Scorpion Shaped Endoscopic Surgical Robot for NOTES and SPS With Augmented Reality Functions

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Abstract. In the process of developing an endoscopic surgical robot system that adapts to NOTES (Natural Orifice Translumenal Endoscopic Surgery) and SPS (Single port surgery), by making the tip a soft tubular structure and adding an augmented reality function to the system, we were able to improve the general function of the surgical robot system. First, we added a haptic sense function to avoid breaking the soft tissue and to avoid the danger of cutting it. These occur due to the small size of the touching surface between the tip of the robot arm and the soft tissue. We were able to conduct operation by feeding back to the surgeon the force applied to the soft tissue by detecting the haptic sense of the small forceps at the tip through measuring the tension variation at the base of the wire that drives the robot arm. We also mounted various numbers of augmented reality function such as grasping the exact location of the surgical robot inside the human body and information on how the robot is reaching the location of surgery. As a result, we were able to build a system that can conduct safe surgery with the system's two main characteristics - the smallness and the high degree of freedom to move.

Keywords: Endoscopic surgical robot, NOTES, SPS, Augmented reality.

1 Introduction

We have been developing a surgical robot under a new concept using microfabrication technology and tele-presence technology [1,2]. Up until now, the basis of building a surgical robot, such as in Zeus™ and da Vinci™ [3,4], was in laparoscope surgery, and their structure was based on the robot arm controlling the laparoscope and forceps. But our surgical robot that we started to develop in the year 2000 has a tip that is small enough to go inside a human body and that part can conduct operations. Our surgical robot has an eye at the tip and robot arms on each side of the eye. It is like a small robot that can operate like human hands inside

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minute space. As shown Fig.1, the distal part of the robot resembles scorpion with those long two arms and a small head with eyes. For this robot, we aimed to build an endoscopic surgical robot system that can adapt to both NOTES (Natural Orifice Translumenal Endoscopic Surgery) [5-8] and SPS (Single Port Surgery). NOTES is a surgery that goes inside through the esophagus via stomach and stomach wall and conducts operation in the abdominal cavity. SPS is a surgery that penetrates through the body surface and goes into the abdominal cavity to conduct operation. In developing the endoscopic surgical robot system, we found out that it was important to develop functions to solve problems that the structure of the robot itself had. The problem lay in robot's smallness and the high degree of freedom to move. These two points were also advantages of the robot but we realized that to conduct safe surgery, we needed to complement it by other technologies.

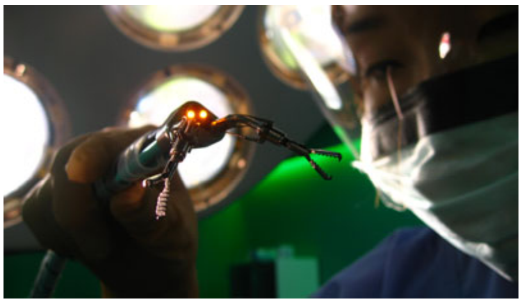


Fig. 1. Appearance of the tip of the scorpion shaped endoscopic surgical robot

First we will explain why the small size of the robot arm is a problem. As we will explain later on the method, the tip of a robot arm is 40mm in length and 6.0mm in width and is shaped like forceps. We found out that as the contact surface of the forceps and soft tissue is so small, if the force applied to the forceps is too big, it would crush or cut the mucosa layer of the stomach wall or the intestinal wall.

We needed to have the small forceps tip that would detect its haptic sense and have the amount of applied force fed back to the surgeon. In this thesis, we report on how we are in the process of developing the haptic sense function.

In addition, this surgical robot can move freely inside a human body during conducting laparoscope operation. But due to this characteristic, there were cases where the surgeon lost the location of the robot inside the body. Therefore, we found out that we highly needed to complement the robot with augmented reality technology so that the surgeon can grasp the exact location of the robot and get information on how the robot is reaching the location of surgery. Moreover, we found out that as the robot is small in size, the surgeon can easily be blinded by small amount of blood. It can also be buried in a stump of soft tissue which was not a problem in open surgery or laparoscopic surgery.

2 Method

2.1 Structure of the Robot

Before we report on the haptic sense function and the augment reality technology we used, we will explain the structure of the robot we are developing now.

Fig.2 shows the block diagram of the surgical robot system in whole. Two robot arms are mounted on the tip of the endoscopic like shape, which goes inside a human body. Each robot arm and the forceps at the tip are driven by wires from the actuator unit. The unit comprises of stepping motor assembly located at the based of the robot arms and forceps.

