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Master And Slave Transluminal Endoscopic Robot (MASTER) for Natural Orifice Transluminal Endoscopic Surgery (NOTES)

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Abstract—**Although the flexible endoscopy has been widely used in the medical field for many years, there is still great potential in improving the endoscopist's capability to perform therapeutic tasks. Tentatively, tools for the flexible endoscope have poor maneuverability and limited Degree Of Freedom (DOF). In this paper, we propose a surgical robotic system MASTER (Master And Slave Transluminal Endoscopic Robot). MASTER is a dexterous and flexible master-slave device which can be used in tandem with a conventional flexible endoscope. Using this robotic system, ESD (Endoscopic Submucosal Dissection) and NOTES (Natural Orifice Transluminal Endoscopic Surgery) have been conducted on *in vivo* and *ex vivo* animal trials with promising results.**

Index Terms—**NOTES, flexible endoscopy, master slave, surgical robotics**

I. Introduction

The flexible endoscope is widely used in the medical field for visually monitoring the interior of the human body in a minimally invasive manner and also allows for Minimally Invasive Surgery (MIS) and endoscopy to be achievable. They brought about a whole revolution in the field of surgery whereby procedures become significantly less invasive, safer, cheaper and patients can recover faster compared with traditional open surgery. Another potential paradigm shift in the field of surgery is Natural Orifice Transluminal Endoscopic Surgery (NOTES). NOTES involves the intentional puncture of one of the viscera such as the stomach, rectum or vagina with an endoscope to access the abdominal cavity to perform an intra-abdominal operation [1]. In the abdominal cavity, the endoscope locates an internal organ that requires treatment and then proceeds with the necessary procedure. Lastly when the necessary treatment is completed, the endoscope return to the natural orifice, mend back the incision made before being taken out of the patient body.

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However for the full potential of NOTES to be used safely and reliably for humans, it is proposed to improve on the available tools for use with the endoscope. Some of the limitations with the available tools are that it has poor dexterity and lack triangulation to be used for NOTES. It is therefore envisaged to develop a multi Degrees of Freedom (DOFs) robotic system that is slender and flexible enough to transverse through a flexible endoscope and possesses high dexterity to execute the elaborate procedures for NOTES.

Currently in the field of medical robotics, there is strong interest to develop robots for performing NOTES. Companies such as the Boston Scientific, Olympus and USGI each have developed their own version of robot to realize NOTES [2]. There are also other robots such as the ViaCath system [3], miniature robot that assembles within the human body [4] and the endoscopic robot [5]. Basically there are two types of NOTES robots; one of them is to actuate the robot by their hands (direct drive) while the other is using actuators to drive the robot movements (actuator drive).

There are pros and cons in using actuator drive compared with direct drive. In actuator drive type, the surgeon can be remote from the patient since it is generally a master slave robot. Furthermore master and slave system allows motion scaling and removing surgeon's hand tremors. The design of the master console is also separated from actuating the tools which makes it easier to design ergonomic control for the surgeon. Actuator drive type also makes it possible for two surgeons to actuate the robot and endoscope simultaneously. However the disadvantages of using actuator driven compared with direct drive are that it requires more space for the actuators and computers, more costly, longer setup time and haptics feedback is a challenge to be implemented. Boston Scientific and Olympus use direct drive actuation while the ViaCath system [3], miniature robot that assembles inside the human body [4] and endoscopic robot [5] are actuator driven robot.

In this paper, the latest prototype of the MASTER (Master and Slave Transluminal Endoscopic Robot) project that is actuator driven is presented. To date, the robotic system has successfully performed 15 *ex vivo* animal trials and 5 *in vivo* animal trials on Endoscopic Submucosal Dissection (ESD) as well as 2 *in vivo* animal trials on NOTES (liver wedge resection).

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II. Methodology

A. System Architecture

The system architecture can be seen in Figure 1. The components on the left side show the human involvement in the system while the components on the right show the various modules of the robotic system. The middle column represents the conventional endoscopy system. For MASTER, there is a need for an endoscopist and a surgeon to collaborate together for treating the patient. The endoscopist controls the position and orientation of the endoscope while the surgeon controls the movements of the robotic system. This configuration allows both the slave manipulator and the endoscope to work simultaneously together on the patient. This synergy is able to enhance the safety and shortens the time taken for performing complicated procedures on relatively large organs during NOTES.

