Development of Flexible Surgical Manipulator for Natural Orifice Transluminal Endoscopic Surgery

Jungwook Suh, Hoseok Song, Kiyoung Kim, and Jungju Lee*

*Dept. of Mechanical Engineering, KAIST, 335 Gwahangno, Yuseong-gu, Daejeon, Republic of Korea
(Tel : 82-42-350-3033; Fax : 82-42-350-3210)
(leejungju@kaist.ac.kr)

Abstract: Natural Orifice Transluminal Endoscopic Surgery is an advanced and experimental surgical technique performed via natural orifices (mouth, anus, vagina, urethra, etc.). Therefore, unlike other surgery methods such as laparoscopic surgery or single port access surgery, NOTES can avoid remaining external incisions or scars. Surgical manipulator for NOTES should be flexible in order to be inserted into channels of overtube. This paper presents a development of flexible robotic manipulator for NOTES, including design and kinematic analysis. Developed thin manipulator has 4 DOF motion and only 5.0 mm in diameter. And it uses multi-revolute joints that have gradual curve in order to enlarge the workspace and minimize the diameter of manipulator.

Keywords: NOTES (Natural Orifice Transluminal Endoscopic Surgery), MIS, surgical robot

I. INTRODUCTION

Laparoscopic surgery, a kind of MIS which stands for Minimally Invasive Surgery, means a surgical technique performed in the abdomen through some small incisions. These days it is common surgical method in the case of simple abdominal surgery such as cholecystectomy because of advantages like short hospital stay and small scars. However it usually takes longer time to operate laparoscopic surgery than traditional open surgery. Development of laparoscopic instruments helped to make the procedure short and simple, and finally the introduction of medical robot caused a shift of power in the medical surgery. Da Vinci®, developed by Intuitive Surgical Inc., is the representative medical robot system for the laparoscopic or thoracic surgery. This kind of surgical robot can operate surgery much more dexterously than traditional manual surgery.

The smaller the incisions for surgery are, the bigger the merits of MIS are. Traditional open cholecystectomy needed an incision bigger than 20 cm, while recent laparoscopic operation makes three to five small incisions of only about 10mm. Furthermore, surgeons are trying to minimize the incision for surgery as ever. Therefore they invented two kinds of new experimental surgical methods for abdominal surgery in recent years. One is SPA(Single Port Access) surgery, and the other is NOTES(Natural Orifice Transluminal Endoscopic Surgery). The SPA surgery is performed using single entry port, typically the patient's navel. Though SPA surgery remains no visible scar after a while, external incision on the patient's skin is still needed. On the other hand, NOTES has significantly different procedure to laparoscopic surgery. The biggest advantage of NOTES is that it makes no incision on patient's skin. Instead, it is performed via natural orifices such as mouth, anus, vagina or urethra, and internal incision on the wall of organ is necessary to approach the surgical site. Patient barely feels pain on the internal incision and can leave the hospital much earlier. Besides, lower anesthesia requirements and avoidance of the potential complications are also big merits of NOTES [1]. Therefore, NOTES can be considered an ideal abdominal surgery from the viewpoint of MIS. However there is an obstacle to carry out this brand-new technique that is absence of proper instruments for NOTES. Unlike SPA surgery, NOTES cannot utilize traditional laparoscopic instruments, because flexible surgical tools should be inserted via bent human orifices [2]. Therefore various surgical instruments for NOTES should be developed so that NOTES can be one of general surgical operations for abdominal surgery. Furthermore, robotic system for NOTES is expected to change the status of NOTES in abdominal surgery as in the case of laparoscopic surgery.

II. DESIGN OF ROBOT ARM

More than two surgical instruments are needed to perform surgical procedures, and they should be exchangeable. Therefore, for the sake of NOTES, two instruments should be inserted along an overtube with an endoscope as shown in Fig.1. At this moment, there is no commercial NOTES robot system, but some NOTES prototypes, such as EndoSAMURAI (Olympus Corp., Tokyo, Japan) and DDES (Boston Scientific, Natick, MA), are considerable for development [3].

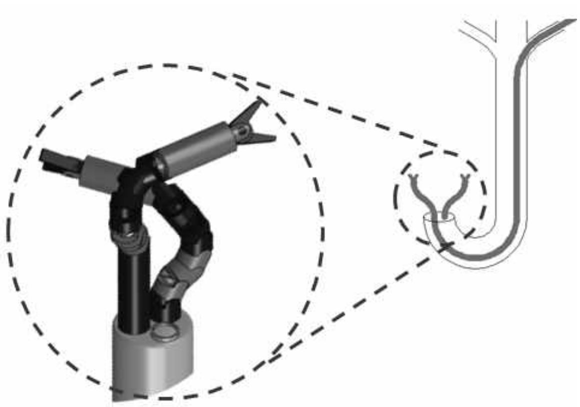

Fig.1. Overview of NOTES robot

The target surgery of this research is transgastric cholecystectomy. The diameter of overtube is limited to 25 mm due to the size of patient's esophagus. Of course, it's obvious that small diameter is good for smooth insertion. In this research, the diameters of overtube and robot arms are determined to 20 mm and 5 mm each. Different from the conventional flexible endoscopic instruments, 2 additional DOF (degrees of freedom) joint can make surgical procedures easy. Thus each robot arm has 4 DOF including translation and axial rotation except grip motion.

