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A Fiber Bragg Grating-Based All-Fiber Sensing Systems for Telerobotic Cutting Applications

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***Abstract*—A fiber Bragg grating (FBG)-based strain sensing system for minimally invasive telerobotic cutting applications is presented in this paper. Investigations assume that a scissor blade can be approximated as a uniformly tapered cantilever beam. A replica of the scissor blade is produced and strain characterization has been carried out using an FBG sensor system. Results are validated against measurements obtained using conventional electrical resistance strain gauges. The scissor blade experiences both direct and lateral forces during cutting, hence the system is characterized for a direct load range of 0–30 N and a lateral load range of 0–10 N. The results show a very good linear response for direct loading and some sensitivity to lateral loading. An actual sensorized scissor blade prototype is also characterized and results compared with that of the replica blade. The FBG interrogation system used was a macro-bend fiber filter-based ratiometric system. The use of FBGs together with macro-bend fiber-based interrogation system eliminates the influence of temperature on the sensing system and hence temperature independent strain information from the blade is obtained. The results obtained using the macro-bend fiber filter are compared with that of a commercial interrogation system and found to be in agreement. By implementing an all fiber sensing system based on fiber Bragg gratings and macrobend fiber filter interrogation system, remote operation of telerobotic cutting applications can be made more cost effective while providing a competitive accuracy and resolution solution.**

***Index Terms*—Fiber Bragg grating (FBG), macrobend fiber filter, telerobotic cutting.**

I. Introduction

FIBER BRAGG GRATING (FBG) sensors have generated much interest in the area of strain and temperature sensing and are being used in many applications such as structural monitoring and smart structures [1]–[3]. However, their use as force feedback sensors in telerobotic cutting applications on minimally invasive robotic surgical systems (MIRS) is still in a state of development. The lack of sensorized surgical instrument end effectors restricts the MIRS systems ability to detect interaction, cutting and grasping during surgical tasks [4]. Resistive strain gauges attached to the tips of surgical graspers have been widely used in MIRS systems to provide for the measurement of the forces during grasping operations [5]–[7]. Sterilization of the arrangement as well as appropriate protection and shielding of the sensors are two of the primary issues associated with the use of resistive strain gauges on these instruments. The influence of magnetic field on electrical sensors prevents their use in many surgical applications. Hence, a need exists for sensorizing instruments used in robotic surgery with optical fiber sensors, which are largely unaffected by the difficulties associated with electrical strain sensing schemes.

Further issues with present robotic manipulators, particularly miniaturized versions used in minimally invasive surgery, include the requirement to transmit actuation forces and sensor information some distance through the structure of the robotic device. The large mass and size of presently available actuators and sensors restricts their direct attachment at locations where the force is being generated in many applications [8]. Therefore, employing instruments where the sensor forms an integral part of the end-effector are desirable to enable accurate measurement of complex interaction and cutting forces. To address these requirements, blades equipped with fiber-based sensors for force feedback could offer an alternative sensing scheme compared to established sensing modes. Some initial work in this direction has been reported by several researchers [9]–[12]. Surgical needles with FBGs attached to detect the deflection is just one such example [11]. Moreover, advancement in the analysis of strain transfer from the host material to an FBG sensor can assist in the development of other potential applications of fiber sensors in robotics [13]–[15].

For any telerobotic strain/force sensing system based on a FBG, the resolution of the system depends on the FBG interrogation system. Most commercial FBG interrogation systems can provide a wavelength resolution of approximately 5–10 $\mu\varepsilon$. But the cost of such systems is very high. In terms of the *in vivo* forces experienced during cutting, insertion, probing, grasping, etc., in actual robotic surgery, there is limited information available, particularly for surgical cutting. Part of the reason behind research is to produce a sensing scheme that will facilitate the collection of this type of force data. Greenish *et al.* [16] have carried out cutting experiments using scissors with blades of similar geometry that is presented in this paper. They cut muscle, skin, liver, and tendon and measured forces up to 30 N (for tendon). Other sensing schemes employing grippers [17] for application in robotic surgery have observed a force range of 20 N.

