3D printed FBG based sensor for vital signal monitoring – Influence of the infill printing parameters

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Abstract. The fused deposition modelling technique has been used in the production of strain sensors in which fibre Bragg gratings (FBGs) are encapsulated during the 3D printing process. This paper reports the study of the influence of the FBG position and the material filling, in this case a flexible polymer material, on the sensors' sensitivity and overall performance. In addition, this study preliminarily evaluated the ability of the strain sensor to monitor (heart rate) HR and (respiratory rate) RR as a wearable on the wrist and as a non-intrusive solution on the back of an office chair.

1. Introduction

Fibre Bragg grating (FBGs) sensors have been increasingly used in healthcare applications, in detriment of conventional sensors due to their advantages such as reduced size and weight, biocompatibility, multiplexing capacity, high sensitivity, immunity to electromagnetic interference, and the possibility of operating in environments in the presence of water [1, 2]. These features make FBGs one of the most used optical sensing technologies in the production of biosensors, both in wearable and non-intrusive sensors (i.e., sensors to be placed on objects that are in contact with the body as chairs, cushions, etc.) [1]. The monitoring of vital signs such as respiratory rate (RR) and heart rate (HR) is of great importance in medicine. FBGs have been especially used in detecting HR and RR both embedded into hosting flexible materials and without any encapsulation [1, 2]. Once in contact with the chest surface/skin movements, the FBGs detect the strain changes applied directly to this material during the RR and HR cycles [1, 2]. Different techniques have been reported so far using flexible materials to embed FBGs, such as resins and other plastic composites [2] or 3D printing by fused deposition modelling (FDM) [3]. This last technique allows the creation of sensors with low cost, simplicity, and high reproducibility [3]. FDM has been little explored to produce biosensors [4], and only one manuscript has been published using this technique to produce sensors for vital signs monitoring [3]. This work complements this first publication, testing two different positions of the FBG and three distinct fillings for the sensor's body to verify which one experiences the greatest sensitivity.

2. Sensor's development 2.1 Design and Simulation

This study is a continuation of the work developed by our team, and therefore the material and general dimensions of the sensors have been already reported in

[3]: flexible and $30 \times 40 \times 2$ mm (Figure 1a). Here, we intend to test the influence of two different factors: the percentage of filling of the sensor body, and the position of the FBG inside the matrix. In detail, three infills' density (10, 20 and 30 %) (Figure 1b) and two positions of FBG (height at which the FBG is on the sensor's body: 1.00 mm and 1.25 mm from the bottom) (Figure 1c) were tested. Therefore, six different sensors (Table 1) were designed in SolidWorks® software exactly with the filling structure obtained by the 3D printer used to print all the sensors, as seen in Figure 1b. Next, the sensors behaviour was simulated using finite element modelling also with SolidWorks®, considering movements in the range of the chest displacement during RR (440 µm) and HR (150 µm) cycles. Figure 2 shows an example of visual result of simulation, and the Table 1 contains the strain values resulting from each simulation.

As it can be seen, in both cases, a lower infill and a higher height (FBG closer to the surface inducing the deformation) are associated with a higher spectral shift, what could indicate that these sensors may have higher sensitivity too. Only the two sensors that presented the highest sensitivities in the simulation were printed (D, E) and after it were subsequently subjected to experimental tests.



Fig. 1: Schematics of the sensor: (a) general dimensions (b) the infills; (c) the height of the FBG in the sensor.

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Fig. 2: Example of visual result of simulation.

Table 1. Features of six sensors and their simulations results.

	Features		$\Delta L/L$ (strain)		Spectral shift (nm)	
Sensor	FBG height (mm)	Infill (%)	150 μm	440 µm	150 µm	440 µm
Α	1.00	10	9.06E-08	1.55E-07	1.09E-01	0.19
В	1.00	20	6.00E-08	9.37E-08	7.20E-02	0.11
С	1.00	30	3.23E-09	6.45E-08	3.87E-03	0.08
D	1.25	10	1.93E-05	6.07E-05	23.20	72.80
Ε	1.25	20	1.75E-05	2.43E-05	21.00	29.14
F	1.25	30	2.90E-06	3.45E-06	3.48	4.14

2.2. Experimental implementation and characterization

To verify the results of the simulation, sensors D and E were characterized experimentally. The movement of the body induced by the heart beating and breathing was simulated with a waveform generator (33220A, Agilent Technologies, Santa Clara, California). The sensors' response was tested following the protocol in [3].

During the experimental tests, frequencies were varied sequentially between 0.5 Hz and 5.0 Hz for a small amplitude motion (150 μ m), and 0.1 Hz and 1.0 Hz for a higher amplitude motion (440 µm). Both sensors were able to respond to all frequencies studied. Then, two frequencies: 1.25 Hz (to simulate HR) and 0.20 Hz (to simulate RR) were considered, varying only the amplitude of motion (from 100 µm to 550 µm in step of 50 µm), first increasing and then decreasing the amplitude. This last test allowed us to retrieve the sensitivity of each sensor. An average sensitivity of 3.56x10⁻⁴ nm/µm (RR) and 3.98x10⁻⁴ nm/µm (HR) was obtained for sensor D. To sensor E, it was obtained an average sensitivity of 2.77x10⁻⁴ nm/µm (RR) and 3.11x10⁻⁴ nm/µm (HR).

Comparing the results obtained in the finite element simulation and in the experimental test, it was possible conclude that in both cases the most sensitive sensor is the one with the lowest filling, the sensor E. For that reason, this was the sensor chosen for the exploratory tests.

3. Exploratory tests on volunteers

The preliminary assessment of the optical sensor feasibility to monitor RR and HR as a wearable and nonintrusive sensor, was evaluated in one user (a man with 20 years old). The user was invited to place our reference device (BioHarness (BH)- ZEPHYR[™] performance systems, Medtronic, Colorado, USA) on their chest and to sit on an office chair. Two tests were carried out: the first with the sensor placed on the wrist, attached to a Velcro bracelet; and the second with the sensor glued to the back of the office chair. In both tests, the user was invited to do

the following breathing exercise: 20 s apnea (Ap), 60 s of normal breathing (NB), 20 s Ap, 60 s NB and 20 s Ap.

To obtain the vital signals from the exploratory tests, different signal processing steps were applied to highlight each signal component. considering the higher amplitude of breathing-induced chest movements only a smooth filter was applied to detect RR. For HR, since the cardiac vibrations are lower in amplitude and higher in frequency than the ones due to RR, a bandpass filter with cut-off frequencies of 0.8 Hz and 2.0 Hz was applied to discharge the breathing contributions and reveal the masked HR signal. Considering the BH values as a reference, a comparison was made between the number of respiratory and cardiac cycles detected in the same time intervals by proposed sensor and the BH (Figure 3).

From the results of all testes, a root-mean-square deviation (RMSD) value of ~0.00 rpm and 3.99 bpm were obtained. As the mean RR and HR was 10.17 rpm and 68.83 bpm, the RMSD corresponded to an error of ~0.00% to RR and 5.80% to HR.



Fig. 3: Example segments for a section of the office chair data acquired (left); RR and HR results represented as bar graphs for two testes (right).

4. Conclusion

This paper presented 3D-printing FBGs, evaluated the influence of both infill density and material on their responses and tested the most sensitive in the monitoring of RR and HR as a wearable (in contact with the wrist) and non-intrusive solution (in contact with an office chair). The sensor showed good performance, with a RMSD value lower than 6%. These promising preliminary results open the possibility of testing the proposed sensor in other wearable and non-intrusive solutions and on more users to confirm the reliability and usability of this device as a sensor for vital signs monitoring.

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