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Human arm-like Surgical Robot System with Force Reflection Measurement for Minimally Invasive Surgery

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Abstract -*The concept design of the suggested robotic surgical system is to measure the position and orientation of the surgeon's arm and to develop the surgical manipulator same 7 degree of freedom as the human arm. The kinematic configuration of the surgeon's arm is obtained by using the hand tool and the elbow supporter. Then the surgical manipulator tracks the movement of the surgeon's arm similarly by using the measured data in real time. The inverse kinematic solution of an additional degree of freedom is derived by using the angle data of the surgeon's elbow joint. And the force measurement system using a fiber bragg grating sensor was developed. The method to measure the 3 axial force applied on the surgical tool was described.*

Keywords: *surgical robot, minimally invasive surgery, robotic surgical system*

1 Introduction

Laparoscopic surgery are less pain, less need for post-surgical pain medication, less scarring and less likelihood for incisional complications [1]. But there is a constraint of degree of freedom (DoF) because tools are inserted through incision points. The surgical tools lose 2 DoF because of this incision points and surgeons have more fatigue and feel more tired than performing open surgery due to the lack of the dexterity.

To solve these problems, the robotic surgical systems are appeared. Zeus and da Vinci system appeared in the late 1990s and da Vinci system is widely used for general surgical applications nowadays [2]. Zeus system has a 4 DoF robot arm but da Vinci system has a 6 DoF robot arm. Surgeons using da Vinci system perform minimally invasive surgical techniques quicker and more efficiently than traditional minimally invasive techniques [3].

Mitsuishi in Japan developed 6DoF surgical systems and link-driven surgical tools. The force applied to the tooltip can be measured by using strain gauge and the force-feedback modes in each surgical task are developed. [4] In this work, we suggest a human arm-like robotic surgical system for laparoscopic surgery. The developed surgical manipulator can mimic the motion of a human arm. If the surgical manipulator to perform surgical tasks moves like the motion of the human arm, the surgeon can predict the motion of the surgical manipulator more easily and intuitively. And we can expect the less time and more agility for performing surgical tasks.

2 Design Concept

The concept design of a suggested system is to make the surgical manipulator perform surgical tasks as if the human arm does. The surgical manipulator has two parts because the surgical tool must be exchanged during laparoscopic surgery. One is the robot base which has 3 DoF and the other is the surgical tool, 4 DoF. The proximal 3 DoF corresponds to the shoulder joint of human arm, 3 DoF. And the distal 4 DoF is correspondent to the elbow joint and the wrist joint of a human arm. This means that the surgical manipulator has additional DoF like human arm. Then if the tooltip of the surgical manipulator is fixed, the manipulator has various configurations. However, if the surgical manipulator has a similar configuration like a human arm, we need position of a human arm in real time. To do this, master system can measure the position of the wrist and elbow of a surgeon. If we assume that the position of the surgeon's shoulder is almost fixed during surgery, we know the configuration of the surgeon's arm by the master system in real time.

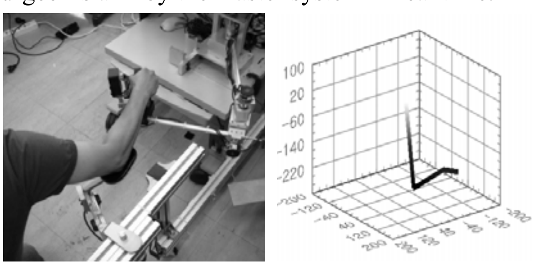

Fig.1.The master system and the obtained kinematic configuration of the human arm

A. Design of the master system

Master system has a display panel to show the view of the laparoscope and a console which is consisted of a hand tool and an elbow supporter. The hand tool has 6 DoF and it can measure the position and orientation of the surgeon's wrist joint. The elbow supporter has 2 DoF and it supports the weight of the surgeon's arm. And also it can measure the position of the surgeon's elbow joint. (Fig.1)

The hand tool can measure the position of the surgeon's wrist joint by using proximal 3 DoF joints and also the orientation of the surgeon's wrist joint by using the distal 3 DoF joints. If we assume that the position of the surgeon's shoulder is nearly fixed during surgery, we set the virtual position of shoulder joint fixed in Cartesian space. Then we can calculate the kinematic configuration of the surgeon's arm. In other words, by measuring the position of the wrist joint and the elbow joint with reference to the shoulder joint, we can construct the kinematic configuration of the surgeon's arm. The kinematic modeling of the surgeon's arm is like Fig.1.

The surgical manipulator in the slave system can follow the configuration of the surgeon's arm in real time. The tooltip of the surgical manipulator is corresponded to the position of the hand and the kinematic base of the manipulator is corresponded to the position of the surgeon's shoulder joint. Although we assume the position of the surgeon's shoulder joint as a virtual reference point, the position of the hand is measured accurately by the hand tool so we can realize the accurate tracking of the surgical manipulator.