Recent improvements in the fabrication of FBGs have reduced their cost, so that the interrogation unit, rather than the sensor, accounts for a large proportion of the cost of a complete sensing system. The FBG interrogation used in this experiment

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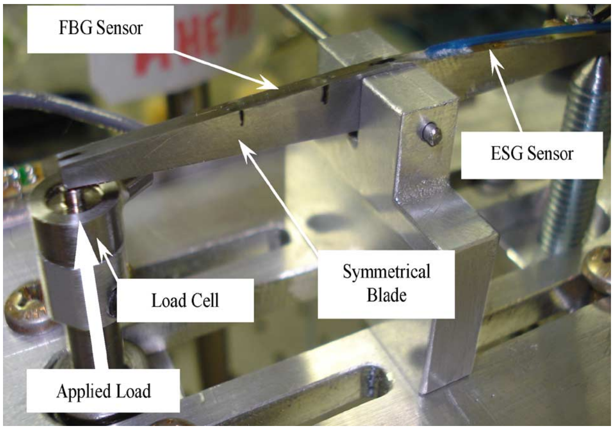


Fig. 1. Simplified blade with surface mounted FBG sensor and strain gauge.

is an economic macro-bend fiber filter-based ratiometric system [18], [19]. The macro-bend fiber filter interrogation system provides a wavelength measurement range within 1500–1600 nm. Two FBGs together with macrobend fiber filters are used for both strain measurement and temperature compensation. A representative replica scissor blade is presented allowing initial characterization of the proposed low cost sensorized instrument. An actual prototype sensorized surgical scissor blade is also characterized and results are also presented. In Section II, the experimental characterization setup of the blade, sensor placement, strain transfer and FBG interrogation system are discussed. Results from the experiments are presented in Section III. Characterization of a prototype scissor blade is presented in Section IV. From the experimental analysis, it is found that an FBG sensor together with the macrobend fiber interrogation system can be used effectively for telerobotic cutting applications and provides competitive strain accuracy and resolution at a lower cost without the influence of temperature from the FBG sensor and the interrogation system. From the characterization results, forces on scissor blades with an FBG sensor mounted directly on its structure can be measured during cutting. This demonstrates the potential of this methodology as a low cost sensing solution in the area of smart sensing surgical instruments.

II. Experimental Arrangement for Strain Characterization

An experimental testing platform has been developed for the initial investigation and characterization of the strain distribution along a stainless steel scissor blade. The test rig consists of a simplified blade arrangement which is representative of one blade of a stainless steel scissor end effector. The blade is symmetrical about its pivot point allowing for the simultaneous evaluation of an FBG and electrical strain gauge sensors under the same conditions. The blade protrudes 39 mm in length either side of the pivot. The test rig and the blade are shown in Fig. 1. Two FBG sensors are attached to the blade, one on the top of the blade for direct strain measurement and the other, used for temperature compensation, is point-attached to the lateral side of the blade. An electrical strain gauge (ESG) is attached at the equivalent position on the symmetrical side of the blade to facilitate comparison with the results obtained from the FBG. Loads were applied using a micrometer translation stage with a load cell attached to the end of the micrometer, as shown in Fig. 1(b). The data from the load cell is collected using a National Instruments load cell module SG-24, which is connected to a data acquisition board NI6221. The data from the strain gauges is obtained using a strain gauge module SG-03. The whole system is controlled using LabView 8.0.

A. Placement of the FBG Sensor

Assuming that the scissor blade can be approximated as a uniformly tapered cantilever beam the point of maximum strain as well as the strain distribution over the bonded region of the fiber is established using the following expression [20]:

$$\varepsilon_z = \frac{6F(L-z)}{Eb(mz+W)^2} \tag{1}$$

where L is the distance from the pivot to the point of application of the load F, z is the distance from the pivot which the strain is to be known $(0 < z > L)$, W is the thickness of the blade at its pivot, b is the width of the blade, E is the Young's modulus of the blade material (185 $\mathrm{GN/m^2}$), and m is the uniform slope of the blade.

The position on the blade where maximum strain occurs can be found by taking

$$\frac{d\varepsilon_z}{dz} = 0 \tag{2}$$

$$\text{i.e.,}\ \frac{d\varepsilon_z}{dz} = \frac{6F(2Lm - mz + W)}{Eb(mz+W)^3} = 0 \tag{3}$$

$$\text{therefore;}\ z_{\max} = 2L + \frac{W}{m}. \tag{4}$$

From (4), for the blade structure, the maximum strain was found to occur at a location 14 mm from the blade pivot point [15]. For an FBG it is important that the strain distribution across the FBG is uniform to avoid distortion of the reflected spectrum. It was estimated that the strain variation across the 5 mm long FBG used here, centered on the 14 mm point, is only 0.003%. Such a small strain field variation will have negligible adverse effect on the reflected FBG signal.

