33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

In Vivo Experiments of a Surgical Robot with Vision Field Control for Single Port Endoscopic Surgery

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Abstract— **Recently, robotics systems are focused to assist in Single Port Endoscopic Surgery (SPS). However, the existing system required a manual operation of vision and viewpoint, hindering the surgical task. We proposed a surgical endoscopic robot for SPS with dynamic vision control, the endoscopic view being manipulated by a master controller. The prototype robot consists of a manipulator for vision control, and dual tool tissue manipulators (gripping: 5DOFs, cautery: 3DOFs) can be attached at the tip of sheath manipulator. In particular, this paper focuses on an *in vivo* experiment. We showed that vision control in the stomach and a cautery task by a cautery tool could be effectively achieved.**

I. Introduction

A. Background

Minimally invasive surgical techniques are continuously being developed to reduce the invasiveness of various surgical procedures. Beginning in the 1990s, the development of new technologies, including advanced laparoscopes, clip appliers, and energy sources for laparoscopy, provided a period of rapid development in minimally invasive surgery [1]. In recent years, research and development has been undertaken of technology such as surgical robots and navigation systems. Expectations of surgery performed by minimally invasive surgical robots have increased, and research and development into surgical robot systems has advanced in many fields [2][3].

Laparoscopy and other minimally invasive surgeries have successfully reduced the patients' postoperative pain, complications and hospitalization time, and have improved cosmesis. Most existing robotic surgical systems are designed for minimally invasive laparoscopic procedures [4]. For example, Intuitive Surgical Inc. provides the da Vinci system commercially[5][6]. During most laparoscopic procedures, two or more incisions are used for surgical instruments, visualization, and insufflation.

Recently, a new surgical method is focused, Single Port Endoscopic Surgery (SPS), which requires only one skin incision unlike laparoscopy. It may decrease patients' pain moreover compared with laparoscopic procedure [7]. Although surgical robot has made it easy to perform laparoscopy [8], very few robot for SPS is existing. So currently manual SPS is performed in limited case [9].

B. Problems

The robotic systems in related work focus on the development of a robotic effector to realize precise tissue manipulation inside humans. In these systems, the robotic effector is initially inserted and positioned within the surgical workspace, and maintains a motionless state while the surgeon manipulates the robotic end-effector to perform surgical tasks. The base of the robotic end-effector and laparoscope may be fixed during operation. In contrast, the laparoscopic field of view is changeable in "multi-incision" robotic laparoscopic surgery such as that using the da Vinci system. Static positioning of the laparoscope and base of the end-effector may result in an increase in difficulty of the surgical task, because a manual change of field of view is not intuitive and is a time-consuming task for surgeons. It would also become a greater problem in the future when the inserted robotic effector becomes smaller, because the robotic effector can perform the surgical task for only a small area in a certain field of view, and this would necessitate many changes of field of view for the treatment. Moreover, a high number of degrees of freedom (DOFs) and a wide range of motion (ROM) are required in the tissue manipulator for it to be able to perform complicated procedures.

Some existing systems have the function of robotic vision changes [10][11]. However, the DOFs (typically four DOFs for pivot movement) are not sufficient and the effective result is only a gross positioning of manipulators for tissue manipulation.

C. Objectives

The objective of this study was to develop a master-slave robotic system to assist abdominal SPS. The main novel advantage of the system is that it includes a master-slave

Manuscript received April 15th, 2011. This work was supported in part by Global COE (Centers of Excellence) Program "Global Robot Academia," from the Ministry of Education, Culture, Sports, Science and Technology of Japan, in part by Grant Scientific Research (A) (21240056), Japan and in part by a Waseda University Grant for Special Research Project (2009B-207, 2010B-169), the High-Tech Research Center Project from MEXT.

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function for not only manipulation of the robotic effector, but also control of vision during operation. For the purposes of this function, we designed our robot to have six DOFs only for the dynamic changes of field of view, while the dual manipulators have different DOFs for the grasper and cautery end-effector. The "dynamic" vision control would enable an intuitive change of field of view and would resolve the difficulties in existing equipment, as well as contributing to reducing the required DOFs and ROM of manipulators. We anticipate that vision control will be necessary for future SPS with smaller manipulators, in which the surgical task can be performed for only a small area.