B. Design of the slave system

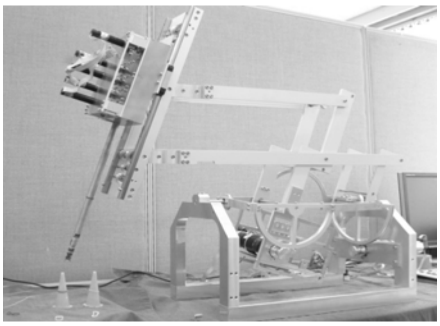

Fig.2 The developed surgical manipulator

The slave system has a laparoscope and a surgical manipulator. The suggested surgical manipulator has 7 DoF that has an additional DoF like a human arm. (Fig.2) The proximal portion adopts double parallelogram which has a remote center so it can avoid the constraint of the incision point. The proximal portion of the surgical manipulator has 2 revolute joints and 1 translational joint, whereas the human's shoulder joint has 3 revolute joints. This is because the translational joint can make the surgical tool move into or out of the abdomen more conveniently and easily than revolute joint does. The surgical tool inserted into abdomen has an elbow joint and roll-pitch-yaw joints to change the orientation of the tooltip. And the surgical tool can be attached to the proximal portion of the surgical manipulator in order to exchange various kinds of tools. Cable-pulley mechanism is used to mechanize the surgical tool and the tension control device is designed for holding the tension of the wire.

3 The Kinematics of the System

A. Kinematics of the master system

The forward kinematics of the hand tool and the elbow supporter is obtained by Denavit-Hartenberg (D-H) parameters. The D-H parameter of the hand tool and the elbow supporter is described in Table.1, 2

The handle and grip are attached to the distal end of the hand tool and the position and orientation of the handle are matched to those of the surgeon's wrist joint. Then we can calculate the kinematic configuration of the surgeon's arm using the measured data. The lengths of the upper and lower arm are simply obtained as described below.

$$L_{upper\ arm} = \sqrt{(x_e - x_o)^2 + (y_e - y_o)^2 + (z_e - z_o)^2}$$

$$L_{lower\ arm} = \sqrt{(x_w - x_e)^2 + (y_w - y_e)^2 + (z_w - z_e)^2}$$

Table1. D-H parameter of 6 DoF hand tool

i	α (i-1)	a(i-1)	d(i)	θ(i)
1	0	0	0	θ1
2	0	L1	0	θ2
3	0	0	-L2	0
4	270	0	0	θ3
5	90	L3	0	θ4
6	90	0	L4	0
7	0	0	0	90
8	180	L5	0	-90+θ5
9	0	L6	0	-45
10	90	L7	0	90
11	270	L8	0	90+θ6

Table2. D-H parameter of 2 DoF elbow supporter

i	α (i-1)	a(i-1)	d(i)	θ(i)
1	0	0	0	θ1
2	0	L9	0	θ2

Where (x_o, y_o, z_o) is the position of the shoulder joint, $(x_e,$

y_e, z_e) is the position of the elbow joint and (x_w, y_w, z_w) is the position of the wrist joint. The angles of the shoulder joints of the surgeon's arm can be obtained algebraically by using the transformation matrix of the human arm.

$$ {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T\ {}^{3}P_{elbow} = {}^{0}P_{elbow} $$

$$ \theta_1 = Atan2(y_e, z_e) $$

$$ \theta_2 = Atan2(x_e, \pm\sqrt{y_e^2 + z_e^2}) $$

The θ_3, which is the rotation angle along the shaft of the upper arm, is not considered. This is because there is no revolute joint of θ_3 in the surgical manipulator. The revolute joint is replaced to a translational joint in the surgical manipulator. And the angle of the elbow joint is also obtained algebraically.

$$ \theta_{elbow} = \cos^{-1}\left[\frac{(x_e, y_e, z_e)\cdot\{(x_e - x_e), (x_e - x_e), (x_e - x_e)\}}{|L_{upper\ arm}||L_{lower\ arm}|}\right] $$

The rolls, pitch, yaw of the wrist joint are corresponded to the 3 DoF joints of the distal hand tool. The roll angle of the wrist joint is obtained by 6DoF hand tool.

$$ \theta_{roll} = \theta_6 $$

The pitch and yaw angle at wrist joint are calculated approximately. Each O, A, B points are elbow, wrist, hand position. Lines OEF, OCD are projections of OAB. Then we find approximate yaw and pitch angle. (Fig.3)

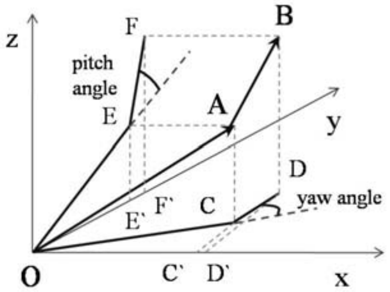

Fig.3 Vector notation of human arm

So we can obtain the kinematic configuration of the surgeon's arm described Fig.1 by measuring the position of the wrist joint and elbow joint using the hand tool and the elbow supporter.