B. Bonding Length and Strain Transfer

The strain transfer from the host material (stainless steel) to the FBG is influenced by the properties of the host material surface, adhesive layer thickness and the protective coating on the FBG, such as polyimide. The adhesive used in our experiment was a two-part fiber-optic epoxy (T120-023-C2) with a Young's modulus of 3 GPa. The FBGs used in the experiment were supplied by Smart Fibres. The length of the FBG used was 5 mm, written in the middle of an 11 mm long buffer stripped portion of a standard singlemode fiber. This region was recoated with polyimide to a thickness of 4–4.5 μm. A simplified schematic of the FBG bonding structure with dimensions is shown in Fig. 2. A view of the embedded fiber, thickness of the fiber with polyimide coating and difference between the stripped and unstripped portion of the fiber are shown in Fig. 3(a) and (b), respectively. Since standard singlemode fiber with a buffer is 250 μm in diameter, the adhesive thickness between the metal

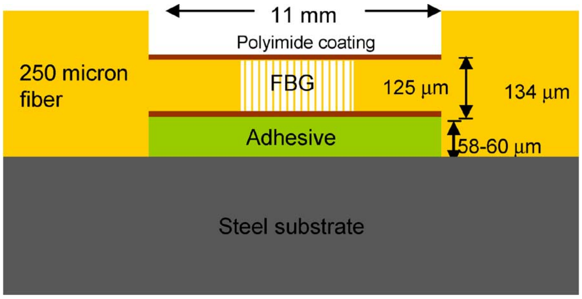


Fig. 2. Simplified schematic of the FBG bonding structure to the blade.

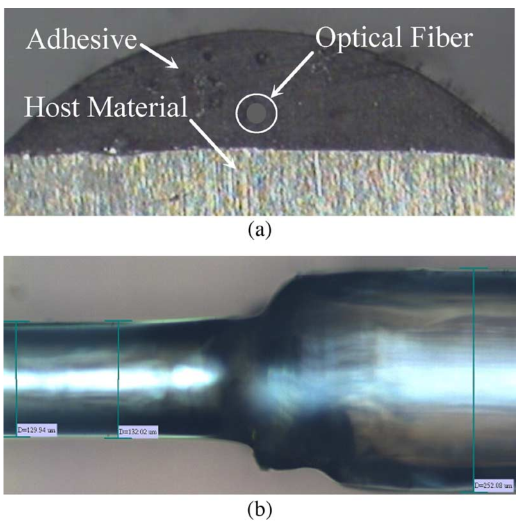


Fig. 3. (a) Cross section view of the embedded fiber and (b) photograph showing the thickness difference between the stripped region and unstripped region (the region to which epoxy is applied).

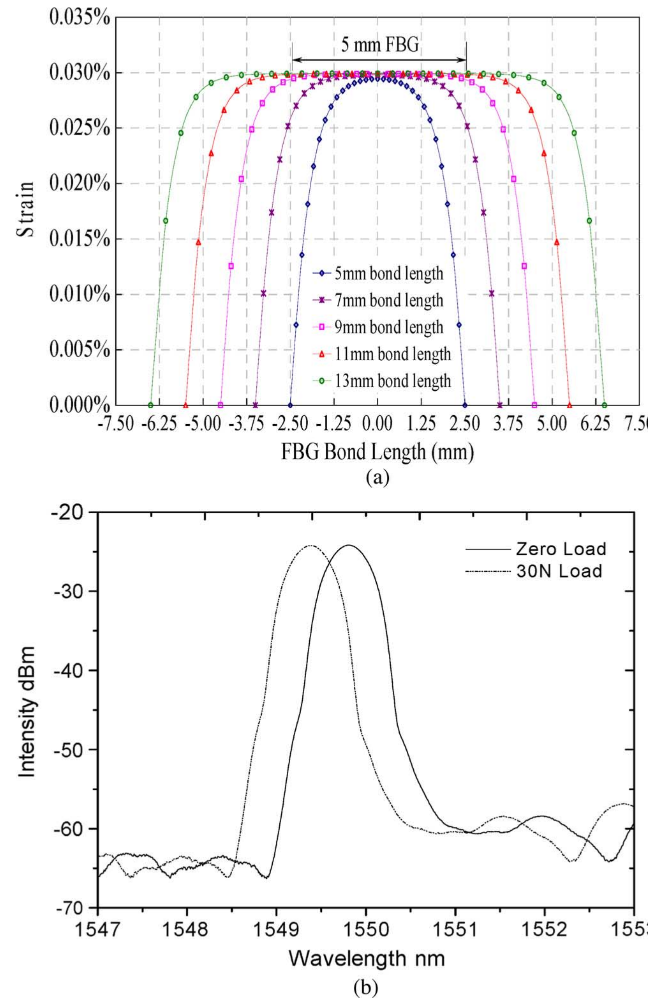


Fig. 4. (a) Strain distribution along the FBG for different bonding lengths. (b) Spectrum of the FBG sensor attached to the blade at 0 N load and 30 N load.

