Multifiber optical bend sensor to aid colonoscope navigation

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Abstract. A colonoscopy's near-blind navigation process frequently causes disorientation for the scope operator, leading to harm for the patient. Navigation can be improved if real-time colonoscope shape, location, and orientation information is provided by a shape-tracking aid, such as a fiber optic bend sensor. Fiber optic bend sensors provide advantages over conventional electromechanical shape-trackers, including low cost and ease of integration. However, current fiber optic bend sensors lack the ability to detect both bending direction and curvature, or the ability to detect multiple localized bends. An inexpensive multifiber bend sensor was developed to aid users in navigation during colonoscopy. The bend sensor employs active-cladding optical fibers modified with fluorescent quantum dots, bandpass filters, and a complementary metal-oxide-semiconductor imager as key components. Results from three-fiber sensors demonstrate the bend sensor’s ability to measure curvature (error of 0.01 mm), direction (100% accuracy), and location (predetermined distance) of a bend in the fiber bundle. Comparison with spectroscopy data further confirmed the accuracy of the bending direction measurement for a three-fiber sensor. Future work includes improvements in fiber manufacturing to increase sensor sensitivity and consistency. An expanded 31 fiber bundle would be needed to track the full length of a colonoscope.

Subject terms: fiber optics; bend sensor; fluorosensor; active-cladding; quantum dots; navigation.

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1 Introduction

1.1 Colonoscopy

Colorectal cancer is estimated to be the third leading cause of cancer-related deaths in the United States, with the cost of treatment reaching $8.4 billion annually. Colonoscopy is the current gold standard for colon cancer screening and diagnosis as it can detect cancer at an early stage, before symptoms are evident and when treatments may be more effective. During the procedure, a 180-cm long, 2-cm diameter flexible scope is inserted into the patient’s colon, beginning at the rectum. The scope is pushed along the path of the colon until it reaches the caecum. The endoscope has four degrees of freedom for manipulation: longitudinal (by pushing and pulling the scope), roll (by twisting the scope), and pitch and yaw at the scope’s distal tip (by turning two dials at the scope handle). Navigation through the colon is guided by video images of a fluorescing colon onto a screen, poses health risks. The Olympus ScopeGuide™ (Olympus, Center Valley, Pennsylvania) uses an antenna to detect magnetic fields generated by coils inside the endoscope to display the shape and position of the colonoscope in real-time during an examination. Though the ScopeGuide™ improves the colonoscopy’s performance, hospitals must purchase new, expensive colonoscopy units compatible with the device to experience benefits. Additional electromagnetic trackers, such as the 3D Guidance MedSafe (Ascension Technology Corporation, Burlington, Vermont), are more easily integrated into existing colonoscopies, but are incompatible with colon geometry, lack of haptic feedback, and lack of perceptual information for spatial orientation. Disorientation can lead to several problems during colonoscopy, including missed detection of tumors, incorrect localization, and looping, which occurs in 91% of cases. When loops are formed, an additional length of scope can be fed into the colon without advancing the tip, causing the colon to stretch, and resulting in pain and harm to the patient. In extreme cases, the scope can perforate the colon through the shear force in the loop.

1.2 Endoscopic Shape-Trackers

Cao showed that providing additional spatial information, such as shape, location, and direction of the scope, in real-time, in a visual display reduces localization errors during a colonoscopy. Shape-trackers have been developed for the purpose of reducing disorientation during the colonoscopy, though the available technologies have shortcomings. Fluoroscopy, which uses harmful radiation to transmit a still image of a fluorescing colon onto a screen, poses health risks. The Olympus ScopeGuide™ (Olympus, Center Valley, Pennsylvania) uses a camera to detect magnetic fields generated by coils inside the endoscope to display the shape and position of the colonoscope in real-time during an examination. Though the ScopeGuide™ improves the colonoscopy’s performance, hospitals must purchase new, expensive colonoscopy units compatible with the device to experience benefits. Additional electromagnetic trackers, such as the 3D Guidance MedSafe (Ascension Technology Corporation, Burlington, Vermont), are more easily integrated into existing colonoscopies, but are incompatible with...
ferromagnetic objects such as surgical tables, instruments, and the endoscope itself.\textsuperscript{11,12}

