Deformation Sensing of Colonoscope on FBG Sensor Net

Yi Xinhua*, Wang Mingjun, Cheng Xiaomin
School of Mechanical Engineering / Ningbo University of Technology
No. 89, Cuibai Road, Haishu District, Ningbo city, China
*Corresponding Authors, e-mail: yixinhua@126.com

Abstract
Owing to the complex condition and non-visualiztion of human intestinal, Loop formation of colonoscope often happens to hurt the patient during the diagnosis of colon. This paper presents a deformation sensing method using Fiber Brag Grating (FBG) sensor net to real-time display the shape of colonoscope that would help the endoscopist how to manipulate the colonoscope into the body and reduce the probability of loop formation. The structure configuration and packing method of a FBG sensor net is described and the relative coefficient matrix was acquired by experiment calibration between the curvature and shift of wavelength. The position of FBG sensor node on the colonoscope can be derived by curvature information relative to the handling part of the colonoscope and the curve fitting method is employed to reconstruct the shape of colonoscope using the position of FBG sensor nodes. Experiment results verified that the deformation sensing method is feasible and the position accuracy of the tip can reach 4.5mm for the colonoscope with the length 1200mm.

Keywords: colonoscope, shape reconstruction, differential geometry, fiber bragg grating

1. Introduction
Colonoscopy is the most important instrument in the minimum invasive surgery (MIS), however it is easy to cause the apex of loop splitting the colonic wall because the shape of colon is invisible for the colonoscopist who relies on his experience to insert the colonoscope into the body. Loop formation of colonoscope often happens during the diagnosis of colon because of complexity of working condition and it brings a great pain and danger to the patient [1-2]. Although the equipment and techniques used during colonoscopy have been refined over the past several decades, the complication rate remains very low. In the operation for straitening the loops, it is necessary to twist the colonoscope. To acquire the turning angle relative to the patient position, it is very valuable for surgeon to real-time know the shape of colonoscope. To reduce patient discomfort and make it ideal for use, so it is necessary to use intelligent sensor and visualization technique to improve performance for traditional colonoscope. Therefore, three-dimension shape detection becomes a key technology for both traditional and intelligent colonoscope.

At present, fluoroscopy was most commonly used to locate the colonoscope tip during manipulation of troublesome loops of colon. Although as an indispensable tool, fluoroscopy has certain disadvantages. On one hand, conventional fluoroscope systems cause the problem of x-ray exposure, costly, bulky and inconvenient to use [3-4]. On the other hand, though fluoroscope provides real time imagery with continuous operation, it does so only in 2D image and it is difficult to provide accurate location. Several other kinds of technique can be used to visualize the 3D shape of colonoscope including magnetic field [5-7], ultrasound [8] and optical sensor technologies [9]. In those prototypes developed, Olympus Company has developed a named Scope Guide 3-D Imager based on magnetic field shape-reconstruction module [10] for colorectal cancer screening and in Shanghai University a shape sensing technology for flexible rod was developed based on the FBG sensor net. In the condition not changing the configuration of colonoscope, the FBG sensor net is embedded into the biopsy channel of colonoscope and the shape of endoscope can be reconstructed by wavelength shift of FBG [11]. This method has an advantage not to be interfered by electromagnetic signals, but it is easily affected by the change of temperature. In this paper, the authors emphasized the research on
the sensing net design and the model of shape reconstruction on the basis of earlier research. Since it isn't negligible for effect of temperature, a configuration of sensor net has been redesigned to eliminate the temperature effect for shape reconstruction. The principle of deformation reconstruction based on differential geometry and quaternion method [12] has been described and some practical experiments have been done to testify the feasibility of sensing sensor.

2. Setting Up of Sensing System

The FBG sensing system is composed of six components as Figure 1 shows. Four-channel FBG demodulator is based on LAN (local-area network) with the sampling frequency 250 Hz which provides high sampling speed for real-time display. Medical colonoscope is traditional fiber colonoscope composed of thin fibers bundled which is flexible and easily bent. FBG sensors net consist of four fibers with the diameter 0.76mm. On every fiber, there are five Bragg Gratings points and the spacing between two neighboring points is 120mm. The basic principle of deformation measuring is that when the wavelength of every FBG point shift with the shape of colonoscope changing, the wavelength change of FBGs acquired by FBG demodulator were sent to computer via TCP/IP protocol and the shape was reconstructed by shape sensing algorithm based on strain information.