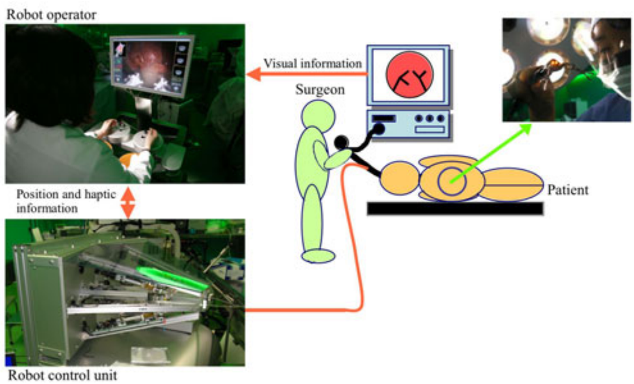


Fig. 2. Block diagram of the surgical robot system

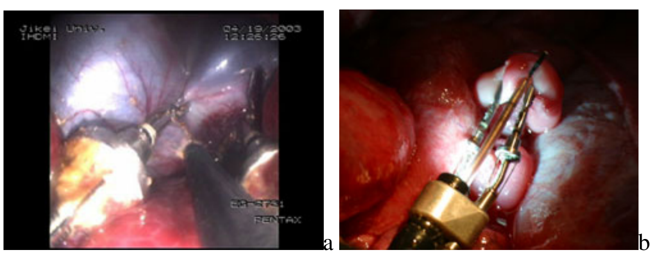


Fig. 3. Scene of the animal experiment using the endoscopic robot system. a: handling of gallbladder, b: clipping oviduct

This endoscopic surgical robot is controlled by two surgeons working in liaison. Surgeon A inserts the robot into the body and moves, rotates and changes direction of the robot near the destination site. Surgeon B sits in front of the console and controls the robot arms and conducts surgery. Surgeon A inserts and withdraws relocation clipping device and surgical needle knife using lumen connecting the tip of the robot and the outside of the body. He also cleans and conducts suctioning the lens and the location of surgery using lumen. Both Surgeons A and B can use the endoscopic screen reinforced by augmented reality. Fig.3 shows the system during animal experiment. Fig.4 shows actuator unit that comprises of stepping motor assembly for each ten robot arms (five on each side). The unit drives the robot arms. The stepping motors in the actuator unit is positioned in a cone shape with the robot's base at the center so that that wire force will effectively be conveyed to the robot arms.

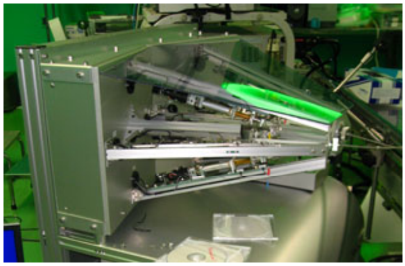
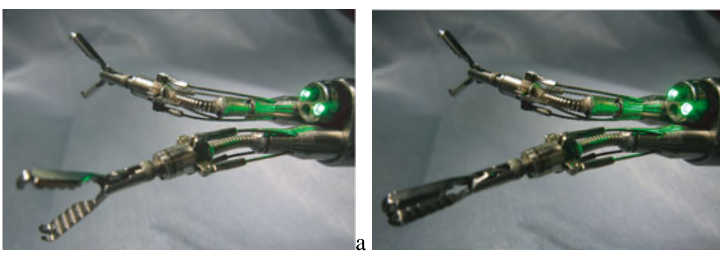


Fig. 4. Actuator unit of the robot system

2.2 Structure of Robot Arms

The robot arms on the left and right have symmetric structures. Each has four wires that move the robot arm up and down, right and left and a wire that open and closes the tip of the arm. The tip of the forceps is 10mm in length and 2.0mm in width. When opened to the limit, it can grab and object of 6mm. The tip of the robot arm can bend maximum 12mm up and down, right and left by four wires driving it in liaison. A robot arm can work in up to 40mm ground from itself, right and left. We also aimed high-efficiency for wire pulling force so that the robot arm can grab soft tissue with a force more than 3N and the forceps can open and close with that force.

