The Optical FBG Contact Force Measurement System for the Haptic Feedback of Minimal Invasive Surgery Robot

Ho-seok Song, Jung-wook Suh, Young-ik Yoo, and Jung-ju Lee*

*Mechanical Engineering Department, KAIST, Guseong-dong, Yuseong-gu, Daejeon, Republic of Korea
(Tel : 82-42-350-3033; Fax : 82-42-350-3210)
(leejungju@kaist.ac.kr)

Abstract: Haptic feedback plays a very important role in medical surgery, but it is difficult to provide haptic information in MIS (minimally invasive surgery) or MIRS (minimally invasive robotic surgery). Recently, many sensors are being developed for MIS or MIRS, but they have some obstacles such as size limit and sterilizability in their application to real situations of medical surgery. Optical fiber sensors are one of the most suitable sensors for this environment. Especially, optical fiber Bragg grating (FBG) sensor is not influenced by intensity of light source. In this paper, we would like to present the initial results of study on the application of the FBG sensor to measure reflected forces in MIRS environments and then suggest the possibility of successful application to the MIRS systems.

Keywords: MIS (minimally invasive surgery), FBG (fiber Bragg grating), Laparoscopy

I. INTRODUCTION

Minimally invasive surgery (MIS) is a broad term to describe all kinds of surgery to minimize injury to the patient. MIS including laparoscopic surgery lessens pain, the need for post-surgical pain medication, scarring, and the likelihood of incisional complications. But there is a constraint of the degree of freedom (DoF) because bar of tools are inserted through ports of incision points. The surgical tools lose 2 DoF because of these ports of incision points and the surgeon can no longer approach tissue from an arbitrary angle. As a result, the surgeon feel more tired than when performing open surgery. In addition, haptic feelings are also impaired because of the long and thin bar of surgical tools. Recently, MIRS (minimally invasive robotic surgery), such as Da Vinci^{TM} has been introduced to solve motion constraint problems in MIS. MIRS uses a telemanipulation system that consists of a master console and a slave manipulator. As a consequence, dexterity of tool and tissue manipulation has been considerably augmented.

However, it is still difficult to provide haptic information in MIS or MIS. Tactile information allows discrimination of the different consistencies of tissue. The surgeon can feel the hardness or tension of tissues, measure the variation of their properties, and evaluate anatomical structures. Also, force-feedback information allows determination of the force applied to the tissue of the patient without damaging the tissue. But up-to-date commercialized MIRS systems are still missing haptic information.

In the previous research, there has been some effort to measure and reproduce haptic information using electric devices [1], [2], [3]. However, electric systems need many connection wires and packaging to shield against electromagnetic interference (EMI). A sterilization method is also should be considered. Peirs et al [4]. have developed a micro force sensor using three optical fibers to measure 3-axis forces for above reasons. However, this system is negatively influenced by fluctuation of the light source.

We decided to use optical fiber Bragg grating (FBG) sensors to solve these problems. Because optical FBG sensor can be used as a kind of wavelength filter, this FBG sensor is not affected by intensity of light but by wavelength of reflected light. Thus, in this paper we suggest an optical FBG system for the safe MIRS. Using 4-bendable beams aligned with the longitudinal axis of the shaft, this system can be used to directly measure the 3-axial forces applied on the surgical tool-tip. These 4-beams are placed at 4-quarters of the external circumference of the shaft, i.e. two couples of two beams facing each other are placed at 180degrees. The fiber Bragg grating (FBG) is used to measure the strains exerted on the 4-beams. This optical FBG sensor system would be effective for the surgeon to perform surgery much faster and more safely.

II. MECHANICAL DESIGN OF THE MANIPULATOR

In this research, the human arm-like manipulator for the MIS that we have developed is used [5]. Some researchers have reported that the development of either mechanical or electromechanical teleoperators, which enable surgeons to move a MIS system in a manner analogous to an open instrument, could potentially reduce the time of current laparoscopic procedures by at least 15%.

Our MIRS system has 7 DoF by adding an elbow-like joint in order to mimic the motion of a human arm; however, one of its rotational motions in the shoulder has been replaced with a translational motion. The proximal part corresponding to a human's shoulder adopts a double parallelogram that has a remote center to avoid the constraint of the ports of incision point. The surgical tool inserted into the abdomen has an elbow joint and roll-pitch-yaw joints to change the orientation of the tooltip. The surgical tool can be attached to the proximal portion of the surgical manipulator in order to exchange various kinds of tools. A cable-pulley mechanism is used to mechanize the surgical tool; the tension control device is designed for holding the tension of the wire.