### 1.3 Fiber Optic Bend Sensors

Sensors that employ optical fibers have several advantages over conventional electromechanical sensors including a low number of parts, low costs, simplicity of design, and small sizes and weights.\textsuperscript{13} Fiber optic sensors are electromagnetically-resistant, electrically isolated, and suitable for hazardous environments.\textsuperscript{14} For these reasons, fiber optic sensors are used extensively in medical diagnosis and would be advantageous for a colonoscopy shape-tracking application.\textsuperscript{15}

An optical fiber is comprised of a glass or plastic cylindrical core and a surrounding cladding layer, which has a lower refractive index than the core. The cladding ensures that light striking the core-cladding interface reflects back into the core due to Snell’s Law. Snells’ Law defines the critical angle, $\theta_{\text{crit}}$, in a fiber optic in terms of the refractive index of the initial medium, $n_1$, and the medium that the light crosses into, $n_2$:

$$\theta_{\text{crit}} = \arcsin \left( \frac{n_2}{n_1} \right).$$  \hspace{1cm} (1)

If light strikes the interface between two materials with an angle greater than the critical angle, reflections take place.\textsuperscript{16} If the striking angle is less than the critical angle, which can occur when an optical fiber experiences a bend, refraction of light into the cladding occurs. This phenomenon, known as bend loss, increases with fiber curvature, and therefore bend loss can be used to indicate the degree of fiber curvature. By doping a fiber optic with a fluorescent medium, light lost during bending and coupled into the medium induces fluorescence. The resulting fluorescence can be detected via spectroscopy, charge-coupled devices (CCDs), or complementary metal-oxide semiconductors (CMOS).

Certain fiber optic bend sensors utilize bend loss, while others adopt other approaches. However, the existing fiber optic bend sensor technology has short-comings that limit their application for a colonoscopy shape-tracking application. They lack the ability to detect both bending direction and curvature, or the ability to detect multiple localized bends, or they require expensive detection hardware that limits their widespread use.\textsuperscript{17–20} Specifically, Kuang et al. created a plastic optical fiber sensor capable of measuring curvature through decreases in light intensity.\textsuperscript{17} However, their sensor provides no means of indicating bending direction. Another bend sensor, utilizing long-period grating (LPG) fibers with three different cross sections, was demonstrated by Zhao et al.\textsuperscript{18} The spectral response of the LPG fiber sensor was shown to be orientation- and curvature-dependent, but was limited to detection at a single location along the length of the sensor. Blanchard et al. demonstrated the ability to measure bending curvature and direction using a multicore optical fiber sensor and interferometric detection.\textsuperscript{19} However, measurements are integrated over the full length of the fiber and, therefore, localized bends within the fiber cannot be distinguished. A distributed bend sensor capable of measuring localized bending direction and curvature over the length of the sensor has been demonstrated by Duncan and Raum.\textsuperscript{20} This sensor uses swept-wavelength interferometry (SWI) to interrogate fiber Bragg grating (FBG) sensors to optically measure strain and track fiber shape.\textsuperscript{21} However, the tunable laser light source and interferometer required for SWI can be very expensive, making the FBG-based distributed bend sensor a very costly option.

We have previously described a fiber-based bend-sensor applicable to a colonoscopy shape-tracking application.\textsuperscript{22} This single-fiber bend sensor uses localized active-cladding fluorescence to measure bending direction and curvature at multiple locations along the length of the sensor. The single fiber bend sensor relies on axial excitation of three active cladding zones, spaced 120 deg apart, circumferentially, during bending. Each zone contains a different colored set of quantum dots (QDs). Each set of QDs has a different peak emission wavelength to allow for signal differentiation using a simple spectrometer. During bending, modes propagating within the fiber bend sensor shift to the outer radius, exciting sensorized zones located on the outer portion of the bending radius. Conversely, zones located at the neutral axis or on the inner radius experience less excitation. The resulting fluorescence intensity reflects the proportion of light coupled into each QD zone, indicating bending direction. Curvature is indicated by fluorescence intensity exhibited by the sensorized region. This single-fiber bend sensor uses inexpensive components and detects both bending direction and curvature. With multiple sensorized regions, each with a distinct set of three new QDs, along the length of the fiber, multiple bending locations can be tracked along a single fiber sensor. However, this design depends on the availability of distinct QDs for each additional sensorized region. Currently, the need for distinct QDs limits the number of sensorized regions to two, using six distinct QDs.\textsuperscript{23} As quantum dot technology advances and the number of QDs available increases, the sensor could incorporate additional sensorized regions. To address these limitations in characterizing bending at multiple locations, a new, multifiber bend sensor that uses localized active-cladding fluorescence is proposed.

