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Large Deflection Shape Sensing of a Continuum Manipulator for Minimally-Invasive Surgery

Hao Liu [Member, IEEE],

Laboratory for Computational Sensing and Robotics (LCSR), Johns Hopkins University, Baltimore, Maryland, USA; State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, China

Amirhossein Farvardin [Student Member, IEEE],

Laboratory for Computational Sensing and Robotics (LCSR), Johns Hopkins University, Baltimore, Maryland, USA

Sahba Aghajani Pedram [Student Member, IEEE],

University of Hawaii at Manoa, Honolulu, HI, USA

Iulian Iordachita [Senior Member, IEEE],

Laboratory for Computational Sensing and Robotics (LCSR), Johns Hopkins University, Baltimore, Maryland, USA

Russell H. Taylor [Fellow Life Member, IEEE], and

Laboratory for Computational Sensing and Robotics (LCSR), Johns Hopkins University, Baltimore, Maryland, USA

Mehran Armand

Laboratory for Computational Sensing and Robotics (LCSR), Johns Hopkins University, Baltimore, Maryland, USA; Johns Hopkins University Applied Physics Laboratory, Baltimore, Maryland, USA

Hao Liu: liuhao.hit@gmail.com; Amirhossein Farvardin: afarvar1@jhu.edu; Sahba Aghajani Pedram: sahbaap@hawaii.edu; Iulian Iordachita: iordachita@jhu.edu; Russell H. Taylor: rht@jhu.edu; Mehran Armand: Mehran.Armand@jhuapl.edu

Abstract

Shape sensing techniques utilizing Fiber Bragg grating (FBG) arrays can enable real-time tracking and control of dexterous continuum manipulators (DCM) used in minimally invasive surgeries. For many surgical applications, the DCM may need to operate with much larger curvatures than what current shape sensing methods can detect. This paper proposes a novel shape sensor, which can detect a radius of curvature of 15 mm for a 35 mm long DCM. For this purpose, we used FBG sensors along with nitinol wires as the supporting substrates to form a triangular cross section. For verification, we assembled the sensor inside the wall of the DCM. Experimental results indicate that the proposed sensor can detect the DCM's curvature with an average error of 3.14%.

I. Introduction

Flexible instruments and dexterous continuum manipulators (DCMs) are commonly used in minimally-invasive surgery (MIS) for their high steerability and capability to increase the operation space within limited anatomical regions. Several groups have proposed a variety of surgical dexterous manipulators. Examples include active cannulae composed from a series of nested and curved tubes [1, 2], shape memory actuation units [3], and cable-driven manipulators [4-6].

We have previously developed a cable-driven 2D DCM for the MIS treatment of osteolysis occurring after total hip arthroplasties [7]. The goal of this surgery is to remove and replace the bone defect caused by polyethylene liner of an acetabular implant. Without removing the well-fixed acetabular implant, the MIS approach uses the holes in the implant to access the osteolytic lesion (Fig. 1). We have previously reported the design and development of a cable driven DCM with a 6 mm outer diameter which was built from two nested nitinol tubes. The major features of this DCM for orthopedics applications include relatively large inner to outer diameter ratio (4 mm/6 mm) and relative structural strength in the plane orthogonal to its bending plane. These features enable inserting custom-designed tools (e.g. cutter, gripper, curette, flexible endoscope) through the lumen of the DCM for the proposed procedure as well as other similar MIS applications.

Previous efforts for intraoperative control of the DCM involved developing models for estimating the shape from cable-length measurements [8, 9], as well as the intermittent use of x-ray for updating the model estimation [10]. This approach would, however, require a trade-off between accurate real-time control and the amount of x-ray exposure to the patient. Real-time shape sensing would reduce the reliance on using intermittent x-rays for estimating the shape of the DCM.

Approaches for shape sensing may include the use of electromagnetic sensors. In the presence of metal implants and tools, however, electromagnetic interference will limit the accuracy of the sensors [11]. Also, these sensors usually have a rigid body and cannot adapt to the continuous bending of the instruments or robots, especially for a small continuum robot [9]. In addition, the tracking frequency is limited to less than 50Hz. Other competitive approaches for large deflection shape sensing include piezoelectric [12] and piezoresistive polymers [13]. However, their size, the stress-strain hysteresis of the piezoresistive polymer and the bias and drifting problem of PVDF are limitations that are difficult to overcome.

