of figure 8, whose frequency spectra are illustrated in figure 9. One can detect the region with the location of the cardiac frequency peaks (e.g. between 0.5 and 1.3 Hz).

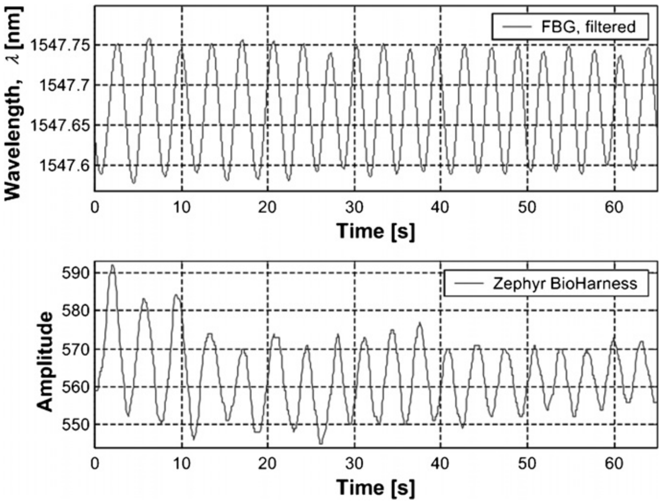

Figure 6. The developed sensing structure response versus a commercial system for the respiratory frequency.

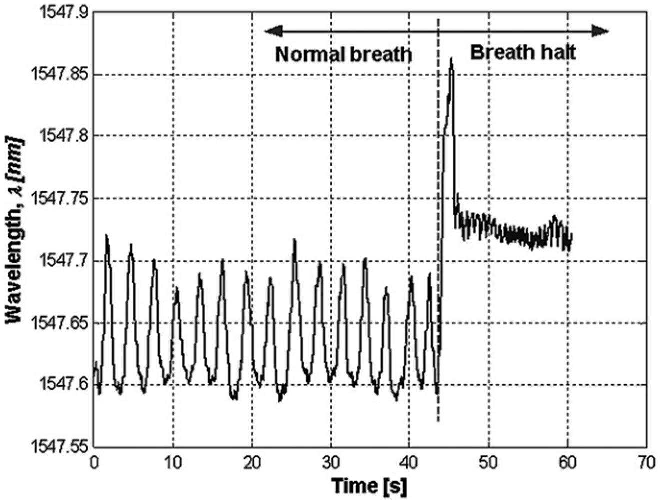

Figure 7. The sensor response to a normal breath followed by a breath halt.

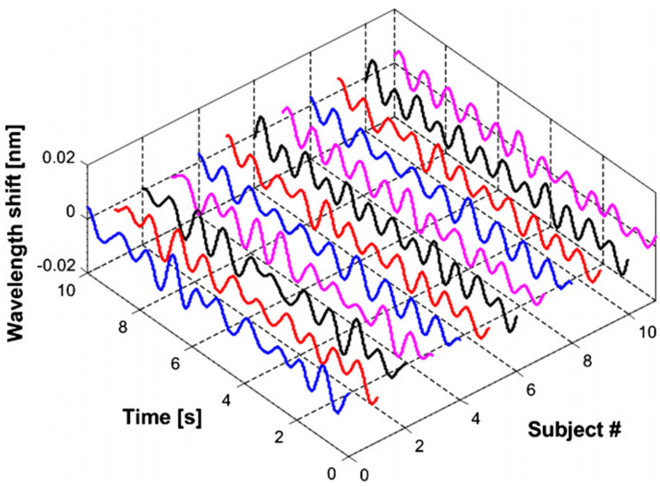

Figure 8. Signals obtained by filtering the acquired raw data from the 12 healthy subjects (#0 to #11). The spectrum of these signals allows the determination of the respective cardiac components—see figure 9.

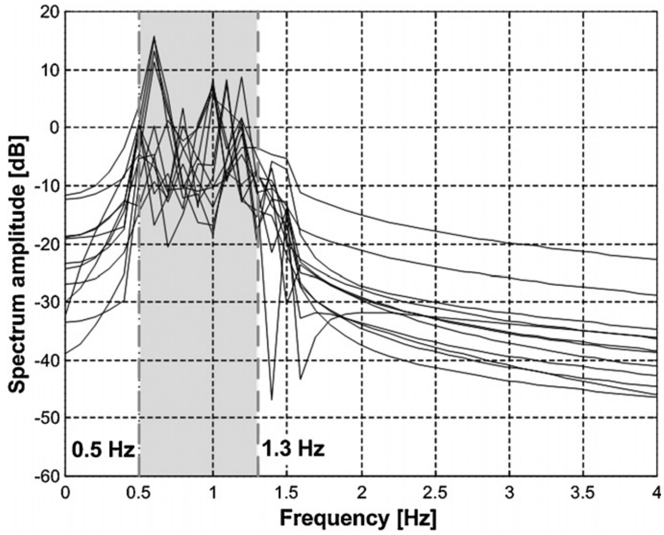

Figure 9. The frequency spectrum of the cardiac frequency for the 12 healthy subjects (#0 to #11).

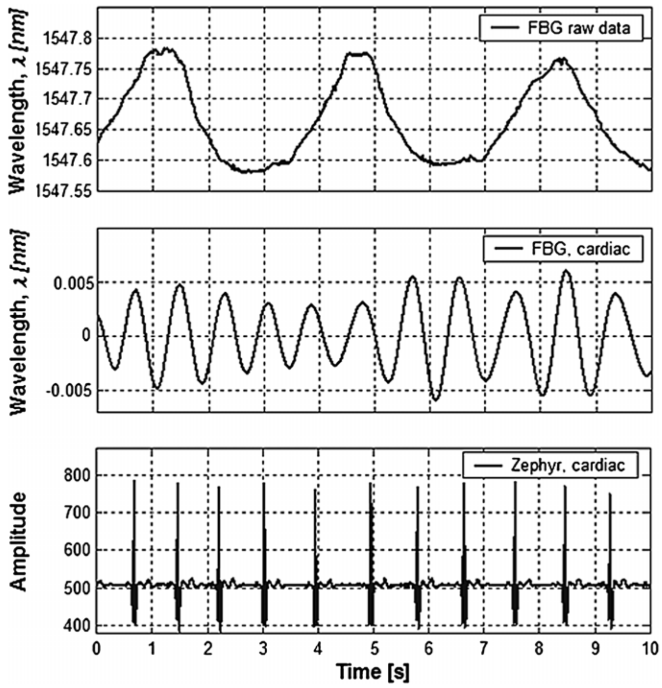

Figure 10. The developed sensing structure response to cardiac frequency and comparison with a commercial system.

The validation of the cardiac components was also done by comparing the obtained results with the commercial device previously used. The comparison between the two systems is shown in figure 10 as well. The FBG signal was filtered in the 0.5–1.3 Hz range. The smart structure with the embedded FBG sensor presents a similar behavior in comparison with the commercial system, both providing the value of 66 heartbeats per minute.

The proposed approach proved to retrieve information about the cardiac frequency in addition to the respiratory component.

4. Conclusions

This paper presents an approach for monitoring both the cardiac and respiratory frequencies with a single optical fiber sensor. The developed structured is made of PVC with an embedded FBG sensor for being fully compatible with the restricted environmental conditions of healthcare institutions. The use of a single optical fiber sensor was mainly possible due to the PVC foil substrate that enabled a large sensitive area, and consequently takes full advantage of the FBG high sensitivity for detecting the respiratory and the cardiac-induced chest displacements.

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