### 1.4 New Multifiber Sensor Design

The proposed multifiber sensor is capable of detecting bending direction and curvature at multiple bending locations along the length of the sensor. It uses off-the-shelf components including optical fibers, a single-wavelength laser diode, and a monochrome CMOS imaging camera. Its small size allows for easy integration into the biopsy channel of a colonoscope, such that its shape within the channel reflects exactly the shape of the scope. A graphical representation of scope shape conveyed by the bend sensor can be used to augment the standard colonoscopy display as a navigational aid (Fig. 1).

The new bend sensor prototype is comprised of three fibers, each containing a uniquely-located sensorized region comprised of three distinct QD zones (Fig. 2). A 405 nm laser diode couples light into the fiber bundle with a dichroic beam splitter (Fig. 3). When the fiber bundle is bent, light leaks from the fibers’ cores into the QDs positioned on the outer portion of the bend. Light emitted by the QDs couples back into the core and travels toward the bundle’s proximal end, through a beam splitter, and is imaged by a CMOS camera. The color of the fluorescence, which is distinguished using bandpass filters placed between the CMOS camera and the output of the fiber bundle, indicates bending direction. The fluorescence intensity indicates degree of bending as a...
higher curvature bend couples more light into the QD zone, resulting in increased fluorescence. The CMOS camera spatially distinguishes the activated fiber or fibers in the bundle and, because the location of the sensorized region for the fibers is known \emph{a priori}, the bend location is established.

2 Bend Sensor Fabrication and Testing

2.1 Fiber Bundle Bend Sensor

Each of the three fibers within the fiber bundle was prepared following the method described by Gavalis et al.\textsuperscript{22} Optical fibers with a 300-μm diameter silica core, 335-μm diameter hard polymer cladding, and 660-μm diameter buffer (Part JTFLH300330650, Polymicro Technologies, Phoenix, Arizona) were used. A 10 to 50 W VL-300 CO\textsubscript{2} table-top Versalaser (Universal Laser Systems, Inc., Scottsdale, Arizona) was used to laser-cut three zones, spaced 120 deg apart around the circumference of the fiber, into the cladding layer of each fiber. Two different methods of fiber modification were used: slotted modified zones and circular modified zones. To create fibers with slotted zones, a 100 μm × 3000 μm slotted pinhole (Thorlabs, Newton, New Jersey) was used in the laser cutting process to create 100 μm × 500 μm cladding slots. To create fibers with circular zones, a 100 μm pinhole was used to create 100 μm holes.

The three cladding zones were each filled with a solution mixture of QDs (Evident Technologies, Troy, New York) and flexible UV epoxy (Part 141-M, Dymax Corp., Torrington, Connecticut). One slot/hole was filled with a 4:1 solution of 617 nm QD:epoxy, the second slot/hole was filled with a 4:1 solution of 596 nm QD:epoxy, and the third slot/hole was filled with an 8:1 solution of 564 nm QD:epoxy (due to weaker fluorescence of the 564 nm QDs). To deposit the QD solutions, a custom-pulled pipette tip was used to touch off 15 drops of the QD solution onto the slot/holes. A protective layer containing 50% toluene and 50% epoxy was added to cover the top of the slot/holes and cured.

The three single-fiber bend sensors, each containing a uniquely-located sensorized region, were then bundled together using a protective, flexible PVC tubing with a 1/16 in. (1.6 mm) ID and 1/8 in. (3.2 mm) OD (Part 5231K124, McMaster Carr, Princeton, New Jersey). A 750 μm SMA connector (Part 10770A, Thorlabs, Newton, New Jersey) which was glued onto the proximal end of the fiber bundle, coupled the sensor to the excitation hardware.