Fiber-optic sensors offer a number of advantages over conventional sensors, including the absence of electromagnetic interference, lightweight structures, stability, repeatability, high sensitivity, fast response, integrated structure, and a potentially low cost. Owing to their intrinsic characteristics, FBGs are particularly well suited for measuring strain with a high bending sensitivity. By analyzing the reflected wavelength from each fiber, the curvature and bending direction can be obtained.

Two different approaches are commonly used for curvature detection with FBG sensors: 1) integrating the sensor with a substrate to form an assembly (e.g. [14, 15]), and 2) creating a bundle of sensors and optical fibers (e.g. [16, 17]).

For both approaches, maximizing detection range has rarely been considered in the literature. In Table 1, we have summarized some approaches and their detection ranges. For our proposed DCM, the largest bending radius can reach to approximately 6 mm, where the curvature is 166.7 m^{-1} . As shown in Table 1, this value is much larger than what current methods of shape sensing can measure. To detect relatively large curvatures, it is not possible to directly connect the FBG sensor to the DCM (i.e. approach 1), because the bending strains of the DCM are much higher than what optical fibers can handle. Therefore, a special supporting structure may be required to reduce the bending strain of the optical fiber for large curvature bending.

By using Multi-core fibers, eccentric-core fibers, and D-shape fibers (approach 2), we can reduce the bending strain to a fairly small value. This, however, may cause light interference for the multi-core fiber or reduce the stiffness of the D-shape sensor. It is also challenging to keep sensors bending in a specific direction.

This paper focuses on designing a novel large curvature detecting Shape Sensor Array (SSA) for the osteolysis DCM. Section II describes the conceptual design. SSA modeling, assembly and calibration are presented in Section III. Section IV describes the algorithm for getting the 2D shape of the DCM. The experiments and evaluation of the shape sensing performance is described in Section V. Section VI offers a summary as well as some recommendations for future studies.

II. Overall Shape Sensing Concept

A. Large curvature detection

Generally, the shape of the sensor is obtained from interpolation of discrete FBG strain data along the arc length. Because of this, the configuration of the FBG sensor should be properly designed to meet requirements of large curvature detection for our DCM. The basic principle of curvature detection is as follows [14, 20]:

$$\Delta\lambda = k_\varepsilon \varepsilon + k_T \Delta T \quad (1)$$

$$\varepsilon = \delta \cdot \rho \quad (2)$$

where ε is the strain for FBG sensor, δ is the bias distance of the optical fiber from the neutral plane of the sensor (Fig. 2), κ is the curvature of the body being tested, λ is the wavelength shift, k_ε is the strain coefficient, and k_T is the temperature coefficient.

If temperature is well compensated, the wavelength shift of FBG optical fiber is proportional to the strain as well as the curvature. Therefore, the maximum curvature is largely dependent on δ which should be kept as small as possible. In contrast to making the core biased or cladding asymmetrical within the optical fibers, our sensor is designed with one FBG optical fiber and two nitinol wires that are bonded together, as shown in Fig. 2. The distance between the FBG core and the line connecting two nitinol wire centers is t and φ represents a certain bending direction which will be used later for evaluating the bending modulus.

The dimensional requirements are as follows:

- a. The FBG allowable strain requires the FBG fibers to be located near the neutral plane of the SSA. FBG fibers should work within certain strain range. Previously it was shown that optical fibers can handle strain values that are less than 0.5% [17]. In this paper, we have used FBG fibers that can measure up to 1% strain without breaking;
- b. In order to distinguish wavelengths for all FBG sensing points, the wavelength ranges must ideally have no overlap. The wave length range for the used interrogator was 40nm (Micron Optics, USA). However, some overlap will enable employing more FBG sensing points within the wavelength range and, therefore, provide higher shape sensing precision.

The nitinol wires prevent local stress concentration. Different materials can be used for this application, but considering the allowable strain under large deformation, nitinol is the most suitable choice for this application. As a result of its superelasticity property, nitinol works in its elastic region (with constant modulus) within the allowable strain range of the optical fiber.

