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Polymer optical fiber strain gauge for human-robot interaction forces assessment on an active knee orthosis

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ABSTRACT

This paper presents the development of a polymer optical fiber (POF) strain gauge based on the light coupling principle, which the power attenuation is created by the misalignment between two POFs. The misalignment, in this case, is proportional to the strain on the structure that the fibers are attached. This principle has the advantages of low cost, ease of implementation, temperature insensitiveness, electromagnetic fields immunity and simplicity on the sensor interrogation and signal processing. Such advantages make the proposed solution an interesting alternative to the electronic strain gauges. For this reason, an analytical model for the POF strain gauge is proposed and validated. Furthermore, the proposed POF sensor is applied on an active orthosis for knee rehabilitation exercises through flexion/extension cycles. The controller of the orthosis provides 10 different levels of robotic assistance on the flexion/extension movement. The POF strain gauge is tested at each one of these levels. Results show good correlation between the optical and electronic strain gauges with root mean squared deviation (RMSD) of 1.87 Nm when all cycles are analyzed, which represents a deviation of less than 8%. For the application, the proposed sensor presented higher stability than the electronic one, which can provide advantages on the rehabilitation exercises and on the inner controller of the device.

1. Introduction

The application of robotic orthosis and exoskeletons on rehabilitation provides advantages over the conventional therapies such as treatment customization, possibility to evaluate the patients progress with quantitative information and objectives [1]. Furthermore, it can optimize human resources in physiotherapy [2].

The treatment customization and the evaluation of the patient progress throughout the rehabilitation can be achieved through the analysis of the dynamic interaction between the exoskeleton and the patient, which happens with the transition between passive, active-assisted and active-resisted movements of the robotic device controller [3]. The information of the human-robot interaction can be achieved through the measurement of the interaction forces between the user and the robotic device [4]. In addition, the interaction forces assessment are also important on the development of control strategies for wearable robots [4].

A common approach to estimate these forces on the lower limb rehabilitation is through the application of electronic strain gauges (ESG) on an exoskeleton [4]. However, ESGs must be carefully attached on the structure that will be submitted to strain and this attachment is made with different resins, which leads to difficult and time-consuming process [5]. Furthermore, the temperature can cause a drift on the sensor response that needs to be compensated in order to obtain a reliable measurement [6]. Other drawbacks of ESGs are nonlinearities between the strain and the sensor response, necessity of frequent calibrations and can present sensitivity to electromagnetic interferences [7].

Optical fiber sensors have been applied throughout the years to measure parameters like temperature [8], liquid level [9], pressure [10], vibration [11] and strain [12]. The advantages of these sensors are its compactness, lightweight, multiplexing capabilities, chemical stability and immunity to electromagnetic interferences [13]. Fiber Bragg Gratings (FBG) sensors are successfully applied as an optical strain gauge and different applications in aeronautics [14], industry [15] and medicine [16] have been proposed. However, optical strain

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gauges based on FBG also have to be attached on the surface with different glues or resins and also need a temperature compensation [12]. Furthermore, the higher cost of the interrogation system imposes a limitation on the technology application [17].

Polymer optical fiber (POF) have additional advantages of higher flexibility, higher diameter (about 1 mm) that enable the application of low precision plastic connectors, which generally results in a lower cost system [18]. Furthermore, its higher numerical aperture allows the application of low cost laser or light emitting diode (LED) [17]. Owing these advantages, different approaches with POF for strain sensors have been proposed. Rodriguez-Cobo et al. [19] presented a POF strain sensor based on specklegrams, but its complexity on signal processing can be a major disadvantage. Another approach to measure the strain is proposed in [20], where the sensor is based on direct curvature on the POF, which leads to a signal attenuation of the output power. However, the polymer is a viscoelastic material, which does not have a constant response with stress or strain [21] and the viscoelastic behavior may lead to errors on the sensor measurement [22].

In order to obtain a low-cost strain gauge that is capable of overcome some of the limitations of the current technologies, this paper presents a POF strain gauge based on the principle of light coupling between two fibers applied on a lower limb orthosis to measure the human-robot interaction forces. The principle of light coupling between two fibers has already been applied to measure acceleration [17], spine bending angle [23] and displacement [24]. The advantages of this sensor are the low cost, ease of implementation and simplicity on signal processing, since it is an intensity variation based sensor [25]. Furthermore, the proposed strain gauge does not have temperature sensitivity. Since the employed POF has 1 mm of diameter, it is possible to design supports to position the fiber on the structure without the need of glues or resins. Moreover, there is no stress directly applied on the fiber. For this reason, the POF viscoelastic response will not lead to errors on the sensor strain measurement [17].

This paper is divided as follows. Section 2 presents the sensor operation principle and its analytical model. Section 3 presents the experimental setup employed for the sensor characterization, model validation and application on the orthosis. The results of the POF strain gauge application on an active knee orthosis and its comparison with an ESG as well as the analytical model validation are depicted in Section 4. Final remarks and future works are discussed in Section 5.