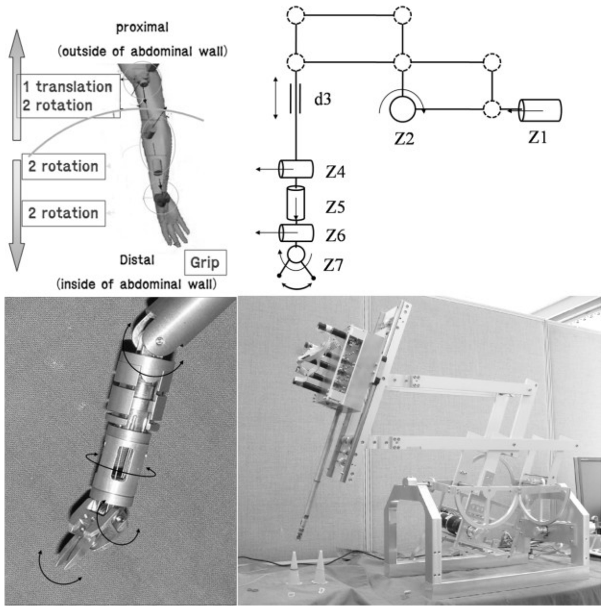

Fig.1. configuration of the manipulator

III. DESIGN OF OPTICAL FBG SENSOR AND MEASURING METHOD

1. Design of Flexure

There are two kinds of forces that are applicable in the surgical situation; 1) the force applied on the tool-tip, 2) The force applied inside forceps i.e. grip force. We have designed a loadcell with FBG sensors to measure the former type of the force. The loadcell can measure 1-axial force and 2-moments. In order for the sensor to measure the 3-axial forces on the tool-tip, the following assumptions are employed.

1) Wires driving wrist joint don't slip and elongate.
2) Sensor is affected by only F_{zs}, M_{xs} and M_{ys}
3) 3 moments were not applied on the tool-tip
4) 3 axial forces always act on the midpoint between the ends of the forceps.

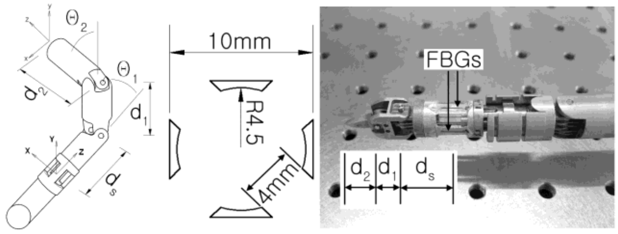

Fig.2. Sensor kinematics, cross section of sensor and developed sensor

F_{zs} is the force of z-axis applied on the sensor, and M_{xs} and M_{ys} are 2 moments of x,y-axes applied on the sensor. F_x, F_y, and F_z are the forces applied on the tooltip. If the wrist joint rotates θ_1 about x-axis and θ_2 about y-axis, then the forces and moments matrix applied on the middle of the sensor can be obtained. (Fig 2)

Because the organs inside abdominal wall act like passive devices, Moments applied on the tooltip are negligible. Then we could calculate the relation between the forces applied on the tooltip and the forces and the moments induced at the sensor by it.

$$\begin{bmatrix} F_Z \\ M_X \\ M_Y \end{bmatrix} = \begin{bmatrix} -C_1S_2 & -S_1 & C_1C_2 \\ S_1S_2d_s & -C_1d_s - d_1 - d_2C_2 & -S_1C_2d_s \\ C_1C_2d_1 + C_1d_2 + C_2d_s & S_1S_2d_2 & C_1S_2d_1 + S_2d_s \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} \quad (1)$$

d_1, d_2, and d_s are already known variables as shown in Fig.2. And θ_1 and θ_2 can be calculated by encoder signal. Hence, we can derive F_x, F_y, and F_z from F_{zs}, M_{xs}, and M_{ys} by using linear algebra. Using shift of central wavelengths of the reflected signal by optical FBGs, we can obtain ε_{33} (strain to the z-axis) of the four beams constituting the sensor: ε_1, ε_2, ε_3 and ε_4. We can derive F_{zs}, M_{xs}, and M_{ys} from ε_4, ε_2, ε_3 and ε_4 using Euler's beam theory. The axial force is able to be measured by means of simultaneous compressions or extensions of 4-beams. The moments of the loadcell are also measured by means of compressions and extensions of 4-beams. In this case, when one beam is applied by compression, another beam standing opposite is applied by extension. Therefore, we can calculate the force applied on the center of the loadcell reversely by using these relationships.

