Tactile sensor array integrating fiber Bragg grating transducers for biomechanical measurement

L.Massari[1], P.Saccomandi[2], F.Sorgini[1], E.Sinibaldi[3], G.Ciuti[1], A.Menciassi[1], P.Cappa[4], E.Schena[5], C.M.Oddo[1]

[1]The BioRobotics Institute,Scuola Superiore Sant'Anna, Pisa, Italy
[2]Institute of Image-Guided Surgery (IHU), Strasbourg, France, S/c Ircad, STRASBOURG Cedex
[3]Center for Micro-BioRobotics @SSSA, Istituto Italiano di Tecnologia, Pontedera (PISA), Italy
[4]Department of Mechanical and Aereospace Engineering,'Sapienza' University of Rome, Italy
[5]Center for Integrated Research, University Campus Bio-Medico, Rome, Italy
l.massari@sssup.it, c.oddo@sssup.it

INTRODUCTION

This paper presents the development and validation of an array of multi-axis tactile sensors that is intended to measure selected part of the components of torque and force vectors acting on the surface where the sensor is integrated. The developed tactile sensor is based on Fiber Bragg Grating (FBG) technology [1].

The proposed tactile sensor can be used to enhance robot-assisted surgical operations by encoding tool-tissue tactile interaction, which then can be displayed to the operator by means of a haptic or other interface on the master console. Furthermore, the sensor is ultra-soft, hence suitable for application in the field of smart textiles; for example, it can be integrated in a glove in order to sense both external forces and hand movements while preserving wearer's comfort [2]. Another main characteristics is the possibility to develop MR-compatible systems thanks to the FBG immunity to electromagnetic interference [3, 4].

The first section of this manuscript illustrates the FBG working principle, the developed sensing system and the experimental setup and protocols. Then experimental results are presented and discussed, and roadmaps for future works are envisaged.

MATERIALS AND METHODS

Transduction principle and sensor design

FBGs are sensitive to both strain and temperature, which are encoded in the temporal modulation of the spatial period of a grating patterned on the optical fiber. The readout of sensor information requires the injection of light from a spectrally broadband source into the fiber. Part of the injected light is transmitted and another narrow part of the spectrum, centered around the so-called Bragg wavelength (λ_B) is back-reflected (Figure 1); the principal wavelength of the reflected light is dependent on: (i) the grating period of the strain and (ii) the temperature to which the sensor is exposed. Hence, the Bragg wavelength λ_B is given by the expression:

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda_B$$

where$n_{eff}$is the effective refraction index of the fiber core and Λ_B is the grating period. The response of FBG is defined both from the physical elongation of the sensor (and the corresponding change in the period) and the change in the fiber index due to photoelastic effect that arises from the thermal expansion of the fiber material. The present tactile sensor uses 12 FBGs in a single optical fiber (Figure 2), being embedded in a thin polymeric sheet to obtain a pad with a low thickness (1mm). An excessively small bending radius can lead to damage or even breakage in the optical fiber, therefore the path followed by the encapsulated fiber is designed accordingly. The encapsulation polymer is Dragon Skin (10 medium, Smooth-on, USA), which has appropriate mechanical properties since it is flexible, stretchable and is able to transmit deformations. Thanks to its characteristics, this sensing pad is able to measure several mechanical quantities (e.g. elongation, strain and pressure) along the whole surface. Furthermore, the pad may be embedded, attached or wrapped on a specific surface.

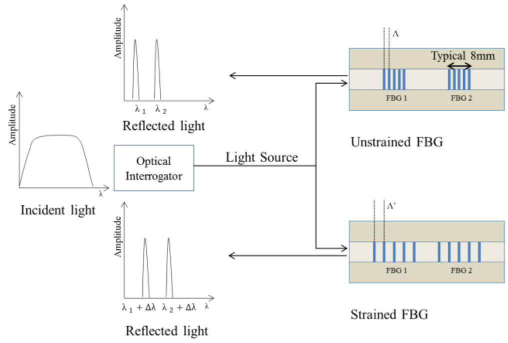

Figure 1 - FBG measurement architecture.

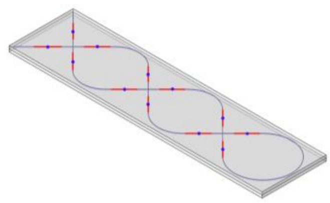

Figure 2-Rendering showing the optical fiber path in the encapsulation polymer, the positioning of the 12 FBG transducers (red lines) and the indentation sites for the experimental evaluation (blue dots).