Fig.5 shows the structure of the tip of the robot arm. The four wires positioned around the forceps enables the robot arm to bend up and down, right and left.



a b

Fig. 5. Structure of the tip of the robot arm

2.3 Acquiring Haptic Sense

We at first tried to acquire haptic sense by positioning a pressure sensor at the mechanical section of forceps. But it was difficult to adequately position piezo element on the surface of the insides of minute forceps. There was also danger of safety problems such as strength of the coat of the wire parts that would be connected to the device was not strong enough and had the danger of electrical leak.

To solve this problem, this system has a “Wire Traction Control” mechanism which monitors the traction of the wires at all times to obtain the best control system anytime.

Needless to say, the traction of the wires obtained at the base is information that includes various disturbance elements such as the change of position, loosening, and twists of the wires themselves. This will occur as to bend the endoscopic surgical robot, the wires run parallel and other wires are positioned to lead and protect them in the pipe. But we tried to distinguished the characteristics of the object the forceps grabbed from the characteristic curve of the pressure change against action. We conducted a mock experiment where the characteristic was a given phantom. We obtained the change of traction according to the change of physicality and succeeded in distinguishing the characteristics of the object. Therefore, we were able to acquire haptic sense function at the tip of the robot arm.

2.4 Integrated Display Function

We separated the monitors in parts and positioned each augmented reality information in a part. We positioned the endoscopic image at the center. Then we positioned superimposed image of the targeted part in 3D where it is difficult to see in the endoscopic image.

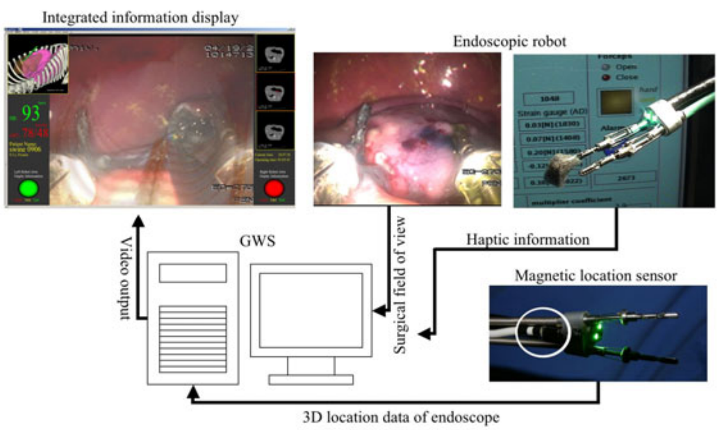


Fig. 6. Block diagram of the integrated display function

In addition, we positioned several kinds of images for navigation surgery. Moreover, we positioned display of haptic sense information of the right and left robot arms in color and the patient’s vital signs. We positioned these images so that the surgeon can instinctively acknowledge and effectively use patient’s information while in operation. We verified the above by conducting trial experiment with volunteers. To obtain the direction of the position of the tip of the robot arm, we mounted Minibird which is 6 DOF magnetic sensor at the lower part of the tip. We aimed to minimize the use of metal at the robot’s tip and used titanium alloy so that disturbance factor by magnetic positioning sensor metal will be small. We show in Fig.6 block diagram of the system for integrated display function.

3 Results

3.1 Acquisition of Haptic Sense

We show in Fig.7, change of traction against wire displacement when the forceps at the tip of an robot arm grabs metal, plastic eraser (soft poly-vinyl chloride), and sponge (expanded polyurethane).

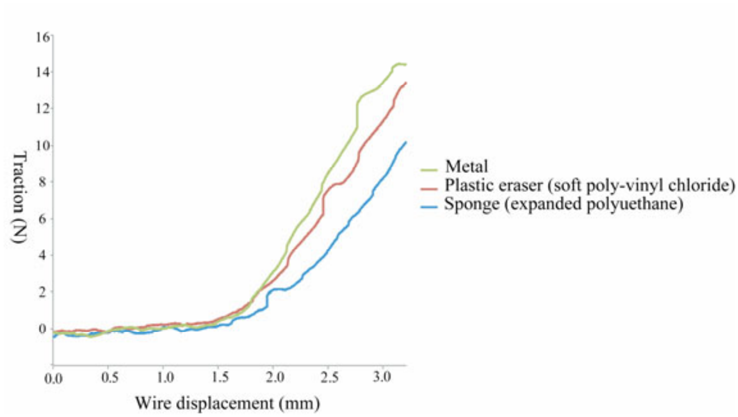


Fig. 7. Traction against wire displacement

As you can see from the change of traction against displacement of wire when the forceps is grabbing a rigid metal object, traction curve shows different characteristics from the action grabbing a rigid object in ideal condition. The following can be assumed for the reason of change displayed on the graph. When the forceps are closed, the wire is not always positioned in a line ideally. The small looseness of wire inside the pipe that protect the wires, and change of shape of the pipe itself when wires are pulled, all show up as peculiar change. The same can be assumed for an elastic body that change shape easily and either way, it looks like it is difficult to acknowledge the shape of the object the arm has grabbed. But as can be seen in the graph, the characteristics of the object the forceps have grabbed showed as differences of change of traction.