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \end{bmatrix} = \frac{1}{E} \begin{bmatrix} 1/A & C/I & 0 \\ 1/A & -C/I & 0 \\ 1/A & 0 & C/I \\ 1/A & 0 & -C/I \end{bmatrix} \begin{bmatrix} F_{zs} \\ M_{xs} \\ M_{ys} \end{bmatrix} \qquad (2)$$

E, A, C, I are Young's modulus, the area of sensor's cross section, the largest distance from the neutral surface, and moment of inertia respectively.

2. Measuring Method

In this research, there are 6 FBGs to measure the strains. Among them, 2 FBGs located outside the abdominal wall are used to compensate for temperature or characteristics of fiber Fabry-Perot (FFP) filter. The other 4 FBGs are used to measure the force on the tooltip. Light from a broadband source is input into a 1x4 coupler via a circulator, and the light reflected by the FBGs is directed via a circulator to a tunable FFP filter, which is swept in wavelength by a control voltage used to adjust the mirror spacing. The magnitude of the spectral light is measured by photo diode (PD). In order to increase stability, a low pass filter is used during data acquisition process and a Gaussian line-fitting algorithm is applied for peak detection [6]. The measured peak location shifts are compensated with two reference FBGs and translated into strains. Finally, forces are calculated by using the strains and the above equations.

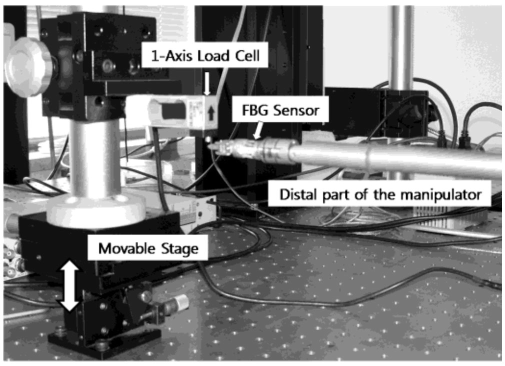

Fig.3. Experimental Setup

IV. FORCE MEASURING TEST FOR SYSTEM VERIFICATION

In order to determine the amount of force precisely, the force on the manipulator was given by a load cell. As shown in Fig.3, the manipulator is fixed on the table and the load cell is mounted on a vertical stage to apply force on the manipulator in a particular direction (x or y). If the force is applied from the x(or y)-direction, there will theoretically be only the force of the x(or y)-axis. However, some cross-talk was induced for several reasons. To measure the cross-talk, constant force in a particular direction is applied and the measured force from FBG sensor is recorded in real time. After a certain period of time, the value converged to a certain value and the proportion of the values was found. Using this value, we were able to construct a calibration matrix.

$$\text{Calibration Matrix} = \begin{bmatrix} -3.083 & -0.666 \\ 0.333 & 5.333 \end{bmatrix}$$

