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Development of a Telemanipulator for Laparoscopic Surgery

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Abstract: This paper describes the design of a dexterous surgical manipulator that performs like a human arm for minimally invasive surgery using a laparoscope. To mimic a human arm, our manipulator has 2 additional joint like an elbow in comparison with the most widely commercialized existing one. It would enable surgeon to move a MIS system in a manner analogous to an open instrument, and the time of current laparoscopic procedures could potentially be reduced. And we validate workspace of surgical manipulators and a laparoscope outside abdomen not to have a collision during the surgery. Furthermore, to measure force applied on the surgical tool-tip quantitatively, we have developed the surgical manipulator attached fiber optic sensor. Accordingly, we expect that the suggested design will provide improved dexterity for MIS to surgeons.

Keywords: MIS, laparoscopic surgery, FBG sensor

I. INTRODUCTION

MIS, which stands for Minimally Invasive Surgery, is a broad term to describe all kinds of surgery to minimize injury to the patient. Laparoscopic surgery is a typical model of MIS. In this procedure, a slender imaging probe is typically introduced via a puncture incision. The surgical site is viewed through a videoscope and a monitor screen displays the resultant image. CO_2 gas is pumped into the abdomen to secure a workspace and a visual field. Tools are fed through additional puncture incisions using trocars. Endoscopic surgery related to abdomen is called laparoscopic surgery, whereas thoracoscopic surgery is about chest or spine.

Traditional open surgery, often requires a lengthy hospital stay and weeks of recovery. With MIS, these periods can be much shorter, because there are only a few small incisions requiring one or two stitch instead of a large incision through the skin and muscles. Other benefits of MIS are less pain, less need for post-surgical pain medication, less scarring, and better cosmetic results. For such reasons, MIS gained widespread acceptance in the late 1980s.

However, the introduction of the endoscope and accompanying tools has brought with it increased technical complexity for the surgeon. Thus, procedures that were simple as open procedures become difficult as endoscopic procedures while procedures that were complex as open procedures are unapproachable as endoscopic procedures. Therefore, endoscopic surgery has been applied to relatively simple operations.

Human arm has 7 DOF, where 3 for the shoulder, 2 for the elbow and the wrist each. In the open surgical situation, 7 DOF motion is transformed to 6 DOF motion in various ways. However, in the endoscopic surgery, surgical treatment is performed with only 4 DOF, because the pivot point restricts 2 DOF. Consequently, the surgeon can only reach points within a restricted volume and cannot fully control the orientation of the tool.

Lack of haptic information also matters in the endoscopic surgery. Haptic information describes both cutaneous (tactile) and kinesthetic (force) information. Tactile information allows discrimination of the different consistency of the tissue, whereas force-feedback information allows determination of the force that is being applied to the tissue of the patient without damaging the tissue. Appropriate applied forces are critical in creating knots that are firm enough to hold but do not break sutures or damage tissue. In endoscopic surgery, attenuation of haptic information is unavoidable, because of long and stiff surgical tools. This phenomenon gives rise to extended completion time and unexpected errors.

In order to overcome the aforementioned difficulties, robotic endoscopic systems have been proposed in the 1990s. This concept requires the surgeon to control the manipulation system by using a master console remote from the patient. The surgeon moves two master devices which resemble surgical instruments at the console, and each motion is translated to robotic arms, which scale down the movements at the end of the instruments inside the patient's body. The robotic slave arm follows all commands of the master arm in a natural way, comparable to manipulation in open surgery.

Many researchers have developed computer aided endoscopic surgical systems. The major advantage of those systems is the introduction of extra DOF at the end of the instruments, allowing surgeons to manipulate the tool in a manner similar to that of open surgery. In addition, the unnatural, detrimental response of the instruments is corrected by computational works. Tremors and trocar resistance are eradicated by the man-machine interface. Digital processing allows the scaling down of the surgeon's hand movements to a level where micro-vascular procedures are feasible. Ergonomic and reduced fatigue features are significant advantages [1].

II. DESIGN CONCEPT

Up-to-date robotic MIS systems have 6 DOF; 4 at the entry portal and 2 at the end of tool except the grip. These are akin to a human arm having only a wrist and shoulder but no elbow. Some researchers have reported that the development of teleoperators, which enable surgeons to move a MIS system in a manner analogous to an open instrument, could potentially reduce the time of MIS by at least 15%. Furthermore, surgeons would be able to perform procedures currently considered too difficult to perform [2]. Thus, a robotic system that can mimic all motions of a human arm by adding additional DOF may have more powerful usages.

Another key consideration is that the entry portal, the trocar, which acts as a fulcrum, has detrimental effects on the dexterity and the repeatability of manipulating the surgical tool. The main reason is that the fulcrum is not firmly fixed. Most movements of conventional endoscopic surgical tools are through the trocar. Thus, we add 2 more rotational joints at the surgical tool such that the added joints can function as a human elbow in the abdomen. Therefore the space where the surgical tool can move independently to the trocar is enlarged and the dexterity and repeatability of manipulation are enhanced [Fig.1].