The FBG center line to the SSA neutral plane distance can be adjusted to a small value by changing the relative distance of two nitinol wires, as shown in Fig. 3. The triangular cross section of the SSA (shown in Fig. 2) has a non-uniform elastic bending modulus which keeps the SSA from twisting.

B. Shape sensing scheme

The DCM in this paper can bend in a plane, called bending plane. The DCM's bending modulus in this plane is much smaller than that of other planes. Therefore, 2D shape sensing is sufficient to track the position of the DCM. Figure 4 shows the overall design, in which two SSAs are inserted through the channels within the DCM wall. At the distal end of the DCM, the SSAs are attached to the DCM body keeping their neutral planes perpendicular to the DCM bending plane. In our proposed design, the SSAs are allowed to freely move parallel to the DCM bending plane. At the proximal end, there is a sliding support with tiny triangular holes in it, through which the SSA will be inserted.

The design features of the DCM sensors are shown in Fig. 4 and described in the following:

- a. The DCM has an inner lumen for the surgical instruments, such as a cutter, or a brush to get through. Sensors cannot occupy this lumen since they may interfere with those instruments. Also, we cannot place the sensors on the outer surface of the DCM since that increases its overall size. Therefore the sensor is inserted in the channels through the wall of the DCM.
- b. The SSA can freely move along the DCM. A single sensor on one side of the DCM is either in tension or compression. This will result in a biased length for the sensor. By using two SSAs in opposite sides, we can compensate for the changes in lengths due to tension and compression effects.

- c. The twisting of the SSA will affect the results of shape sensing to a great extent [21]. Since the SSAs are flexible, they can easily twist as the DCM bends. To prevent torsion, a sliding support was added to the proximal end of the DCM. This, together with the non-uniform bending modulus of the SSA will prevent the sensor from twisting.
- d. The DCM is a segmented structure. The nitinol fibers allow the SSA to maintain a continuous curvature through the DCM channels in order to prevent the FBG fiber from breaking.

III. Sensor Modeling, Assembly and Calibration

A. Neutral plane

To develop a theoretical model for the SSA, it is necessary to find its neutral plane (Fig. 2). We assume the SSA is a composite beam with a different material at each section. The neutral plane can be obtained from the equilibrium equation of forces:

$$\int_{A_1} \sigma_1 dA_1 + 2 \int_{A_2} \sigma_2 dA_2 = F_N = 0 \quad (3)$$

$$\sigma_i = E_i(y - \delta) / \rho$$

where σ_i , A_i and E_i ($i = 1, 2$) are the stress, cross sectional area and Young's modulus for optical fiber and nitinol wire (Fig. 2), therefore the location of neutral plane is:

$$\delta = \frac{2E_2D_2^2t}{\{E_1D_1^2 + 2E_2D_2^2\}}, t \in \left[\frac{d_{core}}{2}, \frac{\sqrt{(D_1 + D_2)^2 - D_2^2}}{2} \right] \quad (4)$$

where d_{core} is the radius of the optical fiber core and D_i ($i = 1, 2$) are the outer diameter of optical fiber and nitinol wire.

B. Equivalent bending modulus

The triangular structure of the SSA leads to a different bending modulus for each side. This causes the SSA tending to bend in the direction that it has the smallest bending modulus.

The equivalent bending modulus can be obtained from equilibrium equation for bending moment on the cross section of SSA:

$$\int_{A_1} y \sigma_1 dA_1 + \int_{A_2} y \sigma_2 dA_2 = M \quad (5)$$

The location of the neutral plane is:

$$\delta = \frac{E_2D_2^2(y'_1 + y'_2)}{E_1D_1^2 + 2E_2D_2^2} \quad (6)$$

where y'_1 and y'_2 are the coordinates for nitinol wires in the direction denoted by φ .

Then, the equivalent bending modules W_e can be written as:

$$W_e = E_1 I_1 + E_2 I_2 + E_2 I_3 = E_1 \left(I_{10} + \frac{\delta^2 \pi D_1^2}{4} \right) + E_2 \left(2I_{20} + \frac{(y'_1 - \delta)^2 \pi D_1^2}{4} + \frac{(y'_2 - \delta)^2 \pi D_2^2}{4} \right) \quad (7)$$

where $I_{i0} = \pi D_i^2 / 64$ ($i=1, 2$) is the moment of inertia for the optical fiber and nitinol wire.