In addition, we found out that if we know the softness of the object when grabbing it, we can feedback grabbing power to avoid breaking the object. For example, we were able to conduct a mock operation by feeding back to the surgeon, the force applied to the soft tissue so that he could operation by not crushing the soft tissue. We experimented by creating a mock stomach wall with soft urethane that would break easily. We conducted an experiment using these function. We mounted haptic sense function on the surgical robot system as following.

3.2 Mounting Function of Distinguishing Softness and Feedback of Grabbing Force

Fig.8 shows projected result of the softness of each sample the forceps have grabbed. The change of colors of the indicators on the monitor, which is at the back of the tip of the robot shows the projected result. The indicator turns green when the forceps grabs a very soft object, yellow when the forceps grab a moderately soft object and red when the forceps grab a hard object.

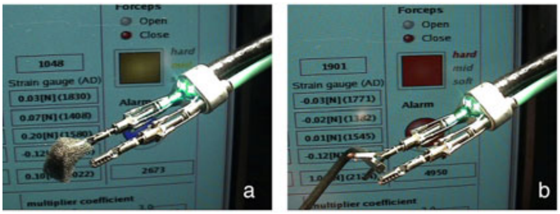


Fig. 8. Result of projection of softness as robot grabs an object. The projected result is shown in the display at the back of the robot arm. The color of the indicator changes. a: When the arm grabbed a sponge, b: When the arm grabbed a metal object.

Fig.8a shows the indicator green as the forceps are grabbing a sponge, Fig.8b shows the indicator is red as the forceps are grabbing a metal object. For functions to avoid damaging the soft tissue when the forceps grab it, Fig.9 shows the result of when the forceps grabbed silicon rubber (Fig.9a-c) which is close to the softness of soft tissues. Fig.9d-f shows the operator trying to lift up the soft tissue adjusting the forceps depending on the indicator. As mentioned before, these projected results are sent to the integrated information display system via the network and is displayed along with other operational information.

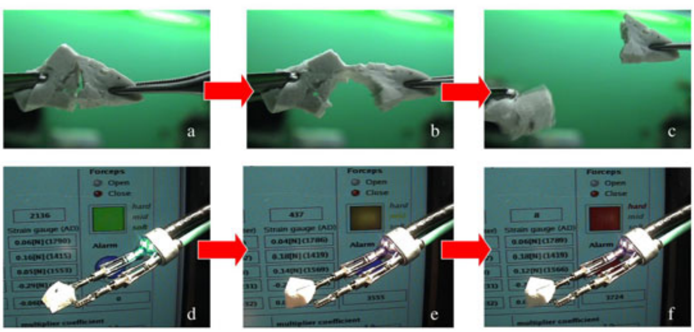


Fig. 9. Result of experiment of the robot arm grabbing the sample without damaging it. Using silicon rubber that has the same softness as soft tissue (a-c), the operator is controlling the opening and closing of the forceps by looking at the change of color or the indicator (d-f) and trying not too damage the silicon rubber by grabbing it too hard.

3.3 Integrated Display Function

As the results, the system has the following five functions. All information is updated in real-time and displayed on the screen in the cockpit for the operator. 1) function that displays the present orientation of the robot by showing patient's X-ray CT and MRI data sets superimposed onto the operation screen, 2) function that displays the position of the tip of the robot on a inner structure model reconstructed in 3D from the patient's pre-operation X-ray CT and MRI data sets, 3) function that displays the present position of the tip of the robot on patient's pre-operation X-ray CT and MRI data set images, 4) function that displays the softness of an object that the robot's manipulator has grabbed (this is being developed in parallel with the system), 5) function that displays patient's medical information such as heart rate and blood pressure.

For function 1), we use the positioning information of the robot obtained from magnetic positioning sensor installed at the tip of the robot. In this way we display in multi-layer, patient's inner structure in real-time on X-ray CT and MRI data sets obtained before operation on the operation screen. The RMS error between the endoscopic image and the superimposed X-ray CT datasets was 2.4mm.