A FBG sensor net consists of a shape memory alloy (SMA) wire whose diameter is 0.76mm as substrate and four optical fibers which are coated around SMA wire at every 90 degrees. Five Fiber Bragg Gratings exist in each optical fiber with the spacing about 100mm between two neighboring grating. The configuration of FBG sensor net is showed in Figure 2. To satisfy wavelength shift scope of every FBG point for change of temperature and strain, center wavelength must have a different value between two neighboring FBGs. According to estimation of measuring scope of wavelengths, the center wavelength of five gratings in one optical fiber respectively is 1524nm, 1532nm, 1540nm, 1548nm, 1556nm and FBG wavelength shift in range of about 8 nm. Because of the dimension limitation of colonoscope's biopsy channel, it is necessary to reduce the diameter of shape sensing sensors. According to experiment result, the diameter of sensing net is about 2mm and it is just good to meet the requirement to insert into the biopsy channel of colonoscope.
2.1. Relation between curvature and wavelength shift

The shape of colonoscope is sensing using curvature information, so the following question is how to get the relation between curvature and wavelength shift. Figure 3 shows distribution of one pair of FBGs in one section. When bending radius of the section is \( r_B \), FBG-a and FBG-c is respectively under tension or compression, and the strain value can be calculated by bending radius. The strain of FBG-a and FBG-c can respectively expressed as

\[
\epsilon_a = \frac{r_p + r_s}{r_s} \sin \phi \\
\epsilon_c = \frac{r_p + r_s}{r_s} \cos \phi
\]

(1)

Where, \( r_f, r_s \) is respectively the radius of fiber and substrate, \( \epsilon_a, \epsilon_c \) is respectively the strain that FBG suffers, \( r_B \) is bending radius of the section, \( \phi \) is the angle between the bending direction and x direction.

According to the relation of Fiber Bragg grating to strain and temperature, we can have the formulation

\[
\frac{\Delta \lambda_b}{\lambda_b} = (\frac{\delta \lambda}{\delta T} + \frac{\delta \lambda}{\delta T} + \delta T + (1 - P) \Delta \epsilon
\]

(2)

Where, \( \Delta T \) is the change of temperature, \( \Delta \epsilon \) is strain, \( \lambda_{b0} \) is Bragg center wavelength, \( P \) is photo-elastic coefficient, \( \delta \lambda_T \) is thermal expansion coefficient, \( \delta \lambda_p \) is the thermo-optic coefficient, the general thermal expansion coefficient is \( 0.5 \text{ ppm}^\circ C \) and the thermo-optic is \( 8 \text{ ppm}^\circ C \).

Since FBG sensor is sensitive to temperature and strain, so we couldn't distinguish the effect of the temperature and strain by measuring the change of FBG coupling wavelength, this cross-sensitivity seriously affect the application in traditional field. So it is necessary to propose a simple and low-cost way to compensate temperature. We adapt two FBG nodes to measure the same direction strain as Figure 3 shows. For FBG-a and FBG-b, letting the FBG-a strain is \( \epsilon_a + \epsilon_{\Delta T} \), and the FBG-b strain is \( \epsilon_b + \epsilon_{\Delta T} \). Considering the effect of temperature for both sensors is the same, so the \( \epsilon_{\Delta T} \) is equal to \( \epsilon_{\Delta T} \). The strain for bending along the x axis and y axis can be respectively written as

\[
\Delta \epsilon_x = (\epsilon_a - \epsilon_b)/2 \\
\Delta \epsilon_y = (\epsilon_a + \epsilon_b)/2
\]

(3)

Without considering the effect of temperature, the relation between change of wavelength and curvature can expressed as
Where \( k_{bx}, k_{by} \) is respectively the bending curvature along the x axis and y axis.