4 Force measurement system


Fig.7 Sensing Element

One of the major limitations of the robotic surgery is the lack of the haptic information. Especially, appropriate applied forces are critical in creating knots firm enough to hold, but do not break sutures or damage tissue. In the robotic surgery, attenuation of the haptic information is unavoidable, because it is helpful for the surgeon to know the information about the forces between the tool and the tissue or the thread to be knotted. Therefore, it is necessary to measure the force applied on the tool.

The 3-axial forces applying on the tooltip can be measured by the sensing element shown Fig.7. For measuring the 3-axial forces, the several assumptions are suggested below.

Ⅰ. 3 moments do not apply on the tooltip of the robot arm

Ⅱ. 3 axial forces always act on the middle of the tooltip.

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

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

The wrist joint rotates θ_1 about axis X, and θ_2 about axis Y and then the forces and moments matrix applying on the middle of the sensor is obtained as described Fig.8. The matrix can be simplified because the sensor is affected by only F_{zs}, M_{xs} and M_{ys}.

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

θ_1, θ_2, d_1, d_2 and d_s are variables already we know. So, the F_x, F_y and F_z is derived by using linear algebra. The strain of four beams constituting the sensor is obtained by the strain gages, but electrical strain gages have a lot of limitations to use in the operating room. In order to sterilize, sensor has to be protected from water or the other liquids. Moreover, because of the space limitation induced by the narrow tool, number of electrical lines has to be minimized. These problems can be overcome by the use of the fiber bragg grating (FBG) sensor.

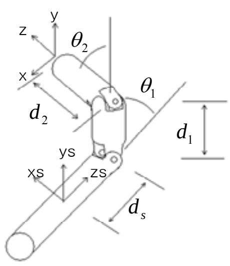

Fig. 8 Kinematic diagram for sensing

FBG sensors aren't 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. So the FBG sensor system can be utilized more effectively.

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)

The intensity of the reflected optical signal is a function of the Bragg grating wavelength, which is related to the applied strain on the FBG. 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 the Bragg wavelength of the FBG, n_e is the effective index of the fiber core, and Λ is the grating period. If there is no temperature change, the mechanical strain detecting the wavelength shift can be measured by

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

Therefore, the change of the strain can be calculated by measuring the change of wavelength.

5 Conclusion

In the developed master-slave system, the surgical manipulator tracks the movement of the surgeon's arm similarly by using the measured data about the position and orientation of the surgeon's arm. The inverse kinematic solution of an additional DoF is derived by using the angle data of the surgeon's elbow joint. Additionally, the force measurement system using fiber bragg grating (FBG) sensor was developed.

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6 References

[1] A.J.Madhani, G. Niemeyer and J.K.Salisbury Jr., "Design of teleoperated surgical instruments for minimally invasive surgery," Ph.D Thesis MIT, 1998.

[2] Fobannes Bonder, Florian Augustin, "The da Vinci robotic system for general surgical applications: a critical interim appraisal," SWISS MED WKLY 2005.

[3] G.Hubens, H.Coveliers, "A performance study comparing manual and robotically assisted laparoscopic surgery using the da Vinci system," Surg Endosc Vol.17,pp. 1595-1599,2003.

[4] M.Mitsuishi, N.Sugita, P.Pitakwatchara, "Force-Feedback Augmentation Modes in the Laparoscopic Minimally Invasive Telesurgical System", IEEE/ASME Transactions on Mechatronics, Vol.12, No.4, pp.447-454, 2007.

[8] Won-ho shin, Dong-soo Kwon, "Development of a 5-DoF laparoscopic assistant robot," International journal of assistive robotics and mechatronics, Vol.7, No.4, pp.21-28, 2006.

[9] Ho-seok Song, Jung-ju Lee, "Develoment of a 5 DoF dexterous manipulator executable inside abdomen for minimally invasive surgery," International journal of assistive robotics and mechatronics, Vol.7, No.4, pp. 3-8, 2006.

[10]A.J.Hodgson,R.A. Pantazopol, M.D.Visser, S.E.Salcudean and A.G.Nagy, "Assessing potential benefits of enhanced dexterity in laparoscopic surgery," Proc. IEEE/EMBS, Oct.1997, pp.1966-1969.

[11] Se Jin Park, Soo Chan Park, Jin Ho Kim, Chae-Bogk Kim, "Biomechanical parameters on body segments of Korea adults," International Journal of Industrial Ergonomics, Vol.23, pp.23-31, 1999,