We report here the design and prototype of a robotic system for realizing this concept and an *in vivo* experiment to evaluate the performance of our robot manipulated by physician. We have already developed a mechanism and control scheme for the tool manipulator to achieve a high level of precision and strong dynamic response [12]. We have also already reported the basic concept and preliminary *in vitro* experiments [13].

The rest of the paper is organized as follows: Section II presents the concept and mechanism of our manipulator with vision control. Section III describes an *in vivo* experiment to evaluate the performance of our robot. Finally, section IV provides a summary and refers to future work.

II. CONCEPT

Robot-assisted SPS with vision control demands the following capabilities: i) the robot manipulating the position and posture of the endoscope can be inside the human body, ii) the endoscope is deployable into a working configuration, iii) the robot should have the manipulator for tissue manipulation inside the endoscope image, iv) the manipulator for tissue manipulation can manipulate target organs and their related tissues (such as gallbladder, hepatic tissues or pancreas.) with sufficient precision and force, v) the robot should be able to be folded to pass through a single small skin incision.

Based on the above specifications, our robot primarily consists of 1) a vision control manipulator, 2) two surgical tool manipulators, and 3) one flexible endoscope. Fig.1 depicts the system overview of our manipulator.

A. Vision control manipulator

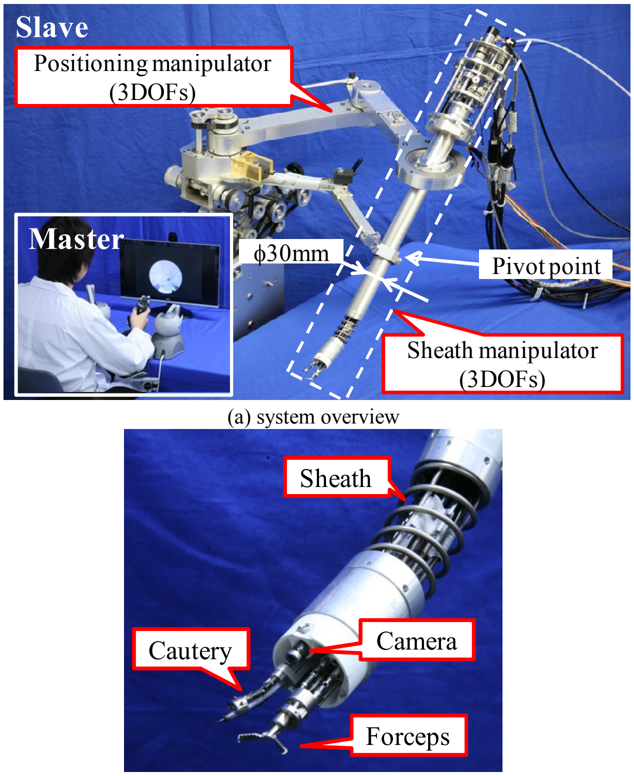
The vision control manipulator consists of a positioning manipulator and a sheath manipulator. The positioning manipulator is located outside the body and is designed to control the position and orientation of the sheath manipulator and tool manipulators inside the body. As a result of the limitation of the small incisions used in endoscopic surgery, the positioning manipulator has a four-DOFs motion space about the entry point, including three spatial rotational DOFs and one translational DOF along the tool axis. For safety, the positioning manipulator is designed to be mechanically constrained except for pivot movement at the abdominal incision. The sheath manipulator is provided for the other two DOFs inside the body. It consists of a 2DOFs snake-like continuum manipulator with a spring backbone. The total of six DOFs of the positioning and sheath manipulator works in a coordinated manner for positioning of the surgical tool manipulators and flexible endoscope. We have already reported the concept and experiments of the vision control manipulator in our previous article [14].

B. Surgical tool manipulator

Surgical tool manipulators are used for tissue manipulation. A flexible endoscope is also fixed in the forefront of the sheath manipulator. The mechanical base of the tool manipulator is the same as that of the flexible endoscope. Thus, two tool manipulators are fixed in the forefront of the sheath manipulator. The manipulators act as a surgical slave for dual arm interventions and delivery of energy sources (e.g. cautery), and the end-effector could be used for various endoscopic instruments. The designated task for the prototype was to perform resection of an organ, with vision control. To realize this task, the robot presented here has the left and right robot arms fitted with a grasper (or gripper) and a cautery end-effector, respectively.