2. POF strain gauge operation principle

The light coupling principle employed on the POF strain gauge (POF-SG) is based on the difference on the alignment between two POFs. There are two fibers, where the POF connected on the light source is the 'illuminated' fiber. The POF connected to the photodetector is the 'non-illuminated' fiber, as shown in Fig. 1. As presented in Fig. 1, the output of the illuminated fiber has a cone of light, known

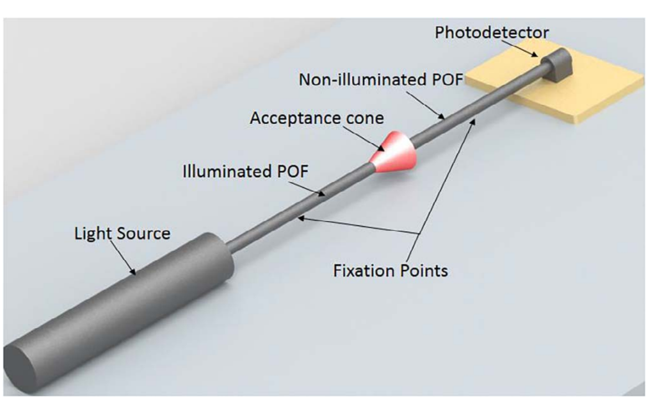

Fig. 1. Operation principle of light coupling based sensors with polymer optical fibers.

as the acceptance cone.

If the non-illuminated fiber input is within the acceptance cone boundaries of the illuminated fiber output, the light will be transmitted to the non-illuminated fiber and the output power is measured by the photodetector. Moreover, any variations of the angular, axial or lateral alignment between the fibers lead to variation on the light coupling efficiency, which can be measured with the photodetector.

The sensor presented in Fig. 1 can be positioned on a cantilever beam under flexural stress. Since the stress causes a deflection on the beam, there will be an alignment difference between the two POFs, which leads to power attenuation when the beam is under deflection. For this reason, it is possible to apply the light coupling principle between two POFs to measure the deflection or the strain of a structure. Fig. 2 shows the application of the light coupling based sensor to measure strain of a structure, which is represented by a metallic beam.

Referring to Fig. 2, the solid lines represent the initial condition of the system, where there is no deflection on the beam. In this case, 'L' represents the distance between the beam support and the region that a force 'F' is applied. Furthermore, 'x' is the distance between the illuminated and non-illuminated POF (POF 1 and POF 2, respectively). The dashed lines represent the beam deflection when a force 'F' is applied, which is deflected by 'δ'. The inset of Fig. 2 shows the geometrical changes of the alignment between the fibers when the beam is under deflection.

If the only variation on the POF response is due to the light coupling between two fibers, the POF power variation $\left(\frac{P}{P_i}\right)$, where P is coupled power into the non-illuminated fiber and P_i is the incident light power, will be equal to the coupling efficiency between the illuminated and non-illuminated POFs. Therefore, the power variation detected by the photodetector is represented by Eq. (1), for a multimode step index POF and considering a uniform power distribution [17].

$$\left(\frac{P}{P_i}\right) = \left[1-\frac{\theta n_0}{\pi NA}\right]\left[1-\frac{xNA}{4an_0}\right]\left[\frac{\pi}{2}\left(\cos^{-1}\left(\frac{l}{2a}\right)-\frac{l}{2a}\sqrt{1-\left(\frac{l}{2a}\right)^2}\right)\right] \quad (1)$$

where n_0 is the medium refractive index. NA and a are the POF numerical aperture and core radius, respectively. The lateral displacement between the two POFs is represented by l. Whereas, the angular displacement and axial gap between the fibers are represented by θ and x, respectively.

The deflection of a beam submitted to the force presented in Fig. 2 can be estimated by Eq. (2), as presented in [26].

$$\delta = \frac{FL}{AE} \quad (2)$$

where 'A' is the cross-sectional area of the beam and 'E' is the Young modulus of the beam material.

The beam deflection represents the lateral misalignment between the fibers. However, as it approaches the region where the force is applied, the deflection increases. For this reason, the deflection that the POF 2 is submitted is δ′, which can be calculated with the relation presented in Eq. (3).

$$\delta' = \frac{x}{L}\delta \quad (3)$$

The axial gap (x) between POF 1 and POF 2 after the beam deflection can be calculated by applying the Pythagorean Theorem on the triangle of the inset of Fig. 2 and the difference between x and x′ gives the variation of the axial gap between the illuminated and non-illuminated fiber. Furthermore, the angular misalignment (θ) caused by the beam deflection can also be calculated from geometry, as presented in Eq. (4).

$$\theta = \tan^{-1}\left(\frac{\delta}{L}\right) \quad (4)$$

By substituting the results obtained by the longitudinal, lateral and