The sensor bundle was excited using 53 mW 405 nm laser light from a laser diode system (Part 1069413, Coherent Connection, Santa Clara, California), positioned perpendicular to the sensor’s longitudinal axis (Fig. 3). A dichroic mirror/beam splitter with transmission above the 505 nm cutoff wavelength (Part DMLP505, Thorlabs, Newton, New Jersey) was positioned at a 45 deg angle between the laser diode and the sensor to couple laser light into the sensor. At the proximal end, bending-induced QD fluorescence was transmitted through the dichroic mirror and passed through a filter wheel containing bandpass filters. Three bandpass filters with central wavelengths of 560, 600, and 620 nm, and a 10 nm full width half maximum (Thorlabs, Newton, New Jersey), were used to differentiate fluorescence intensity attributable to each of the three QDs. Transmitted fluorescence was imaged by a 1.3 Mp monochrome 1/2 in. CMOS USB camera with an 18 mm working distance and 3.0×-fixed magnification lens (Parts NT62-841 and NT54-680, Edmund Optics, Inc., Barrington, New Jersey).

A custom LABVIEW (National Instruments, Austin, Texas) program was written and used to display the CMOS image in real-time, and to record the average per-pixel fluorescence intensity value for each fiber in the bundle. Average fluorescence intensity values were captured with each of the three bandpass filters in place by rotating the filter wheel. The LABVIEW program also controlled the CMOS settings. A maximum gain of 100, which corresponded to a 13× gain, was used. For sensors made with circular zones, exposure...
times were set to a maximum value of 343 ms, and pixel clock values were 5 MHz for the 560 nm filter and 6 MHz for the 600 and 620 nm filters. For sensors made with slotted zones, the exposure time and pixel clock values were individually adjusted and optimized for each fiber, and ranged from 30 to 250 ms and 10 to 25 MHz, respectively.

2.2 Free-Bending Test
A 0.8-m long sensor, made using one fiber with circular QD zones located 35 cm from the fiber’s proximal end and two unmodified fibers, was bent in four different directions (along the pitch and yaw axes) using cylinders arranged in different configurations (Fig. 4). Three cylinders, with curvatures of 0.01, 0.02, and 0.03 mm$^{-1}$, were used to induce bending in 13 distinct bending positions (4 pitch and yaw directions for each of the 3 curvatures, plus the straight fiber case). A distinct bending position was defined by a unique combination of bending direction and curvature. To perform testing, the sensor was first calibrated using the 13 distinct bends in a LABVIEW program. For each bend, three fluorescence intensity values were stored for the active fiber: one with each of the three bandpass filters in place. After calibration, the sensor was tested using the same 13 bends. Real-time fluorescence intensities were captured and compared with the 13 sets of stored data to identify the bend based on the best match. This was done by summing the absolute values of the comparison errors for each of the three bandpass filters, to generate one error value for each bend. The LABVIEW program then identified the bending direction and curvature associated with the lowest error. A total of 15 test trials were conducted, with each trial corresponding to a different bend (several bend positions were duplicated).

2.3 Rotational Test
A 1.2-m long fiber bundle containing three sensorized fibers with slotted sensorized zones was axially rotated to simulate bending the sensor in all directions. Sensorized regions were located at 70, 80, and 90 cm from the sensor’s proximal end. The sensor was clamped inside two rotational connectors, at each end of the bundle, which provided a controlled, axial rotation. The sensorized region of interest for a given test was positioned on a cylinder with a 0.02 mm$^{-1}$ curvature to induce bend loss fluorescence. Averaged fluorescence intensity data were captured in 20 deg rotational increments until a full revolution of 360 deg of the bundle was completed. For each sensorized region, three full revolutions of the sensor bundle were performed and the results were averaged.