The intended setup and usage of our robot are as follows: a single incision is made in the abdominal wall of the patient. After a patient's abdomen is insufflated, first, the positioning manipulator only is positioned above the patient and the pivot point of the positioning manipulator is set just above the incision. The insertable tool, sheath manipulator and tool manipulators are placed into a linear position and then slightly inserted into the peritoneal cavity through an incision. An operator then manipulates the field of view to the target area using the master controller. Finally, the operator performs the surgical task using the combination of vision control and tool manipulators.

The design overview of our prototype robot presented here is as follows (Fig.1). The diameter of the insertable component is approximately φ30 mm, and this insertable part in its folded and straight configuration can be inserted into the abdomen through a φ30 mm skin incision. The diameter of the flexible endoscope, and tool manipulator for gripping and cautery were φ30 mm, φ8 mm and φ6 mm, respectively. The length of the sheath manipulator, which is a 2DOFs snake-like continuum manipulator, is 50 mm. It should be noted that this study focuses on development of the prototype, and evaluation of the design concept and vision control. It must be further miniaturized to enable its comfortable use in human subjects; while a typical diameter for SPS is now 30 mm. Development of a robot with smaller configurations will be the subject of further studies and will possible in the near future, because each component and mechanism presented here will be available.



(a) system overview

(b) enlarged view of tip

Fig. 1. System overview of the robot with vision control

III. EXPERIMENT

We needed to understand how to perform the procedure using our robot hearing physicians' opinion. It is a major advantage that the sheath manipulator can focus the organs vertically [13]. We also needed to determine if the range of movement of the manipulator is feasible inside the body. Specifically, we performed a resection task with forceps and a cautery moving the sheath manipulator inside the animal body. From this experiment we hoped to be able to determine any potential difficulties.

A. Experimental method

To better understand our robot for this initial feasibility study, *in vivo* experiments were performed as shown in Figure 2. The designated task for the prototypes was to perform resection of the bladder and liver, with vision field control. A pig was used for the experiment because pigs have similar physical properties and anatomy of the abdomen as those of the human. The procedure was performed with the animal under general anesthesia. The robot was set next to the surgical bed and positioned to an approximate location for the restriction task. A return electrode for the cautery knife was attached to the dorsal side of the pig.

We performed the following tasks using the above experimental setup (the operators of this experiment were physicians). A port to the peritoneal cavity was created on the lower abdomen by a diathermy knife. The sheath manipulator with a forward-viewing endoscope was then was inserted into the stomach, which was insufflated with air to lift the anterior abdominal wall. The sheath manipulator was at an approximately 45-degree angle to the ground to approach the bladder and liver. We added ports for anesthesia and a laparoscope to record the manipulator externally.

First, to search for the bladder and liver, the vision field control of the sheath manipulator was moved. After finding the bladder and the liver we tried to resect them with the gripper and the cautery.

B. Result and discussion

Vision control in the stomach and the cautery task by the cautery tool were effectively achieved (Fig. 3,4). The physicians manipulated the sheath manipulator to approach the liver. He then controlled the forceps and cautery with the master manipulator.

These experimental procedures demonstrated the feasibility of our robot for performing restricted tasks. The vision control manipulator provided a stable mounting platform with smooth repositioning of the vision field and the tool manipulators. In addition, the operators could intuitively manipulate the vision field. The operators could also manipulate the tool manipulators in the experiment. These abilities are important for the surgeon to explore, manipulate and cauterize tissues.

However, there are some limitations. The space of the cavity was too small to search for the organs and air slowly leaked from the trocar and the spring of the sheath manipulator. We changed the method to lift the abdominal wall before the manipulator was inserted. We found that insertion of the sheath manipulator with air inflation was difficult under these conditions. We stopped insufflation of air and held up the stomach with an instrument externally (Fig. 5).

There are other problems with respect to the mechanism. First, the tool manipulator operated accurately until commencement of the experiment; however, the positions of the end-effectors were shifted as the experiment progressed. The cumulative error of the manipulator position may have resulted from flexible shaft-power transmission. Second, it is difficult to change the surgical tool during an operation. The physicians would like to change tool manipulator such as the forceps and cautery. The surgical tools attached to the tool manipulator can be changed but not during surgery. Finally, the working space of the tool manipulator was small for abdominal surgery, and therefore, the range of movement was limited.