Fiber "a" and Fiber "b" are one pair, Fiber "c" and Fiber "d" are the other. According the principle, pair of FBG sensors is positioned at 90 degree. Then, we can get spatial curvature by the two sensors positioned at 90 degrees. Let \( k_s \) denotes the spatial curvature, then

\[
(1 - P_s)\frac{r_x + r_y}{r_{bx}} = \frac{\Delta \lambda_{bx}}{\lambda_{b}} \Rightarrow \frac{1}{r_{bx}} = \frac{\Delta \lambda_{bx}}{(1 - P_s)\lambda_{b}(r_x + r_y)} = k_{bx}
\]

(4)

\[
(1 - P_s)\frac{r_x + r_y}{r_{by}} = \frac{\Delta \lambda_{by}}{\lambda_{b}} \Rightarrow \frac{1}{r_{by}} = \frac{\Delta \lambda_{by}}{(1 - P_s)\lambda_{b}(r_x + r_y)} = k_{by}
\]

(5)

As Figure 3 shows, let \( \phi \) denote the angle of direction of bend relative to x-axis under pure bend, then \( \phi \) can be expressed as

\[
\phi = \arctan\left(\frac{k_{bx}}{k_{by}}\right)
\]

(6)

### 2.2. Calibration of Relative coefficient

In order to analyze the relation between curvature and wavelength shift, it is necessary to calibrate every FBG sensor by experiment and acquire the relative coefficient. Therefore we set up a calibration board as Figure 4 shows, which is taken many holes on a series of standard radius by vertical drill press. And then sensing net was bended into different radius by position block. Figure 5 respectively shows the linear relation between curvature and wavelength shift about the five FBG nodes on the fiber-a in theory maximum tension-compression. According to experiment, calibration coefficient of 20 FBGs sensing points have been obtained and the calibration matrix \( K \) can be expressed as

\[
K = \begin{bmatrix}
465.983 & 470.83 & 491.787 & 477.975 & 536.278 \\
548.48 & 482.871 & 448.779 & 521.919 & 538.802 \\
-423.312 & -449.979 & -404.087 & -374.494 & -426.044
\end{bmatrix}
\]

### 2.3. 3D Shape reconstruction algorithm in cartesion coordination

When knowing the spatial curvature of every FBG section in the instrument shaft, it is necessary to derive the relative spatial position of every FBG section. Here, an assumption has been proposed: the curvature of random position between two FBG sections is linear to curvature of two FBG sections. So when acquiring the curvature of two sections, random curvature between them can be calculated. To facilitate the calculation, the FBG sensing net is simplified as a curve, every FBG section is considered as a node. The position calculation of nodes is based on a kinematic model as Figure 6 shows. The world coordinate system \( O \) is located at the inlet of biopsy channel, the moving coordinate system \( o_{i-1} \) is on the node \( i-1 \) and the coordinate system of the next node \( i \) is \( o_i \) where the FBG sensor located. To get the relation about coordinate \( o_{i-1} \) and \( o_i \), it is necessary to obtain the rotation matrix and translation matrix from \( o_i \) to \( o_{i-1} \). The increasing amount in X, Y, Z direction between the two neighbours nodes is diagramed using differential geometry in Figure 7. Let the \( d_x, d_y, d_z \) respectively denote the increase amount of translation from \( o_{i-1} \) and \( o_i \), so we can get:
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\[
\begin{align*}
    d_x &= \frac{1}{k} \cdot (1 - \cos \theta) \cdot \cos \phi \cdot d_s \\
    d_y &= \frac{1}{k} \cdot (1 - \cos \theta) \cdot \sin \phi \cdot d_s \\
    d_z &= \frac{1}{k} \cdot \sin \theta \cdot d_s 
\end{align*}
\] (7)

where, \( \theta = d_s \cdot k_b \), \( d_s \) is the differential curve.