Experimental setup and protocol

A quasi-static calibration process was performed to establish the relationship between the applied force and the sensor output. Figure 3 shows the experimental setup for this aim. A testing machine (Instron, 5900

Series, Figure 3B) was used to apply known values of force on the sensor surface. A cylindrical probe with diameter of 5 mm (Figure 3A-1) was used to apply deformation to the surface of the array (Figure 3A-2). The Instron was used to move the indenter along the Z-axis with constant speed of $0.1\ mm \cdot s^{-1}$. During the indentation experiments, the probe was applied in 12 selected sites of the sensor surface (Figure 2). Multiple runs (N=6) were performed to evaluate repeatability with load stimulation range up to 1 N, 2 N and 3 N (see Figure 5 for related results). No temperature variations occurred during the experiments, anyway a dummy FBG sensor could be integrated in the future in the final device, for compensating the possible occurrence of temperature variations in operational conditions.

Two stages were used to translate the sensor along the two other axes, X and Y. The output of each FBGs was measured by an optical spectrum interrogator (sm125, Micron Optics), and recorded by PC with the dedicated software.

Figure 3-Experimental Setup: (A1) cylindrical indenter, (A2) sensor array integrating FBG, (A3) Y-translational stage, (A4) X-translational stage, (B) Testing machine.

RESULTS

The variation of the wavelength was dependent on the applied force. From an examination of Figure 4, where paradigmatic time histories of the applied force and sensor output are reported, it emerges that the indentation force F_Z was tracked by the transducers with a consistent variation of the wavelength.This variation was highly repeatable (±1% fitting variation) and monotonic. Figure 5 displays the wavelength variation as a function of the applied force, providing evidence of linearity between these two physical quantities (0.040 nm/N sensitivity).

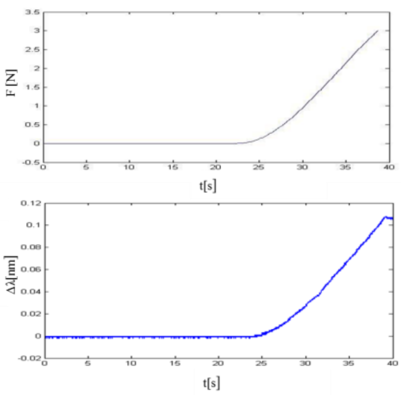

Figure 4 - The upper plot shows indentation force Fz as a function of time. The plot below displays wavelength variation as a function of time.

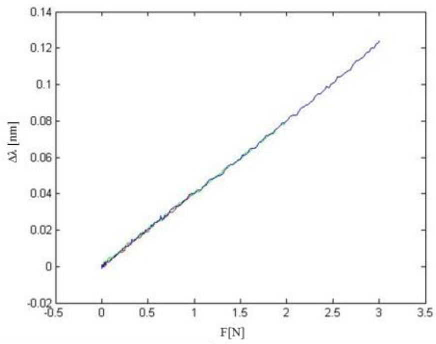

Figure 5- Repeatable monotonic modulation of wavelength as a function of the normal indentation force F_Z. The trends with stimulation up to 1 N,2 N and 3N are shown in the plot.

DISCUSSION AND CONCLUSION

This extended abstract deals with the presentation and the design of a tactile sensor array integrating FBG transducers for biomechanical measurements in several application scenarios. Due to the known immunity to electromagnetic interference, the chosen technology allows the use of such tactile sensor in MR environment, that will be tested in future studies. Furthermore, unlike traditional sensing elements, increasing the number of FBGs will not lead to a huge wiring encumbrance since a single optical fiber (or a few fibers) can convey information from multiple transducers.

The obtained results are promising and give encouraging perspectives for this prototype. Future investigations will target a more accurate fabrication process, the elaboration of a FEM model of mechanotransduction, and the experimental evaluation within real application scenarios such as with surgical robotics instruments.

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REFERENCES

[1] C. Massaroni, P. Saccomandi, and E. Schena, "Medical Smart Textiles Based on Fiber Optic Technology: An Overview," *Journal of functional biomaterials,* vol. 6, pp. 204-221, 2015.

[2] A. F. da Silva, A. F. Goncalves, P. M. Mendes, and J. H. Correia, "FBG sensing glove for monitoring hand posture," *Sensors Journal, IEEE,* vol. 11, pp. 2442-2448, 2011.

[3] A. Grillet, D. Kinet, J. Witt, M. Schukar, K. Krebber, F. Pirotte, *et al.*, "Optical fiber sensors embedded into medical textiles for healthcare monitoring," *Sensors Journal, IEEE,* vol. 8, pp. 1215-1222, 2008.

[4] P. Saccomandi, C. M. Oddo, L. Zollo, D. Formica, R. A. Romeo, C. Massaroni, *et al.*, "Feedforward Neural Network for Force Coding of an MRI-Compatible Tactile Sensor Array Based on Fiber Bragg Grating," *Journal of Sensors,* vol. 2015, pp. 1-9, 2015.