2.4 Spectroscopy Verification
To compare results obtained through color filters and CMOS detection to the spectroscopy method used by Gavalis et al.\textsuperscript{22} a single fiber sensor was tested using a modified rotational testing method. A three-fiber bundle was not used because the spectrometer cannot distinguish signals from three fibers (each with the same set of three QDs). CMOS data and spectroscopy data were simultaneously obtained by moving the filter wheel and CMOS camera to the distal end of the fiber, placing the laser diode directly in line with the fiber at the proximal end, and placing a miniature fiber optic spectrometer (Part USB2000, Ocean Optics, Inc., Dunedin, Florida) perpendicular to the laser diode. A 50/50 beam splitter was placed between the laser diode and the fiber to couple light into the spectrometer (Fig. 5). Spectroscopy data was stored using a LABVIEW program. An initial spectroscopy reading was first captured while the fiber was held straight. Subsequent readings taken during testing were recorded as the difference between each bent reading and the initial, straight reading.

During testing, the single fiber was rotated axially through three full revolutions in 20 deg increments. The increment spacing of 20 deg was experimentally determined to be the maximum spacing that adequately captures the sensing behavior of the fiber as a function of rotational position. At each incremental position, CMOS images were captured with each of the three bandpass filters in place, and a spectroscopy curve was generated. To evaluate the CMOS data, the per-pixel intensity values associated with each filter were summed across the fiber face, generating a representative intensity value for each filter, at each rotational position. Values for a given filter and a given position were averaged, generating three curves: one for each filter as a function of rotational position. To evaluate spectroscopy data, a custom MATLAB code was written and used to extract the maximum intensity value of each plot as a function of rotational position and averaged the data. This generated a curve indicating local fluorescence intensity maxima that was used to verify the CMOS data.

Fig. 4 Sensor bent in a downward pitch direction around a cylinder.

Fig. 5 Bend sensor excitation and detection using both CMOS and spectroscopy. The solid arrows indicate fluorescence excitation toward the CMOS detector and the dashed arrows indicate spectroscopy fluorescence detection.
3 Results and Discussion

3.1 Free-Bending Test Results
In the 15 test trials performed using free-bending, bend direction was correctly identified in 100% of the cases. Bending curvature was correctly identified in 87% of the cases. In the two cases in which curvature was incorrectly identified, one was an overestimation to the smaller bending radius while the other was an underestimation to the larger bending radius. As the bending cylinders had increasing curvatures in increments of 0.01 mm$^{-1}$, the curvature sensitivity can be approximated to be 0.01 mm$^{-1}$. Given the stiffness of the colonoscope and the dynamic nature of the clinical procedure, this small, and relatively infrequent (13%), error in curvature estimation is insignificant in clinical applications. Free-bending tests demonstrated the sensor’s ability to characterize bending direction and curvature in a less controlled, and therefore more realistic, environment than the rotational testing performed.

3.2 Rotational Test Results
Results from the rotational test demonstrate that bending location can be determined. As Fig. 6 shows, the fluorescence from each of the three fibers captured by CMOS was spatially distinct. The distinct fluorescence profile for each fiber indicates the bending behavior at that fiber’s sensorized region. For a three-fiber sensor, bending behavior at three distinct locations is conveyed.

Figure 7 shows the results obtained from the rotational test. Fluorescence intensity values as a function of fiber rotation (simulating sensor bending in all directions) were normalized against the maximum intensity value obtained with a given filter in place. Each curve reflects the fluorescence intensity of a different QD zone as a function of axial bundle rotation. When a particular QD zone was positioned on the outer portion of the curve, the maximum amount of light was coupled into that zone due to bend loss, resulting in maximum fluorescence. A unique data set made up of three intensity values, one representing each QD zone, characterizes each rotational position and, thus, bend direction. A post-hoc multiple comparison test based on Tukey’s honestly significant difference criterion was performed to determine the sensor resolution. When the data set at each rotational position was compared to its neighboring data sets 20 deg away, 8 out of the 18 pairs were significantly different. When the data set at each rotational position was compared to its neighboring data sets 40 deg away, 8 out of the 9 pairs were significantly different. Therefore, the bending direction resolution in this sensor is approximately 40 deg.