Table 2 shows the properties and dimensions of the material used in the SSA (see Fig. 2)

With these parameters, we can calculate the position of the neutral plane, δ , and the equivalent bending modulus in 360 bending orientation. The maximum difference in directional bending modulus was found to be 20MPa. To increase this value, we can reduce the distance between the centers of fiber and nitinol wires. Therefore, using this triangular structure, we can meet both requirements of reducing the working wavelength range and creating an non-uniform bending modulus.

Twisting is a common problem in the design of shape sensors. Some researchers have reduced this effect by using anti-twisting structures such as the braided polymer tube [22]. In our design, we have used a ring with triangular holes reduce the effect of twisting. This ring maintains the orientation of the SSA at the proximal end.

C. SSA Assembly

The optical fiber used in this study contains an array of 3 FBG sensors distributed 10 mm apart. The length of the active area for each sensor is 3 mm (Technica SA, China). LOCTITE 3101. A modified acrylate UV glue (Henkel, Germany) was used to glue two nitinol wires with oxide surface (NDC Technologies, USA) to the FBG optical fiber. An assembly device was designed to precisely maintain the relative position between the optical fiber and these wires. Fig. 5 shows the SSA assembly under microscope (ZEISS, Germany) at 25 times magnification. After the assembly, the SSA was placed inside the DCM wall channels. The optical fiber was fixed at the distal end, and a triangular slot (shown in Fig. 4) was manufactured by laser cutting (Lasera Technology Corporation, USA) to maintain its orientation at the proximal end.

D. Calibration results

To validate the linearity of the curvature-wavelength relationship, a multi-channel calibration board with different curvatures was designed and 3D printed (Fig. 6). For this experiment, two clamps with triangular slots were fabricated to preserve the orientation of the SSA on both sides. Fig. 7 illustrates the results of calibration for all 3 sensors within the SSA. The slopes of the fitting lines are slightly different. This may be due to the precision of the assembly or the use of a varying amount of glue. Fig. 7 shows the calibration results for 3 FBG sensors. The relationship between curvature and wavelength shift were written in equation (8).

$$\begin{aligned}
\Delta\lambda_1 &= 0.091 \cdot \kappa_i + 1556 \\
\Delta\lambda_2 &= 0.103 \cdot \kappa_i + 1545 \\
\Delta\lambda_3 &= 0.093 \cdot \kappa_i + 1533
\end{aligned} \quad (8)$$

IV. Shape Sensing

A. 2D Shape Reconstruction

The wavelength range for each FBG sensor, and the number of FBG sensors that we can use are limited due to the wavelength range of the interrogator. In this case, within the 40 nm wavelength range of the interrogator, 3 FBG sensors were placed along the optical fiber. For the 2D shape reconstruction, a linear relationship was assumed between curvature and the arc length so linear interpolation is done for two segments connecting these three FBG sensors. Usually, the coordinate system is built at one end of the shape sensor and the tangential direction at the end is set to be and the Y axis.

The tangential angle with respect to X axis, θ is calculated from the integral of curvature and the coordinates can be calculated numerically using the equations below,

$$\theta(s) = \int_0^s \kappa(s) ds + \theta_0 \quad (9)$$

$$\begin{cases} \Delta x = \cos\theta(s) \cdot \Delta s \\ \Delta y = \sin\theta(s) \cdot \Delta s \end{cases} \quad (10)$$

where θ_0 is the tangential angle at the starting point, s is arc length and x and y are the increments for an arc length infinitesimal Δs .

B. Shape sensing scheme of DCM

Fig. 8 shows the arrangement of the FBG sensors (yellow dots) on SSA along the DCM.

There are two segments without sensor covered. The curvatures are assumed to be constant. When the DCM bends, the arc length for the side where SSA 1 is located increases and the 3 FBG sensors cannot cover the whole length of the DCM. On the other hand, the arc length for the side where SSA 2 is located decreases and its 3 FBG sensors can cover the arc length. When the DCM bends towards the opposite side, the opposite is true about these sensors. Therefore, the two SSAs are highly complementary and by using the combination of their shape in their coordinate system Σ_1 and Σ_2 , we can construct the 2D shape for the DCM's centerline.