and the FBG fiber will be approximately 58–60μm. It is also important to estimate the bonding length to ensure that the distribution of the strain over the FBG is uniform. In our analysis, we have found that where the adhesive thickness between the metal and the FBG is 60 μm and a polyimide layer thickness of 4.5 μm, a minimum bond length of 11 mm ensures uniform strain distribution along the 5 mm length of the FBG [15]. The strain measured by an FBG sensor is taken to be the average strain over the bonded portion of the fiber. The average strain transfer coefficient is defined as the ratio of the average strain over the bonded fiber to that of the host material. The effectiveness of the strain transfer from the blade to the fiber core is influenced by the extent of shear concentrations through the adhesive layer thickness upon loading. Moreover, the stiffness of the adhesive layer also greatly influences the strain transfer effectiveness with a stiffer adhesive inducing great strain transfer to the fiber core. Fig. 4(a) shows simulation results of the strain distribution over the FBG sensor for different bonding lengths and it is clear from the figure that an 11-mm bonding length ensures a uniform strain distribution over the 5 mm long FBG sensor.

To check the uniformity of the strain distribution, the spectra of the FBG sensor was measured using an optical spectrum analyzer for zero load (0 N) and maximum load (30 N). The measured spectra for zero load and maximum applied load have the same bandwidth with only a peak shift due to the induced strain being observed [Fig. 4(b)]. Since there are no distortions to the measured spectra, this confirms that uniform strain is being induced over the grating length and hence that the bond length of 11 mm in use is correct.

C. FBG Interrogation System

The experimental arrangement for the interrogation system used to interrogate the FBG sensors is shown in Fig. 5. Two FBG sensors are used in the system, one attached to the top of the blade to measure the direct strain and the other for temperature compensation (only one end is fixed to the lateral side of the blade). The FBG sensors used have a peak wavelength of 1550 nm. The temperature and strain sensitivity of the FBG sensors were 1.2 $\mathrm{pm}/\mu\varepsilon$ and 10 $\mathrm{pm}/^{\circ}\mathrm{C}$, respectively, at 1550 nm. The interrogation system used is-based on a macrobend fiber filter-based ratiometric system, previously described in [19]. A broadband source is used as the input source. A 2×2 fiber coupler is used to split the signals between the two the FBGs. The reflected signals from the FBGs are directed to the fiber edge filter ratiometric system by using fiber circulators, as shown in Fig. 5.