Other important considerations are force-sensing and force-feedback. Da Vinci® system includes a force-feedback module that measures the force applied on the forceps. However, in this system, the force applied on the tool-tip is not considered and, furthermore, force applied on the forceps is measured indirectly. Mitsuishi's research group has developed a minimally invasive surgical system that can measure the force applied on the joints of the manipulator with a link-mechanism [3]. In the present work, 4 bendable beams aligned with the longitudinal axis of the shaft are used to directly measure the 3-axial forces applied on the tip of the manipulator.

III. WORKSPACE SIMULAION OF ROBOTIC SURGICAL TOOL

The surgical manipulator mounted on the ceiling gives surgeons good accessibility to the patient. However, the surgical manipulator can be collided by another manipulator or a laparoscope because the space on the abdomen of the patient is small and the distance between incision points is short like 7-15 cm. To prevent this, the workspace of these instruments should not be overlapped during their working, or collision detection algorithm is needed. In our research, we performed a simulation to prove that there is no collision between surgical manipulators and a laparoscope because their workspace is not overlapped outside abdomen.

We simulated cholecystectomy because laparoscopic surgery is mostly used in cholecystectomy and cholecystectomy is performed frequently. The surgery make three or four incision points, but only three incision points are mostly used nowadays in cholecystectomy . We have some criteria to simulate.

Ⅰ. A laparoscope is inserted into the umbilicus and mounted on the left or right to the patient.

Ⅱ. Robotic surgical tools and a laparoscope have passive joints to translate to the x-y-z axis and rotate to the z-axis. And the workspace of the laparoscope is ±40°to the left and right [4].

Ⅲ. The position of the gallbladder is varied according to the changing of abdominal size and the umbilicus position. The medium distance between the umbilicus and the right subcostal margin is 15-20 cm and we suppose gallbladder is positioned in subcostal area[5].

Fig.1. Two degrees-of-freedom elbow motion

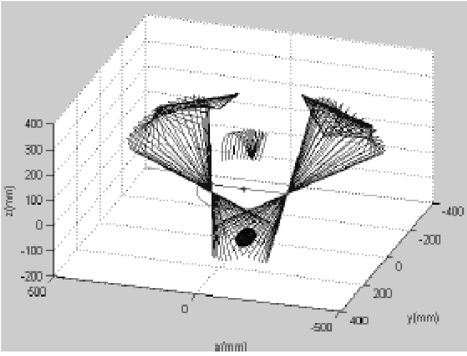

Fig.2. Workspace of surgical manipulators and a laparoscope

Ⅳ. The range of surgical tool's incision points is in the semicircle on which the umbilicus is centered, radius of 15 cm, as medium size of abdomen [5].

Ⅴ. The robotic surgical tools are reached enough to the gallbladder and it is not swerved in the range of incision point.

We found the solution to satisfy all criteria. [Fig.2] indicates the workspace of one robotic surgical tool and a laparoscope. Their workspace is not multiplied. The workspace of the laparoscope developed by Kwon [4] can be reduced because of cooperation of the 3DOF tool inserted into abdomen and the 2DOF tool outside abdomen. Thus we changed workspace of a laparoscope to ±20° and simulated how many robotic surgical tools can be inserted without collision. In case that the size of abdominal cavity is smaller than 15cm-radius semicircle, three surgical tools and one laparoscope are difficult to set up. And we found available number of robotic surgical tools without collision according to varying the size of the abdominal cavity.

IV. FORCE SENSING

Aforementioned lack of haptic information is very important matters of the laparoscopic surgery. Especially in robotic MIS, it is even worse. Without haptic information, surgeon could perform surgery only through the image on a screen, then a dangerous situation might be caused. According to previous researchers, force is required within ±10N during surgical tasks. They said that ±3N of force is particularly important. Therefore, it is necessary to measure the force applied on the tool [6].

What we exactly want to measure is the 3-axial forces applying on the tool-tip. We have performed a FEM simulation with a sensor shaped figure that 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.

Ⅰ. 3-moments are not applied on the tool-tip.

Ⅱ. 3-axial forces always act on the middle of tips of forceps.

Ⅲ. The wires driving wrist joint and forceps don't slip and elongate.

Ⅳ. Sensor is affected by only F_{zs}, M_{xs} and M_{ys}.