Fig.2. Flexible shaft composed of short links

Fig.3. 2 DOF multi-spherical joints driven by 8 wires

Further, flexibility and force are important requirements for robot arm for NOTES. Thin and flexible robot looks nearly impossible to apply heavy radial force on the tip. Therefore, flexible shaft composed of lots of short rigid links are used in order to apply axial and torsional forces effectively. 2 DOF active joint also can be composed of similar links. There are several types of small sized joint mechanism that can be applied to NOTES instruments [4]. Multi-spherical joints design is frequently applied for many researches because of the advantage that it's relatively easy to product small sized joints [5][6]. However this kind of manipulators has a severe problem that they are so weak to external forces that the assembled joints are easily bent. In order to prevent the S-shaped bending by applied external forces, French CNRS fixed lots of actuating wires on each links and actuated them with different speed using pulleys [6]. 5 mm sized Endowrist, laparoscopic instrument for da Vinci® system, has similar but advanced mechanism using universal joint at proximal driving part. It helps the system minimize the size of driving part. Notched nylon rod or superelastic NiTi tube can be used for bending joint similarly, and they are good to serve a working channel for gradual bending [7]. Nevertheless, they cannot beat muti-spherical joints because of elasticity and small applicable forces.

Although there is no commercial robotic NOTES system now, lots of researchers are trying to develop NOTES system. Purdue University develops a NOTES robot based on the laparoscopic surgery robot named Laprotek, while Columbia Univ. and Intuitive Surgical, Inc. are developing SPA surgery robot [7][8]. These three systems have elbow-out function in common, because the scope and two arms should be located in small sized overtube head. Therefore the distance between two robot arms is so narrow that it's difficult to secure enough workspace and field of view without elbow-out joints. They are essential for NOTES robot, but wire-driven toggles are sufficient for them. As shown in Fig.4, surgical robot arm consists of tooltip, long flexible shaft and driving part. Three DC motors in the driving part drives the 2 DOF bending joints and the forceps using stainless steel wire ropes. And Fig.5 shows the actual built robot arm combined with the overtube. The overtube serves three working channels for a camera and two arms.

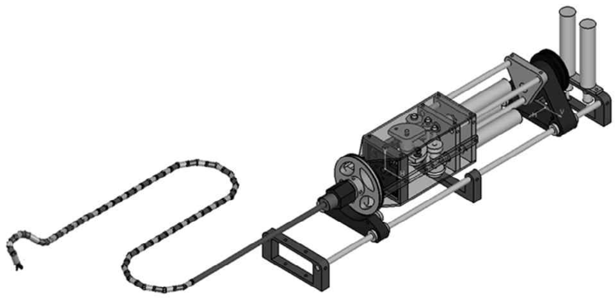

Fig.4. Designed NOTES robot arm

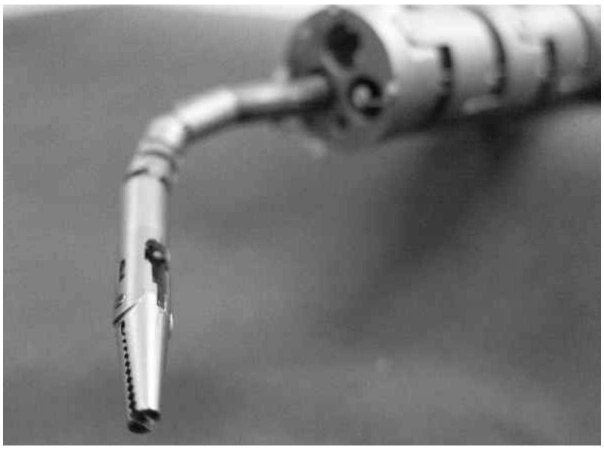

Fig.5. Built robot arm combined with the overtube

III. KINEMATIC ANALYSIS

2 DOF bending section is composed of 4 unit revolute joints. If the number of segmental revolute joints is large enough, this kind of 2 DOF joint can be considered as a long flexible shaft even though it consists of rigid links. Furthermore, it makes a circular arc shaped bending under the assumption of zero gravity and no friction. This bending section is difficult to express using traditional D-H (Denavit-Hartenberg) parameters. It causes some duplicated symbols like θ_3 and θ_4 as shown in Table.1. There are four variables (θ_1, d_2, θ_3, and θ_4) because this manipulator has 4 DOF. And here d_3 is a function of θ_3 as follows.