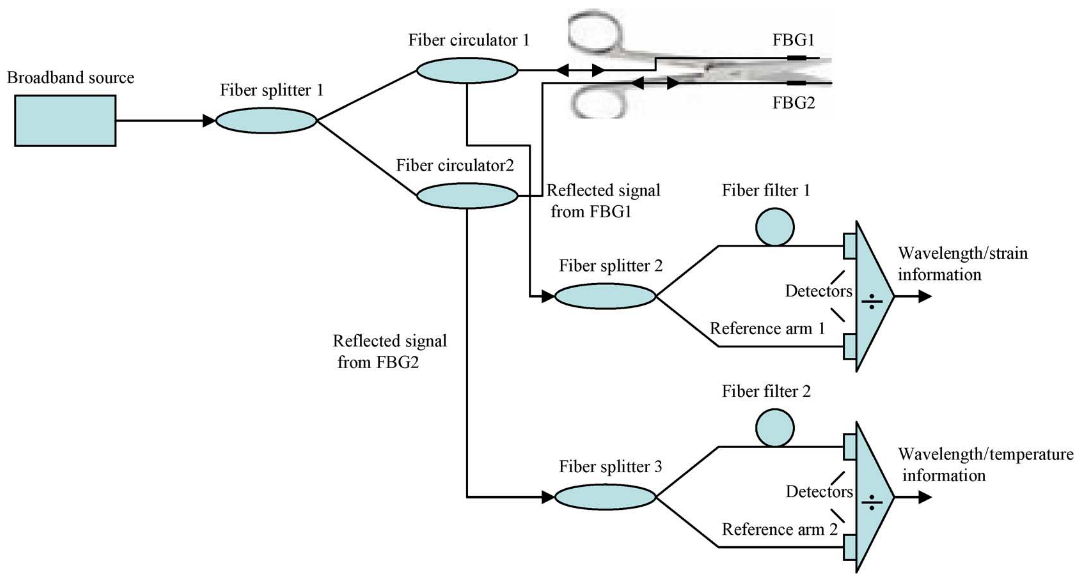
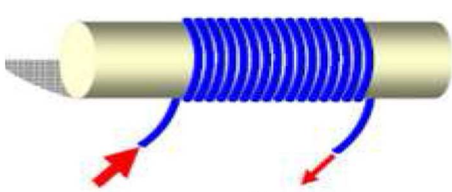
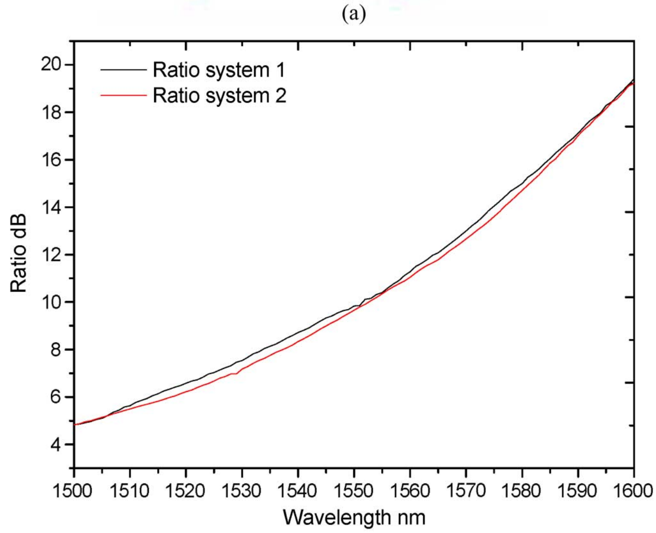


Fig. 5. Schematic of the FBG interrogation system using macrobend fiber filter ratiometric systems.



(a)



(b)

Fig. 6. (a) Schematic of a macrobend fiber filter. (b) Responses of the two fiber filter ratiometric systems.

In order to use a macrobend fiber edge filter ratiometric system to interrogate FBGs, both the fiber edge filter system needs to be calibrated in the wavelength range of interest which in this case is from 1500 to 1600 nm since the FBGs peak reflected wavelength was 1550 nm. The schematic of a macrobend fiber filter and the measured ratio responses of both the fiber filters ratiometric system are shown in Fig. 6(a) and Fig. 6(b), respectively. The ratio responses of both the ratiometric fiber edge filter system are obtained by scanning the wavelength from 1500–1600 using a tunable laser at a wavelength interval of 1 nm. Both fiber edge filters used have the same slope, that is 0.15 dB/nm. As the FBGs are sensitive to strain and temperature, the difference between the two ratios in the above configuration can provide temperature-independent strain information. This is attained because the slope of the edge filters are set to the same and hence the wavelength change and power ratio due to change in FBG temperature (for both FBG1 and FBG2) will be the same for both the edge filter system and the difference between the ratios yields strain information from FBG1 without the influence of temperature. The filters used 10 turns of standard single-mode fiber (SMF28) with a 10.5 mm bend radius to obtain this slope value. The wavelength measurement resolution of the system was 20 pm, which gives a strain resolution of approximately 16 $\mu\varepsilon$. The wavelength resolution of the system can be varied by changing the slope of the fiber edge filter, by changing the bend radius or the number of fiber bend turns.

The resolution and accuracy of any ratiometric system are limited by signal-to-noise ratio of the optical source and also the noise in the receiver system [21]. In the present case, for both edge filters, the peak-to-peak ratio fluctuation was approximately 0.005 dBm, which limits the wavelength accuracy to ± 15 pm. The strain inaccuracy due to this will be in the range of ± 12.5 $\mu\varepsilon$. It is also known that the macrobend fibers are slightly temperature sensitive and the temperature dependence of the fiber filter can lead to a measured strain error [22]. The variation in the output ratio of the system due to ambient temperature is oscillatory in nature and hence the temperature compensation calibration is a complex task [23]. However, in this configuration, since we are using two identical fiber edge filters the system has an advantage that the influence of ambient temperature on the fiber filters will be cancelled out. The proposed macrobend fiber filter interrogation system can therefore effectively measure strain with competitive accuracy and independent of the influence of ambient temperature on both the FBG sensors and also on the interrogation system.