If the wrist joint rotates θ_1 about axis X, and θ_2 about axis Y, then the forces and moments matrix applying on the middle of the sensor is obtained.

$$\begin{bmatrix} F_{zs} \\ M_{xs} \\ M_{ys} \end{bmatrix} = \begin{bmatrix} -C_1S_2 & -S_1 & C_1C_2 \\ S_1S_2d_s & -C_1d_s - d_1 - d_2C_2 & -S_1C_2d_s \\ C_1C_2d_1 + C_1d_2 + C_2d_s & S_1S_2d_2 & C_1S_2d_1 + S_2d_s \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}$$

θ_1, θ_2, d_1, d_2 and d_s are variables already we know. So, we can derive F_x, F_y, and F_z, the forces applying on forceps, from F_{zs}, M_{xs}, and M_{ys} by using linear algebra. F_{zs}, M_{xs}, and M_{ys} can be derived from ε_1, ε_2, ε_3, and ε_4 by using Euler's beam theory and least-square method.

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

The resultant data was not exact, but a consistent tendency still provides the possibility to use. It shows that we can expect a dangerous moment. However, electrical strain gages have a lot of limitations to use in a surgical situation. In order to sterilize, sensors have to be protected from water or the other liquids. Moreover, 4 strain gages needs 12 electric lines, it's so bulky.

These problems can be overcome by the use of fiber bragg grating (FBG) sensor. It's not affected by electro-magnetic field and fluidic environment. As the input and the output light are transmitted in one optical fiber, this FBG sensor system requires only simple wiring. Moreover, using the WDM method, many signals can be detected by one optical fiber that has a number of FBGs with different Bragg wavelengths.

The basic principle of an FBG-based sensor system lies in the monitoring of the wavelength shift of the returned Bragg-signal (Bragg wavelength), as a function of the measurand (e.g. strain, temperature, and force).

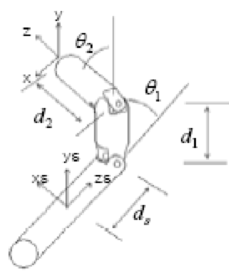

Fig.3. Kinematic diagram for sensing

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The Bragg wavelength is related to the refractive index of the material and the grating pitch. Sensor systems involving such gratings typically work by injecting light from a spectrally broadband source into the fiber, with the result that the grating reflects a narrow spectral component at the Bragg wavelength, or in transmission this component is missing from the observed spectrum. [Fig.4] illustrates this process [7].

The intensity of the reflected optical signal is a function of the Bragg grating wavelength. Therefore, the dynamic strain can be derived from the intensity change measurement as a function of the wavelength of the reflected optical signal. The operation of an FBG is based on a periodic, refractive index change that is produced in the core of an optical fiber. This grating structure results in the reflection of the light at a specific narrow band wavelength, called the Bragg wavelength. The Bragg condition is given by $\lambda_B = 2n_e\Lambda$ where λ_B is the Bragg wavelength of the FBG, n_e is the effective index of the fiber core, and Λ is the grating period. The change of the strain or the temperature shift the Bragg wavelength shift. If there is no temperature change, the mechanical strain can be measured by

$$\Delta\varepsilon = \frac{1}{(1-p_e)}\frac{\Delta\lambda_B}{\lambda_B}$$

where p_e is the strain-optical coefficient of the optical fiber, and $p_e = 0.227$ was measured experimentally and used for this study. Therefore, the change of strain can be measured as measuring the change of wavelength. [Fig.5] shows the measuring system.

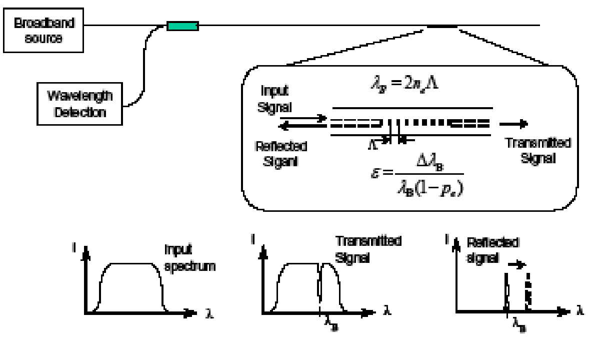

Fig.4. The principle of FBG sensor

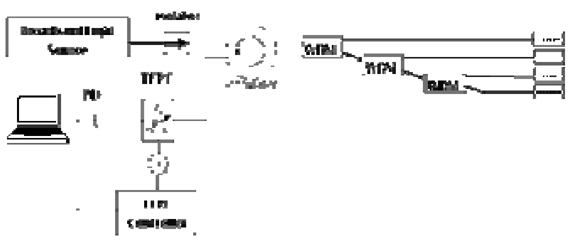

Fig.5. configuration of sensor system

As using this system, the boundary of a safety zone can be set. The safety zone may contribute to more safe surgical environment.

V. CONCLUSION

This paper presents the design of a dexterous surgical manipulator for minimal invasive surgery using a laparoscope and the methods to simulate the workspace of robotic surgical tools without collision and to measure the 3 axial forces applied on the tool tip. As a result, we calculated available number of robotic surgical tools without collision according to the size of abdomen. And FBG sensors are expected to be used widely to get haptic information in the MIS

The improved manipulability and force-feedback mechanism may contribute to the performance and the popularization of the minimally invasive surgery.

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