IV. CONCLUSIONS

In this paper, we proposed a surgical robot with vision control for the SPS, for the purpose of reducing the difficulty of the manual change of field of view in surgical tasks. We described the design concept of a prototype robot which consists of positioning (3DOFs) and sheath (3DOFs) manipulators for vision control, as well as dual tool manipulators (left for gripping: 5DOFs, and right for cautery: 3DOFs) for tissue manipulation. In particular, this paper focused on *in vivo* experiments. Vision control in the stomach and a cautery task by a cautery tool were then effectively achieved.

Future studies will need to increase the range of movement to change the mechanism of the tool manipulator and add the

DOFs. It is necessary for the tool manipulator to unfold its arm similar to a human's arm. Moreover, a calibration method is needed to solve the problems of cumulative error of the tool manipulator. We plan to obtain the end-effector position of the tool manipulator from the endoscope image, and to feed it back to the robot controller to attempt to minimize generation of cumulative errors.

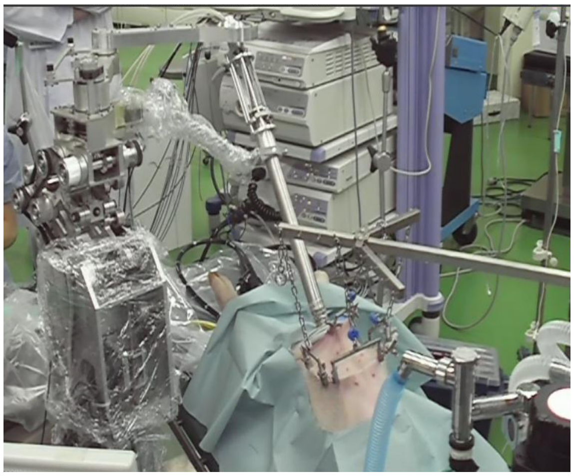


Fig. 2. Experimental setup of the *in vivo* experiments.

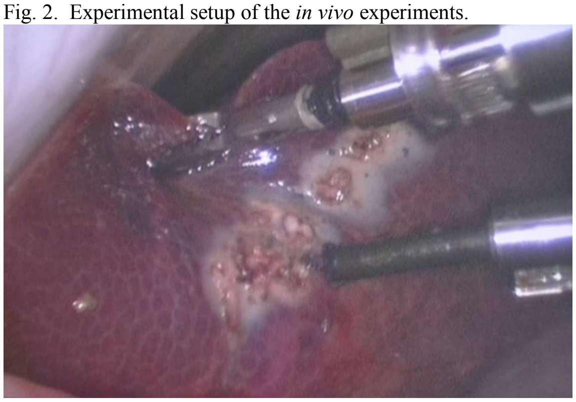


Fig. 3. Experimental result of cautery task.

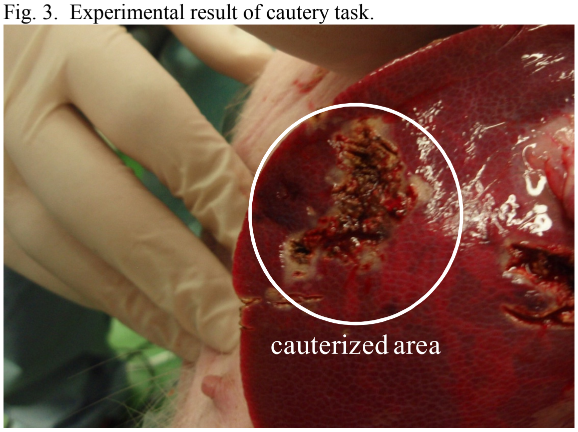


Fig. 4. Experimental result of cautery task.

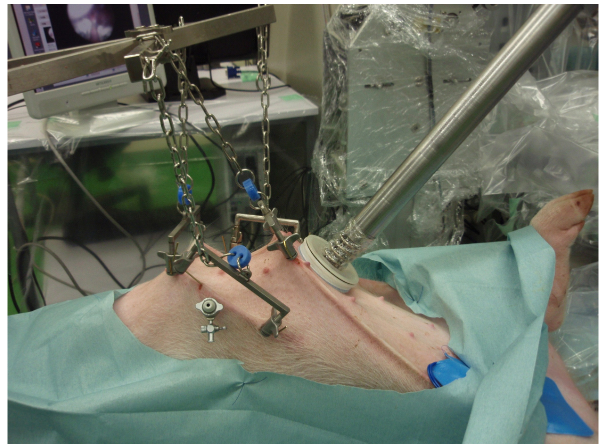


Fig. 5. Experimental setup to hold up the stomach with instrument externally.

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