So the translation matrix can be written into

\[
P_{i}^{i-1} = \begin{bmatrix} d_x & d_y & d_z & 1 \end{bmatrix}^T
\] (8)

Rotation matrix can be gotten using the quaternion method

\[
R_{i}^{i-1} = \begin{bmatrix}
    n_x & n_y & n_z \\
    o_x & o_y & o_z \\
    a_x & a_y & a_z
\end{bmatrix}
= \begin{bmatrix}
    1 - 2b^2 - 2c^2 & 2ab - 2sc & 2ac + 2sb \\
    2ab + 2sc & 1 - 2a^2 - 2c^2 & 2bc - 2sa \\
    2ac - 2sb & 2bc + 2sa & 1 - 2b^2 - 2c^2
\end{bmatrix}
\] (9)

where, \( s = \cos(\frac{\theta}{2}) \), \( a = \sin(\frac{\phi}{2}) \), \( b = -\cos(\frac{\phi}{2}) \), \( c = 0 \)

So orientation matrix in a single 4x4 transformation matrix about the \( o_i \) coordinate system relative to the \( o_{i-1} \) coordinate system can be expressed as

\[
T_{i}^{i-1} = \begin{bmatrix}
    R_{i}^{i-1} & P_{i}^{i-1} \\
    0 & 1
\end{bmatrix}
\] (10)

Then, the random dynamic point on curve relative to the world coordinate system can be written as

\[
P_i = T_{i}^{i-1} \cdot P_{i-1}
\] (11)

When the coordinate value of every discrete point on the curve is acquired, the shaft shape of colonoscope can be reconstructed using curve fitting. To verify the algorithm, we use the helix curve giving the parameter \( r \) and \( p \). Let \( r \) denote the radius of helix \( r = 100mm \) and \( p \) denote the pitch \( p = 5mm \). As figure 8 shows, shape of simulation curve and real helix curve overlap well.
3. Experiment result analysis

To verify the reliability of shape reconstruction based on curvature information, the testifying experiment had been done using colonoscope to bend into the approximate colon shape, and the detection system are employed to acquire the strain change of every FBG nodes by FBG sensors net to reconstruction the shape of colonoscope. Figure 9 shows the software system of shape reconstruction and real-time shape display when the shape of colonoscope changing. Table 1 shows one set of data about the spatial reconstruction position of eight detecting point comparing with actual spatial position. In order to verify the repeatability, five sets of data experiments had been done.

Figure 10(a). Position error in x direction

Figure 10(b). Position error in y direction

Figure 10(c). Position error in z direction

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<th>Position in x axis (mm)</th>
<th>Position in y axis (mm)</th>
<th>Position in z axis (mm)</th>
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Figure 10(a), 10(b), 10 (c) respectively shows the position error of ten detection points in the X, Y and Z-directions, and the maximum error reached 4 mm. The position errors come from two
aspects, one is the FBG sensor packing error and the other is reconstruction algorithm error. Due to the constraints of packaging technique, actual packing position of FBG sensor is not consistent with theory position. To minimize the effect of the packaging error on shape reconstruction, it can be rectified by calibrating packing error. Shape reconstruction error comes from a process of integrating micro-arc segment, so accumulated error is the negative complication.

4. Conclusion

This paper made a precise description of the colonoscope deformation sensing method using FBG sensor net. The curvature information is derived using the wavelength shift of FBG sensor and the curvature of random nodes can be calculated by the assumption that the curvature is linear between the two neighboring FBG sensor nodes. Differential geometry method and quaternion method is employed to calculate the translation amount in x, y, z direction. The following conclusions are included by theoretical and experimental analysis.

(1) It is feasible using curvature information to derive the position of random point on the curve and reconstruct the shape of colonoscope by differential geometry and quaternion method.

(2) It can’t ignore the effect that packing error of FBG sensing net and temperature changing for colonoscope shape reconstruction. Packing error can be rectified by calibration and the effect of temperature can be compensated by layout of sensing net.

Intelligent colonoscope is an important issue for the future development of colonoscope. This research provides a convenient and safe means for the visualization of the colonoscope shape, further clinical experiment is needed for promotion from the precision and safety.

Acknowledgment

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Reference