C. Sensor Calibration inside the DCM

For reconstructing the shape of the DCM in real-time, we first found the wavelength-curvature relationship for SSA inside the channels within the walls of the DCM. For this purpose, we designed and manufactured a calibration board that contained 5 slots with different curvatures, ranging from 15.6 m^{-1} to 50.8 m^{-1} . These slots were built according to the dimensions of the DCM (6 mm outer diameter and 35 mm length) such that it could fix

the position of the DCM within a constant curvature. The DCM was manually placed in the slots and wavelength data were recorded for all of the FBG sensors. This process was repeated 10 times for each slot. Fig. 9 shows the constant curvature bending of the DCM inside the slot. Since the curvature was constant, the wavelength shifts for all of the FBG sensors within SSA were expected to be the same.

D. Results and Error Analysis

For a preliminary verification of our proposed method, we generated the calibration curve from wavelength data obtained from four of the slots at each time. The wavelength data from the fifth slot was then used for predicting the curvature of that slot (leave-one-out experiments). The leave-one-out verification experiments were performed for the three middle slots. The mean error was found to be 7.14% for the 16.7 m^{-1} curvature, 1.02% for 23.5 m^{-1} curvature, and 1.25% for 30.1 m^{-1} curvature. Fig. 10 shows the mean wavelength shift of the FBG sensors for different curvatures. In this case, the verification was done for the slot with a 23.5 m^{-1} curvature.

V. Discussion and Conclusions

The main contribution of this paper was to develop a novel shape sensor for the DCM. For this purpose, we used FBG fibers along with nitinol wires as the supporting substrate to form a triangular cross section. The neutral plane of the SSA assembly was adjusted to reduce the wavelength shift of the FBG sensors. In addition, the bending modulus was kept non-uniform causing the SSA bend in the same direction as the DCM. The calibration curves showed a fairly linear curvature-wavelength relationship for SSA sensors. For verification, we assembled the SSA within the wall of the DCM and performed leave-one-out experiments.

Experimental results indicate that curvature detection is more accurate for larger curvatures. However, the largest error for smaller curvatures will not cause a significant error for the DCM's tip position. Therefore, an average error of 3.14% can be used to evaluate the performance of our shape sensor. Since the DCM was manually placed in the slots, the friction between the sensor and its lumen was a major source of error in the verification experiment. Although this error can be minimized in future studies, but for the application at hand, the millimeter accuracy will not jeopardize the safety since there are no critical tissues or organs in the working space of DCM.

Future work will involve creating methods and algorithms for temperature compensation using two distributed FBG arrays. In the future, we will also extend the application to shape sensing of 3D continuum manipulators for other applications.

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Fig. 1.
MIS treatment of osteolysis [7].

Fig. 2.
Sensor configuration for larger curvature detection.

Fig. 3. Strategy to reduce the range of wavelength shift by increasing the center distance between nitinol wires ($L_1 > L_2$) a) reduced wavelength shift and b) larger wavelength shift.

Fig. 4. Shape sensing for osteolysis dexterous manipulator.

Fig. 5.
The (a) Parallel nitinol wires and (b) whole assembly under microscope.

Fig. 6.
Calibration board for 2D Shape Sensor Array.

Fig. 7. Calibration results for an array of 3 FBG sensors

Fig. 8. Arrangement of the FBG sensors for Shape reconstruction

Fig. 9.
Shape sensing with constant curvature bending.

Fig. 10.
Wavelength shift for different curvatures, calibration (blue) and verification (red).

Table 1

Existing shape sensing methods with FBG sensors.

Author	Type	Max Curvature (m^{-1})
X. Yi et al. [18]	4 FBG sensors with nitinol wire	8
Y.L. Park et al. [14]	3 FBG sensors with grooved nitinol wire	2
R. J. Roesthuis et al.[19]	3 FBG sensors with grooved nitinol wire	10
W N MacPherson et al. [15]	Multi-core FBG sensor	22.7
X. Chen et al. [16]	Eccentric FBG sensor	3.5
F M Araújo et al. [17]	D-shape FBG sensor	10

Table 2

Material properties and dimensions.

FBG optical fiber	
Young's modulus E_1	70 GPa
Outer diameter D_1	100 μm
Nitinol wires	
Young's modulus E_2	75GPa
Outer diameter D_2	125 μm
Assembly	
t	80 μm