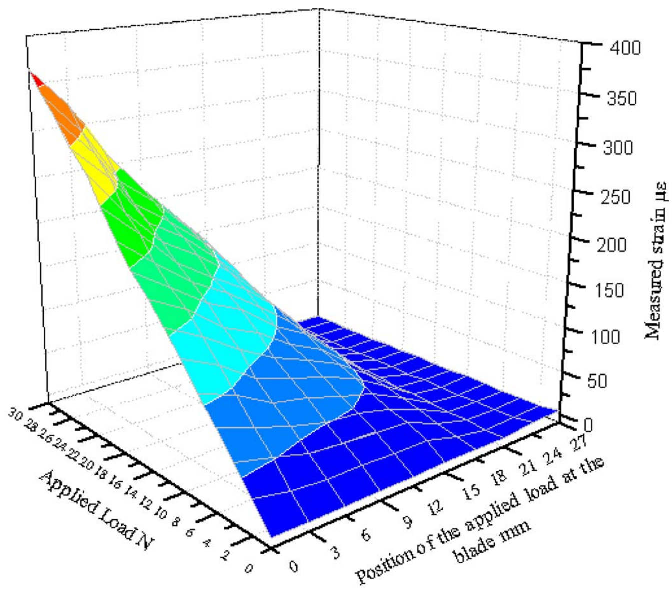


Fig. 7. Direct strain measured along the blade for different load conditions.

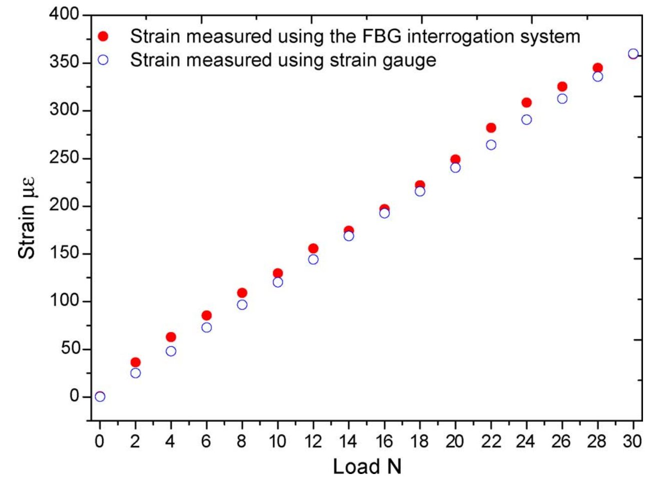


Fig. 8. Comparison of the strain measured using FBG sensor and strain gauge at the tip of the blade.

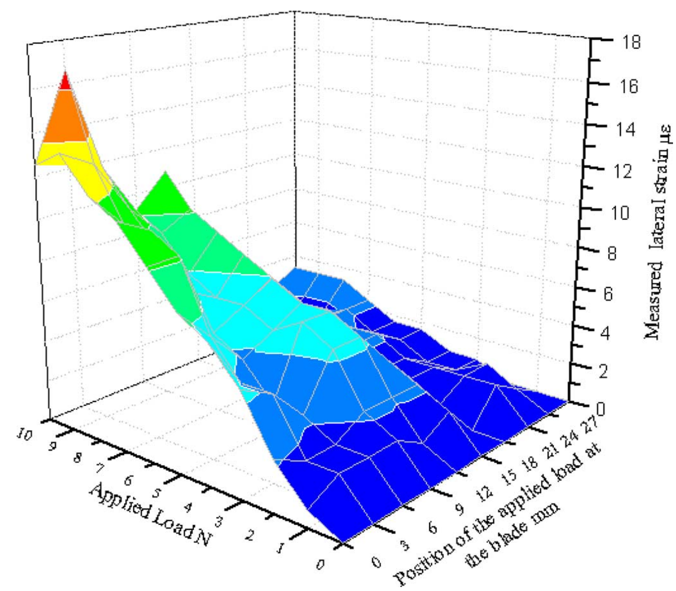


Fig. 9. Impact of lateral load on the direct strain measurements.