Link	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	0	a_1	d_2	0
2'	0	0	0	θ_4-90°
2''	-θ_3/2	0	0	0
2'''	0	0	d_3	0
2''''	-θ_3/2	0	0	0
4	0	0	0	90°-θ_4
5	0	0	d_4	0

Table.1. Denavit-Hartenberg parameters

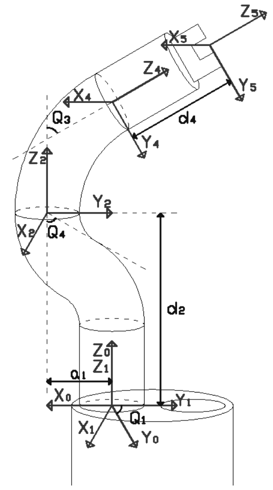

Fig.6. Kinematics of 4 DOF manipulator

$$d_3 = \frac{2L_T}{\theta_3}\sin\frac{\theta_3}{2} \tag{1}$$

L_T is the length of bending section when unfolded, and θ_4 is the angle between x_2 axis and the projected line of bending section on the x_2 y_2 plane. As a result, the bending section has 2 DOF motion and it can be expressed as a transformation matrix with two variables, θ_3 and θ_4, as follows.

$$T_4^2 \approx T_{2'}^2\, T_{2''}^{2'}\, T_{2'''}^{2''}\, T_{2''''}^{2'''}\, T_4^{2''''} = \begin{bmatrix} c_3 c_4^2 + s_4^2 & (c_3-1) c_4 s_4 & s_3 c_4 & \frac{L_T(1-c_3)c_4}{\theta_3} \\ (c_3-1)c_4 s_4 & c_3 s_4^2 + c_4^2 & s_3 s_4 & \frac{L_T(1-c_3)s_4}{\theta_3} \\ -s_3 c_4 & -s_3 s_4 & c_3 & \frac{L_T s_3}{\theta_3} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

By the benefit of assumption on the bending section, the overall kinematics also can be expressed with quite simple transformation matrix. (eq.4) and (eq.5) indicate the rotation matrix and the position vector in (eq.3).

$$T_5^0(\theta_1, d_2, \theta_3, \theta_4) \approx T_1^0\, T_2^1\, T_4^2 T_5^4 = \begin{bmatrix} R_5^0 & P_5^0 \\ 0 & 1 \end{bmatrix} \tag{3}$$

$$R_5^0 = \begin{bmatrix} c_{14}c_3c_4 + s_{14}s_4 & c_{14}c_3s_4 - s_{14}c_4 & c_{14}s_3 \\ s_{14}c_3c_4 - c_{14}s_4 & s_{14}c_3s_4 + c_{14}c_4 & s_{14}s_3 \\ -s_3c_4 & -s_3s_4 & c_3 \end{bmatrix} \tag{4}$$

$$P_5^0 = \begin{bmatrix} c_{14}((1-c_3)\frac{L_T}{\theta_3}+s_3d_4) \\ s_{14}((1-c_3)\frac{L_T}{\theta_3}+s_3d_4) \\ d_2+c_3d_4+\frac{s_3L_T}{\theta_3} \end{bmatrix} \quad (5)$$

In spite of the rough assumption, this result does not show a significant error. Besides, the bending amount is meaningless in the NOTES arm because of long and flexible shaft, while the bending direction is quite accurate.

IV. EXPERIMENT

A simple experiment was performed to confirm the linearity between commanded angle and actual measured angle in the bending section. Angles were observed for several cycles of simple bending motion in order to check the repeatability. This experiment was performed with 8 segmented bending section and 400mm long flexible stem in S-shaped experimental working channel whose size is only 70 mm in radius of curvature. The two values of commanded and actual angles would be same on the idealized assumption. Unfortunately, however, the plot shows severe hysteresis. It's impossible to eliminate this phenomenon completely. Nevertheless, it can be improved by minimizing friction and tolerance and slope correction technique [7].

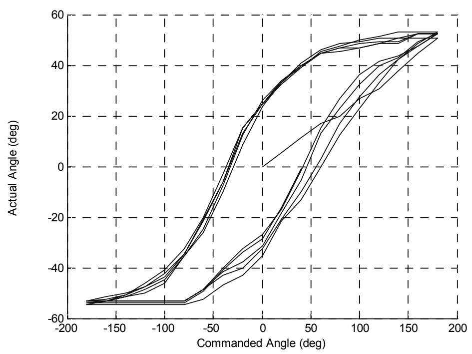

Fig.7. Hysteresis loop for repeated bending motion

V. CONCLUSION

Long, thin and flexible surgical robot suitable for NOTES procedure was developed. Although the diameter is only 5 mm, it serves 4 DOF motion except grip. It's designed to apply high axial and torsional forces and to have small radius curvature for smooth insertion into bent channel. Even though the result of the repeating experiment was not so good, it showed the possibility of NOTES. In the near future, NOTES is expected to be established as one of the standard procedures for abdominal surgery.

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