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Application of Machine Learning Algorithms for the Analysis of an Optical Fiber Sensor for Use in Endovascular Coiling of Intracranial Aneurysms

S. Shojaei Khatouni[1], J. C. E. Ewald[1], H. K. Trieu[1]
[1]Institute of Microsystems Technology, Hamburg University of Technology, Hamburg, Germany.
Sohrab.shjoaei@tuhh.de

Summary:
Using a test rig, two different fiber bragg grating sensors were exposed to temperature changes, compressive loads and bendings. The light spectrum reflected by them was analyzed with respect to these three effects, utilizing machine learning algorithms. The results show that the models of the sensors are suitable for detecting and differentiating the effects of bending and temperature changes with sufficient accuracy.

Keywords: fiber Bragg grating, pressure measurement, temperature measurement, curvature measurment, machine learning

Background

Compared to other diseases like coronary heart disease, intracranial aneurysms (IA) have a fairly low incidence of 2-6% in adult population [1]. Regardless, this pathological condition of intracranial arterial blood vessels has a very high 30-day mortality of approximately 50% after rupture, and therefore subarachnoidal haemorrhage [2]. A commonly used approach to prevent intact IA from rupturing, or stabilize already ruptured IA is endovascular coiling. During this procedure IAs are filled with coils, to stop blood circulation, initiate coagulation and therefore stabilize the bulge. The coils are administrated by pushing them through a catheter into the IA. Currently, there is no method to perform any in situ measurement of the pressure applied on the wall of the aneurysm during this procedure, even though studies indicate, that high pressure can lead to intraoperative ruptures, which appear in 2,6–4,4% of coiled intracranial aneurysms [3]. This work presents machine learning (ML) algorithms for data evaluation of a fiber optic, fiber bragg grating (FBG) based sensor, which was developed to be integrated into the coiling procedure.

Machine Learning for FBG Sensors

The most commonly used parameter for evaluation of FBG based sensors is the Bragg wavelength λ_B . Light with this wavelength is reflected by otherwise almost unreflective FBG. The Bragg wavelength is a function of the grating period Λ as well as the refractive index n:

$$\boldsymbol{\lambda_B = 2n\Lambda} \qquad (1)$$

Unfortunately, the refractive index and the grating period of a fiber Bragg grating are influenced by its temperature, axial strain, and curvature. These dependencies are given by:

$$\boldsymbol{\Lambda = \Lambda_0(1 + \frac{1}{E}\sigma_z + \alpha_T \Delta T)} \qquad (2)$$

$$\boldsymbol{n(x) = n_0 - \frac{{n_0}^3 x}{2R}[-(p_{11} + p_{12})\nu + p_{12}]} \qquad (3)$$

Therefore, mere axial pressure measurements are possible, only if measures are taken in order eliminate the cross-sensitivity of FBG sensors, or to extract the feature of interest. The sensor described in this work is designed to measure axial strain while being bent and under changing thermal conditions. There, these disturbances have to be taken into consideration while measuring the pressure. The simultaneous exposition of FBG sensors to these three influences is uncommon. Therefore, no appropriate analysis models can found in literature. Hence, analysis carried out in this work is focused on the fundamental decoupling of the different parameters. For this purpose a fiber-optical sensor with three FBGs was analyzed, using multilayer perceptrons (MLP) and Gaussian process regression (GPR). This approach is based on congeneric analyses performed in [4] and [5]. The fiber-optic sensor was put into a thermo-regulated (±0.1 °C) hydrostatic pressure (±0.1 bar) chamber. In addition, the sensor war put into a variable radius fixture. Measurements were performed with following parameters:

Tab. 1: Measurement parameters

Series	A	B
Number FBGs	1	2
Bending radius	15–105 mm	–
Pressure	0–10 bar	0–10 bar
Temperatur	35–37 °C	34–39 °C
Number of Measurements	359	400

Results

To choose proper input signal features for the ML algorithms a manual feature extraction was performed on the raw sensor data. A combination of signal energy, 3dB bandwidth and the Bragg wavelength showed the best performance, allowing sufficient distinguishability of bending curvature, temperature and pressure acting on the FBG sensor. Cross validation (CV) and root-mean-square-error (RMSE) values were used for evaluation of estimation accuracy.