III. Results and Discussion

Using the experimental setup described above, direct strain on the blade is measured with a load applied at multiple points along the blade from its tip towards the pivot at 3 mm intervals. The FBG was placed at a position of 14 mm from the pivot and the length of the blade was 39 mm. The measured direct strains for different loads applied at different blade positions are shown in Fig. 7. It can be observed that the maximum strain is registered by the FBGs when the load is applied to the tip of the blade and the strain response is linear with respect to the applied load. However, during a typical cutting cycle the forces on the blades vary along its length over a typical working envelope between 10° and 23°. This is equivalent to a linear range of between 0 and 26 mm from the blade tip. In the experiment, we have obtained data at increments along the length of the blade from the tip (0 mm) up to 27 mm which covers the entire working envelope of a scissor blade. In practical cutting applications, the load position can be obtained if the blade opening angle is known and hence the corresponding strain can be measured assuming the system is calibrated.

Strain measured using the FBG and the macrobend fiber filter interrogation system is referenced against that of a standard electrical strain gauge, allowing the sensitivities of both measuring techniques to be directly compared under the same loading conditions. This is achieved by attaching both the FBG and the strain gauge at exactly the same location on opposing arms of the symmetrical blade as indicated in Fig. 1(b). Both sets of results are compared in Fig. 8. During the coarse of the experiment the ambient temperature around the FBG is varied to $\pm 5\,^{\circ}$C. However, it can be seen that both the strain gauge results and the strain measured from the macrobend fiber interrogation system agree. The FBG measured strain, for a corresponding load, is unaffected by temperature variations indicating effective compensation is being achieved with the compensation techniques described. This confirms that the proposed fiber-optic solution is accurate and independent of the influence of temperature change on the system.

In practice, during a typical cutting cycle, scissor blades experience laterally applied loading due to the curved nature of the blade. To examine the influence of these effects, lateral loads are applied to the blade along its length, with the FBG at the same longitudinal position, 14 mm from the pivot. A load in the range of 0–10 N is applied to multiple points along the lateral side of the blade from the tip towards the pivotal region at 3 mm intervals. The strain resulting from the lateral load registered by the FBG attached to the top side of the blade is shown in the Fig. 9. The nonlinearity in the measured strain is due to the limited accuracy of the interrogation system used in measuring low value strain in the region of 10 $\mu\varepsilon$. Although the FBG sensor is less sensitive to the lateral load, it is clear that the lateral loading of the blade impacts the direct strain output from the FBG sensor. A lateral load of 10 N applied to the tip of the blade introduces a maximum of 16 $\mu\varepsilon$ error in the measured direct strain and the value of error decreases when the applied load

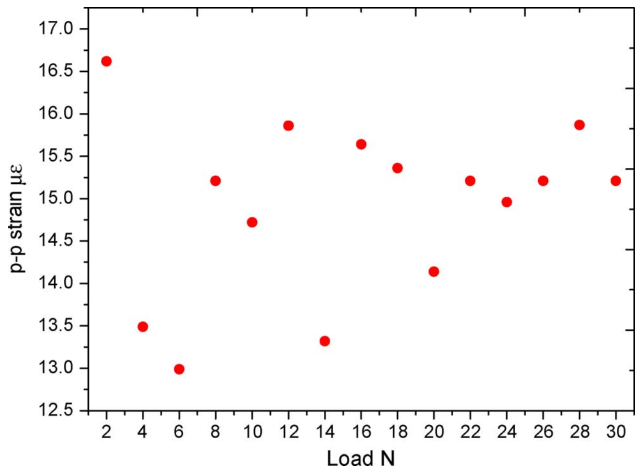


Fig. 10. Peak-to-peak strain fluctuation for a range of applied loads at the tip of the blade due to the noise in the receivers of the interrogation system.

shifts towards the pivotal region. Thus, the accuracy of the direct strain measurement is limited due to the inadvertent lateral loading, arising from the deflection of the blade during cutting. However, this can be minimized by characterizing the blade for a dry cut (without any tissue) and using the results a calibration correction factor can be made to eliminate the impact of the lateral force.

An additional factor that introduces inaccuracy to the measured strain values is the inherent noise in the receiver system as explained in Section II-C. To estimate the inaccuracy in strain measurements due to the receiver noise, the peak-to-peak strain fluctuation is measured for a range of applied loads and is shown in Fig. 10. From the figure it can be seen than the peak-to-peak strain fluctuations are in a range circa 15 $\mu\varepsilon$. Thus, it can be concluded that the smallest strain variation that can be effectively resolved using the proposed sensor interrogation configuration is above 15 $\mu\varepsilon$. This strain value corresponds to a load of 1.1 N (when applied to the tip). However, the influence of receiver noise can be minimized by low noise design of the receiver system and the strain resolution can be improved if higher resolution is required.