For function 2), using the same position information at the tip of the robot as in 1), we display the position of the tip of the robot on the patient's 3D model structured before the operation. In this function, we enabled the operator to observe the 3D model from any point so that the operator can look over the whole picture to grasp the orientation of the robot and by doing so this function complements function 1).

Function 3) also uses the magnetic positioning sensor information and displays the position of the tip of the robot on X-ray CT and MRI images. The width of the window screen of the image display can be changed, the level can be changed and also the operator can enlarge and minimize the screen so that the operator needs to take his/her eyes off the operation as little as possible. Function 4) uses functions to calculate the softness of an object that a robot manipulator has grabbed. This is being developed by this project also. Function 4) can display in three different colors the softness the two manipulators each grabbed. We also created the system so that the operator can confirm patient's various medical information if it is needed during an operation in function 5).

Fig.10 shows what the system's screen displays in the operator's cockpit in an animal experiment using a pig. In the center of the screen shows function 1) mentioned earlier, at the upper left, function 2), at the upper right, function 3), at the center left, function 5) and in the lower right and left function 4) which displays the softness of the object the 2 robot manipulators grabbed. In the same figure, for function 1), the structure of the backbone and costal bones from the volume rendered X-ray CT data sets are superimposed onto the endoscope's image. For function 2), a green pointer is displayed on the surface rendered organ model and shows the position of the tip of the robot. For function 3), three consecutive images of X-ray CT images are displayed and a red cross in the center of the image shows the position of the tip of the robot. For function 4), the left is colored green and the right is colored red. This shows that the left manipulator is grabbing a soft object and the right manipulator is grabbing a hard object.

The frame rate in this experiment was 5-15 fps. For example, the frame rate was 5 fps when we used heavy X-ray CT datasets such as 512x512x512 pixels (when we used function 1).

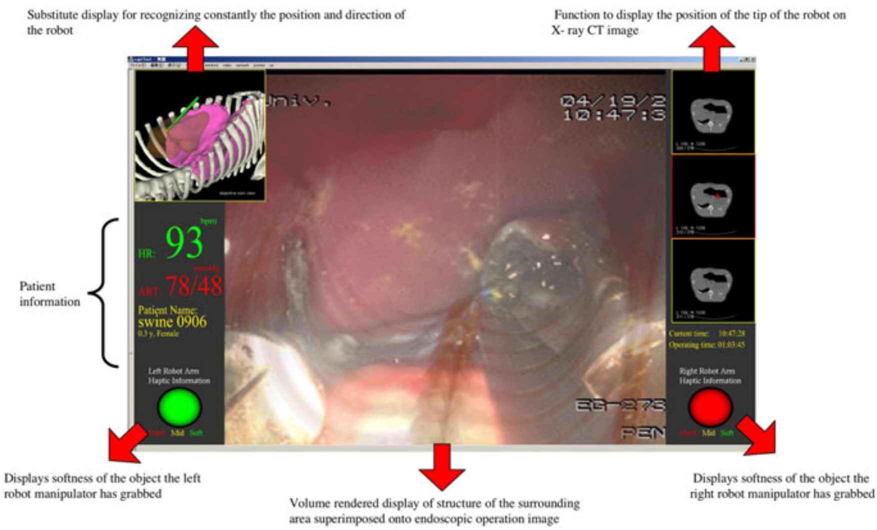


Fig. 10. Integrated information display system screen

4 Discussion

We were able to improve the function of the whole system by mounting the following function in the process of developing an endoscopic surgical robot system that adapts to NOTES and SPS. First we were able to overcome the problems due to the structure and shape of the robot system in development. We were able to reinforce the system by using augmented reality functions including haptic sense of robot arms and overcoming inadequate points such as the smallness of the robot and its freedom of movement inside the body.

As a result, we can say that by developing surgeon's console with augmented reality function including haptic sense function of the minute robot arm, we were able to build a system that can conduct safe operation with the two main characteristics of this robot system - the small size and the freedom of movement inside the body. In addition, the haptic sense device which does not need a haptic sense sensor that touches the part of operation can be applied to various other surgical robots. The integrated display system which can be display various information of the operation part including haptic sense from a various points of view can be applied to existing laparoscope type surgical robots, vascular catheter devices and radiotherapy devices. The endoscopic surgical robot system that we developed is planned to undergo clinical trials after conducting safety trials.

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