Tab. 2: Performance of GPR vs. MLP

Variable	Measurement series	Method	Error
Curvature	A	GPR	4,1 mm (CV)
		MLP	7,7 mm (RMSE)
Temperatur	A	GPR	0,12 °C (CV)
		MLP	0,12 °C (RMSE)
	B	GPR	0,11 °C (CV)
		MLP	0,13 °C (RMSE)
Pressure	A	GPR	2,8 bar (CV)
		MLP	2,9 bar (RMSE)
	B	GPR	2,1 bar (CV)
		MLP	2,1 bar (RMSE)

The CV and RMSE of curvature and temperature estimations being within the accuracy of the devices used for reference measurements indicate a sufficiently high number of measurements. The GPR model performed better or equally well as the MLP model with regard to all three parameters. The axial pressure estimations of both of the two models were insufficient in accuracy, with a coefficient of determination of $R^2 = 0{,}05$ and a CV error of 2.1 bar.

The bending curvature predicted by the GPR model is shown in Figure 1, with its coefficients of determination being $R^2 = 0{,}98$.

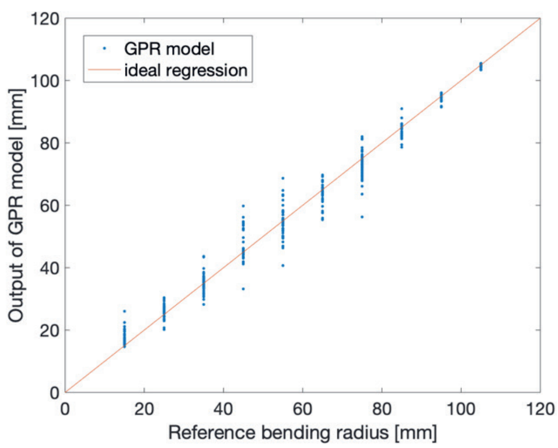

Fig. 1. Estimations of sensor bending by the GPR model for given, actual reference bending of the sensor.

Figure 2 shows the GPR models predictions of the temperature having a lower but similarly sufficient coefficient of determination ($R^2 = 0{,}96$).

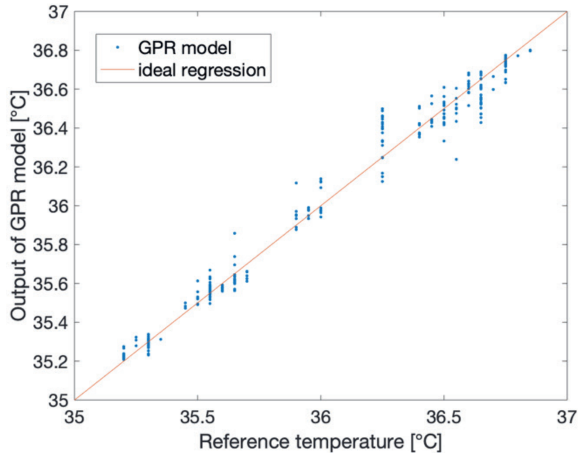

Fig. 1. Temperature estimation by the GPR model,

Conclusion

We have shown that both Gaussian process regression and multilayer perceptron modelling are suitable for differentiating and quantifying the effects of temperature and curvature on FBG sensors. In order to enable a sufficient prediction of pressure, we suggest that temperature sensitivity of the sensor is decreased by adding a liquid crystal polymer cladding to the sensor. This could partially compensate the thermal strain and therefore reduce cross-sensitivity.

Literature

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