IV. Characterization of a Prototype Scissor Blade

After gaining an understanding of the basic requirements that need to be satisfied in order to use a FBG-based sensing system for a scissor blade, experimental studies were conducted on an actual scissor blade. The positions of the FBG sensors are similar to those of the simplified blade and the load is also applied in a similar manner. The experimental arrangement which facilitates the application of a range of loads to the scissor blade is shown in the Fig. 11. In this case, the measured strain from the FBGs using the macrobend fiber filter interrogation system is additionally compared with that measured by a commercial FBG interrogation system to evaluate the accuracy and stability of the macrobend fiber interrogation system. The commercial interrogation system used was the Smart Fibers Wx-02. The comparison between the measured strain values using the two systems is shown Fig. 12. From the results, it can be seen that the macrobend fiber interrogation system is well equipped for use

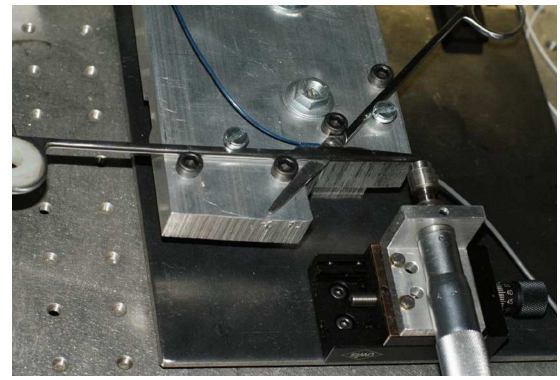


Fig. 11. Experimental arrangement for application of a load to a scissor blade.

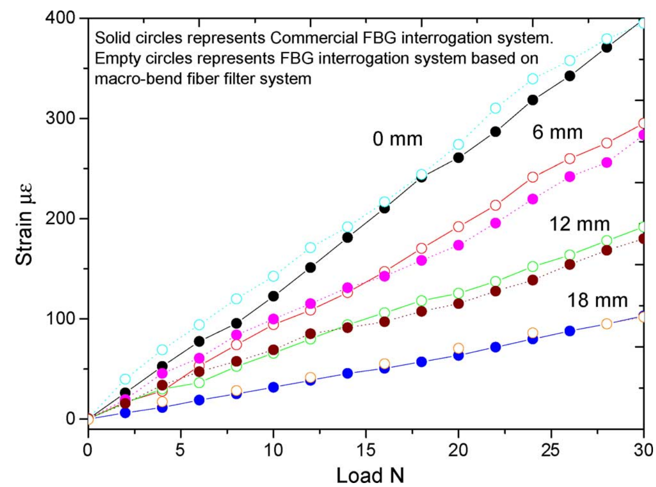


Fig. 12. Comparison of measured strain along the scissor blade at different locations and with different applied loads using a macrobend fiber filter interrogation system and a commercial FBG interrogation system.

in applications such as telerobotic cutting procedures. It should be noted that the strain values measured for the scissor blade for the same applied load are slightly different from that of the simplified blade. This is due to the fact that, in the case of the simplified blade, we have considered a uniform thickness for the blade, but for the standard surgical scissor blade, the thickness is not uniform. The strain measured using both the interrogation systems agrees very well and this confirms that, to obtain the force information from surgical blades, the FBG-based sensing system together with a macrobend fiber filter-based interrogation system can be used effectively. Empirical formulae for the force information can be obtained from the results of the characterization. Thus, for telerobotic cutting applications, the remote operation of the blade can be made possible by using the force measurements and in this paper we have successfully demonstrated and also presented the characterization results of scissor blades for telerobotic cutting applications. Further research on embedding the FBGs inside the blade and force feedback from the scissors for real tissue cuts are underway.

V. Conclusion

In this paper, we have presented the characterization results of an FBG sensing system together with a low-cost macrobend fiber filter interrogation system for telerobotic cutting applications. The interrogation system was fabricated using a macrobend fiber filter in a ratiometric scheme and temperature compensation for strain measurements was achieved. The strain characterization of the scissor blade using a simplified blade model and a test rig were carried out. The FBG sensor position for maximum strain transfer was determined and the FBG is attached to the blade without strain gradient effects. Direct and lateral strain characterization of the blade was carried out and the accuracy of the direct strain measurements was determined. A prototype of an actual scissor blade incorporating an optical fiber sensor was also tested. Using the obtained direct strain versus applied load characterization results, empirical formulae for force information can be obtained. In summary, we have experimentally demonstrated the use of FBG strain sensors, interrogated using a low cost macrobend fiber filter-based interrogation system, for force measurement in surgical cutting applications.

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