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Shape Estimation for Flexible Medical Instruments
An Approach Based on FBG Sensors Embedded in a Biocompatible Polymer Filled Tube

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Abstract—Real time shape estimation is important in several applications involving flexible medical instruments for minimally invasive investigations and surgery. Optical fiber sensors have been shown to be effective in this regard as compared to other methods. However, constraints arising out of bonding onto alloy substrates restrict the bending radius due to high strains and spectral distortion. Algorithms based on simple strain measurements from multiple FBG sensors to obtain exact radius of curvature impose the need for very high precision in placement. In this work, we propose a method based on Fiber Bragg Grating (FBG) sensors embedded in Polydimethylsiloxane (PDMS) placed in plastic tubing to overcome these shortcomings.

Keywords—Shape Estimation; Flexible Medical Instruments; FBG Sensors; PDMS;

I. INTRODUCTION
Real time shape estimation of flexible instruments is important in building assistive systems for surgeons performing minimally invasive procedures. Limitations of methods based on fluoroscopy [1] and electromagnetic tracking [2] have been studied earlier. In this context, methods based on optical sensing and especially those based on fiber optics are interesting. Sophisticated methods involving multicore fibers [3] and Bragg waveguides in coreless fibers [4] have been proposed. However, reliance on fibers and fabrication methods that are not readily accessible and expensive interrogation methods make them difficult to deploy. The work presented here attempts to address the shape estimation problem using FBG sensor arrays fabricated using commercially popular methods while reducing complex requirements on very precise sensor placement and alignment.

II. EXPERIMENTS AND RESULTS
A. FBG Sensors Bonded to Nitinol – Results and Limitations
Methods and algorithms for shape estimation by bonding FBG sensors on Nitinol (a nickel-titanium alloy) have been studied earlier especially in the context of needle guidance [5]. However, prior applications [6] to flexible instruments like endoscopes that undergo much larger bending have not considered the very high strain values and FBG spectrum distortion that lead to substantial difficulty. Also, the stiffness of the wire adversely affects the flexibility, and thus the maneuverability of the instrument. Table 1 shows the strains measured on a FBG sensor bonded on a nitinol wire of diameter 1.2mm. For radius of curvatures below 120 mm, the strains are very high and often lead to sensor breakage.

TABLE I: Strain on FBG sensors bonded to a nitinol wire of diameter 1.2mm for different radius of curvatures

<table>
<thead>
<tr>
<th>Radius of curvature (mm)</th>
<th>Measured Strain (μstrain)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>164</td>
</tr>
<tr>
<td></td>
<td>3800</td>
</tr>
</tbody>
</table>

B. Embedded FBG sensors
One of the major advantages of FBG sensors is that they can be embedded inside other materials. In the method proposed here, FBG sensors fabricated using phase mask method using 125 micron germanosilicate optical fibers were placed inside a medical grade plastic tube used for intravenous injections and then the tube was filled with Polydimethylsiloxane (PDMS) and allowed to cure. PDMS provides the dual advantage of high flexibility and biocompatibility. It was ensured that the sensors are apart by more than 60° but no specific constraint was put on the angle as it is difficult to place multiple sensors with exactly the same angle between them. Furthermore, no specific constraint to have a perfectly straight tube after the curing process is imposed.

![Device Cross Section]

A calibration phase was performed consisting of measuring FBG peak wavelength for different radii of curvature ranging from 15cm to 3 cm and at six different
positions of the sensors relative to the neutral axis of the tube. The device was inserted into another tube with a uniform curvature as shown in Fig 2.

Fig. 2. Experimental Setup for calibration

Fig. 3 shows the plots of measured Bragg peak wavelength for different radii of curvature at two different rotation positions inside the larger tube.

The nonlinear relation between the radius of curvature, position of the sensors relative to the neutral axis and the reflected wavelength shift can be seen in Fig. 3. Multi Layer Artificial Neural Networks (ANNs) are good at learning such non linear relations. Hence, an ANN with two hidden layers was trained using the statistical computing software ‘R’ to perform non linear regression to estimate the radius of curvature from the delta Bragg wavelengths that correspond to strain. Only 30% of data was used for training while the rest 70% was used as test set to ensure good generalization over the different positions. The estimation errors for test positions are shown in Fig 4.

Fig. 3. Reflected Bragg Wavelength at different R values

The estimation errors for test positions by the trained ANN

A 2D curve can be built from small segments using Frenet-Serret equations and the algorithm mentioned below which is explained in detail in [7]. The curvature $\kappa$ can be obtained from the estimated radius of curvature $R$.

$$
\begin{bmatrix}
T_1 \\
N_1 \\
B_1
\end{bmatrix} =
\begin{bmatrix}
0 & \kappa(t) & 0 \\
-\kappa(t) & 0 & \tau(t) \\
0 & \tau(t) & 0
\end{bmatrix}
\begin{bmatrix}
T(0) \\
N(0) \\
B(0)
\end{bmatrix}
$$

Given $x(0), T(0)$ and $N(0)$ and $v(t)$ and $k(t)$, in some range $0 \leq t \leq t^*$ such that $k(t) \neq 0$ in the range, define $h=t^*/N$ for some large $N$. Defining $x_h(0)=x(0)$, for $0 \leq h < N$

Centre

$$
x_c(t) = x_h(t_j) + \frac{1}{k(t_j)} N_j 
$$

$$
x_c(t) = C_j + \frac{1}{k(t_j)} \left[ -\cos(k(t_j)v(t_j)(t-t_j)N_j \right] 
$$

$$
T_{j+1} = \sin(k(t_j)v(t_j)h)N_j + \cos(k(t_j)v(t_j)h)T_j 
$$

$$
N_{j+1} = \cos(k(t_j)v(t_j)h)N_j - \sin(k(t_j)v(t_j)h)T_j 
$$

|III. FUTURE WORK|

It is proposed to create a more robust calibration step for a complete sensor array. Also the 3D shape reconstruction used for an earlier setup utilizing strain gauges [8] will be applied to the FBG setup.

REFERENCES