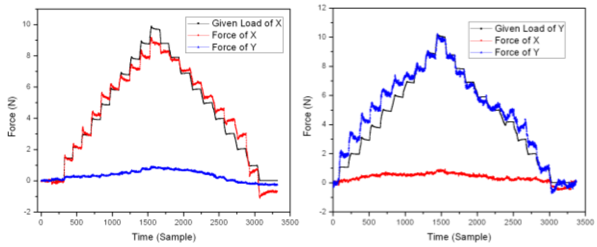

Fig.4. Real time observation of x and y-axis force

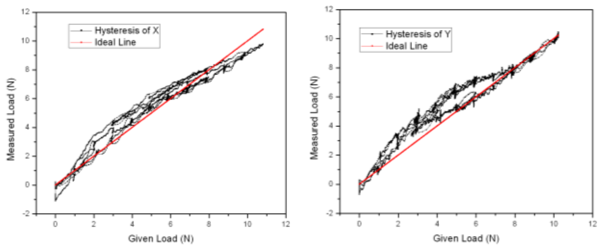

Fig.5. Hysteresis curve of x and y-axis force

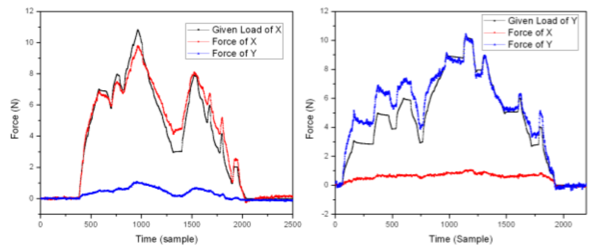

Fig.6. Random history measure of x and y-axis force

For the performance test, the forces are exerted from zero to nearly 10N and removed gradually. Each force was maintained for about twenty seconds and then we went on the next step. Measured forces are shown in Fig.4. Cross-talk was significantly reduced but still a small portion is remained. Fig.5 shows the relationship between the given forces and the measured forces. Hysteresis occurred on both the x and the y-axis. In the case of x-axis, measured load followed ideal line until 7N. Over 7N, stiff increment of estimated load was occurred. In the case of y-axis, there is no stiff increment of load, but estimated load strayed from the ideal line a little earlier. It is considered to be occurred by complicate structure of manipulator. Compliances induced by joints, driving wires and miss-align of joints make error. Additionally, frictions on the movable joints seem to make a hysteresis. Fig.6 shows real-time measurement histories of randomly applied load. Even though these measured reflect forces are not highly accurate, however we can recognize a collision or have the amount of force applied on the tool-tip approximately. Thus this force measuring system can help a surgeon operate safe surgery within a safe zone of applied force.

Originally, the optical FBG sensor system was designed for measuring 3-axis forces. However, at this time, the force of the Z-axis was excluded for lack of consistency induced by drift effect of the FFP filter system. In continuous work, we are looking for a method that is not influenced by the characteristics of the FFP filter system. At that time, the force of the Z-axis will be added.

V. CONCLUSION

We developed an optical FBG force sensor system for the application to minimally invasive surgery (MIS). The FBG sensor has many advantages compared with traditional electrical or optical sensors. It is sterilizable in an autoclave, flexible, and immune to water and EMI. It has simple wire connections compared to an electronic sensor, has a small diameter, and isn't influenced by light intensity. Therefore, the FBG sensor is one of the most suitable sensors for minimally invasive surgery. The test results show that the force sensor can be operated until over 10N but we need some more continuous effort to obtain high accuracy of measured forces. However, the most important fact is to warn the surgeon not to exceed the safe zone of applied forces rather than absolute accuracy of measured forces. Therefore this system which is equipped with optical FBG sensor is very useful and effective to warn of the breakage of a suturing thread or an unexpected collision. Hysteresis and unexpected cross-talk can be reduced with advanced system of ongoing work in near future.

Additionally, In order to verify usefulness of FBG sensor system, the test of tele-operation using haptic device like a Phantom will also be performed.

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REFERENCES

[1] Ulrich Seibold, Bernhard Kuebler, and Gerd Hirzingger (2005), Prototype of Instrument for Minimally Invasive Surgery with 6-Axis Force Sensing Capability, ICRA 2005, 498-503.

[2] P. Valdastri, K. Harada, A. Menciassi, L. Beccai, C. Stefanini, M. Fujie, and P. Dario (2006), Integration of a Miniaturised Triaxial Force Sensor in a Minimally Invasive Surgical Tool, IEEE Transactions on Biomedical Engineering, 53(11).

[3] Mamoru Mitsuishi, Naohiko Sugita, and Phongsaen Pitakwatchara (2007), Force-Feedback Augmentation Modes in the Laparoscopic Minimally Invasive Telesurgical System, IEEE/ASME Transactions on Mechatronics, 12(4).

[4] J. Peirs, J. Clijnen, D. Reynaerts, H. V. Brussel, P. Herijgers, B. Corteville, ans S. Boone (2004), A micro optical force sensor for force feedback during minimally invasive robotic surgery, Sensor Actuat A-Phys, 115, 447-55.

[5] Ho-seok Song, Ki-young Kim and Jung-ju Lee (2006), Development of a 5 DoF dexterous manipulator executable inside abdomen for Minimally Invasive Surgery, Assistive Robotics and Mechatronics, 7(4).

[6] H. W. Lee and Minho Song (2005), FBG interrogation with a scanning Fabry-Perot filter and Gaussian line-fitting algorithm, IEEE LEOS Annual Meeting, Sydney, Australia, Oct.