3.3 Spectroscopy Verification Results
Figure 8 compares the bending direction for a single fiber characterized by two different methods: fluorescence detection by CMOS, and by spectroscopy. The spectroscopy curve (dotted line) shows the maximum intensity value at
each rotational position, but does not distinguish the different fluorescence wavelengths. The fluorescence wavelengths associated with each peak have been extracted from the individual spectroscopy plots that do distinguish fluorescence wavelength and are added as labels in Fig. 8. This comparison with CMOS results shows good agreement between the two methods. The peak locations of QD fluorescence detected by the CMOS method exactly match the locations detected by spectroscopy. Spectroscopy data have been shown to accurately characterize bending direction.22

Even though the two sets of spectroscopy and CMOS data match perfectly, the three peaks that correspond to their respective QDs do not appear at a spacing of 120 deg apart as expected. Instead, they appear at 70, 215, and 330 deg rotational positions. This is likely due to variations in the manufacturing method. Specifically, the rotational position of the fiber in the cutting fixture during laser cutting and the pattern of QD deposition could have affected the peak locations. The speculation that unequal zone spacing in the tested fiber was due to shortcomings in the manufacturing method was not formally verified. However, in previous batches, manufactured fiber sensors had been produced with visibly unequal zone spacing due to the fiber sticking and slipping in the cutting fixture during rotations between laser cutting passes. While the fiber stick-slip was reduced during the course of this work, it has not yet been eliminated.

4 Limitations and Future Work

The accuracy of the sensor could be improved, as indicated by the 40° resolution of the three-fiber bundle in the rotational test. To improve accuracy, an end cap should be placed at the distal tip of the sensor to remove variations in how much laser light is reflected by the environment and coupled back into the fibers. Variations in reflections back into the sensor can affect fluorescence and cause data to vary from trial to trial. The data analysis method should also be modified to improve accuracy. Instead of looking only at bent-fiber fluorescence values, straight-fiber fluorescence values should be subtracted from bent-fiber fluorescence values. Subtracting straight-fiber fluorescence values will better capture the behavior of the QDs with lower baseline fluorescence values, as in the case with the 564 nm QD. Reducing fiber stick-slip in the rotational laser cutting fixture to ensure equal distribution of QD zones during manufacturing would also improve sensor accuracy.

The sensor robustness could also be improved. Sensors made with 100 μm round zones were less fragile than the slotted-zone fibers, though they exhibited less fluorescence. To reduce the fragility of the slotted-zone sensors, slots could be reduced in length from 500 to 300 μm or 200 μm. Experiments could be conducted to determine how far the slots can be reduced before the fluorescence signal is deemed too weak for adequate sensing. Reducing slot width could also decrease fragility. Changes to the slot size can be achieved through modified laser cutting settings and through a different slotted pinhole (e.g., one with a decreased width and length).

This three-fiber bend sensor prototype is limited to detecting bending at three discrete locations. Future bend sensors will bundle together 31 fibers with a sensorized zone spacing of 6 cm from fiber to fiber, allowing for discrete interval coverage along the length of a 1.8 m colonoscope to track loop formation inside the colon.

5 Conclusions

The need for an inexpensive bend sensor capable of aiding navigation during colonoscopy by detecting bending direction and curvature at multiple locations is presented. A bend sensor prototype capable of meeting these requirements is demonstrated. The bend sensor is comprised of a three-fiber bundle embedded with three 120-deg-circumferentially-spaced QD zones that characterizes bending through bend loss. Bandpass filters and a CMOS camera are used to measure the bending direction through fluorescence color, and bending curvature through fluorescence intensity. The known location of the fluorescing fiber within the three-fiber bundle indicates bending location. Bending direction detection results compared with those obtained using spectroscopy showed perfect agreement. The proposed bend sensor uses inexpensive components and could be easily integrated into a colonoscope to aid navigation and reduce looping. With a set of three distinct QDs, this new bend sensor prototype can track bending at three locations, as opposed to a single location in the previous design, thereby reducing the current limitation in available QDs.

To implement this technology into an effective navigational aid for colonoscopy, bend sensor information can be conveyed through a graphical user interface. A three-dimensional graphics program, such as Open GL (SGI, Fremont, California), can be used to generate real-time images, similar to the image shown in Fig. 1.

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