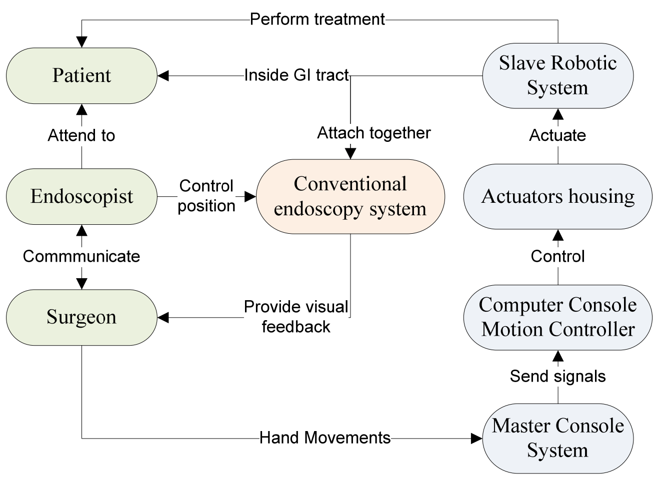

Figure 1: System Architecture of MASTER

The robotic system consists of the slave robot, the actuator housing, the computer console and the master console to read in the user's intention. The various modules of MASTER are elaborated in the following sections

B. Slave Manipulator

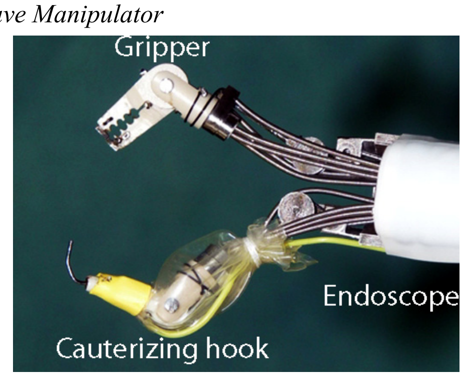

Figure 2: Slave Prototype

The prototype of the robotic slave manipulator can be seen together with the endoscope in Figure 2. It is a two-armed robot with a total of nine DOFs and with seven DOFs driven by tendon sheath actuation and two by direct drive. The left arm is in the form of a cauterizing hook while the right arm is a gripper to grip and manipulate the tissue of the patient. The configuration of the DOFs of the slave prototype can be seen in Figure 3.

Due to the high importance and involvement of the endoscopist in performing the therapeutic procedures, the slave manipulator is designed to ensure the endoscope can be handled and controlled as if no modification is made to the endoscope at all. Unlike other NOTES robot, the tendons and sheaths are small enough to be housed within the tool channels of the Olympus 2T160 endoscope. This removes the need of an external tube that contains the endoscope and reduces its steerability. It should be noted that the translating DOF slides within the interior feature of the slave manipulator and do not require an over tube. The exterior of the endoscope is just like any other endoscope and can be push or control as usual. The length of the tendons and sheaths are also purposely kept as long as two meters long to ensure there is less interference between actuation wires and the endoscopist. As such, the endoscopist can contributes and works with the surgeon in performing the necessary treatment with minimal adjustments.

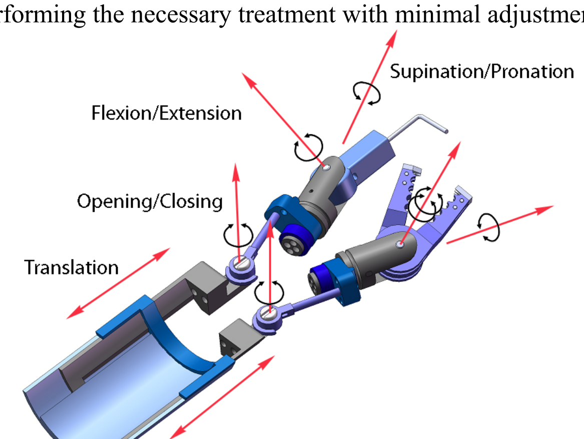

Figure 3: Configuration of DOFs for slave prototype

The slave manipulator has two joints that can perform bending motion namely the opening/closing joint and flexion/extension joint. These two DOFs allow the slave manipulator to have triangulation by making the arms spread out from the base with the opening and closing joint before the tip of the manipulator closes in with the flexion/extension joint. In this manner, the arms of the robotic manipulator do not block the view from the endoscope excessively and the condition of the environment can be clearly known by the surgeon. These two DOFs also allow the slave manipulator to straighten to the center of the endoscope and become relatively thinner when it is inserted into the patient. The size of the slave manipulator with the endoscope can go to as low as 16mm and it is small enough to go through a commercial overtube to access the stomach of the patient. This smaller size allows the whole system to be inserted and removed from the patient safely and with ease.

Other than the two joints, the slave manipulator also possesses translation as well as the supination/pronation joint. This makes it easier for the slave manipulator to orientate itself to perform the intended procedure.

The workspace generated from the DOFs of the slave manipulator is shown in Figure 4. The blue and red shell of the slave manipulator is formed by the motion range of the tip at the left and right arms respectively. It can be seen that the workspace, where the two arms can interact, cover a large part of view from the endoscope. With such design, the robot can perform a variety of complex tasks with minimal blockage of the camera view. The actual view from the endoscope can be seen in Figure 8.

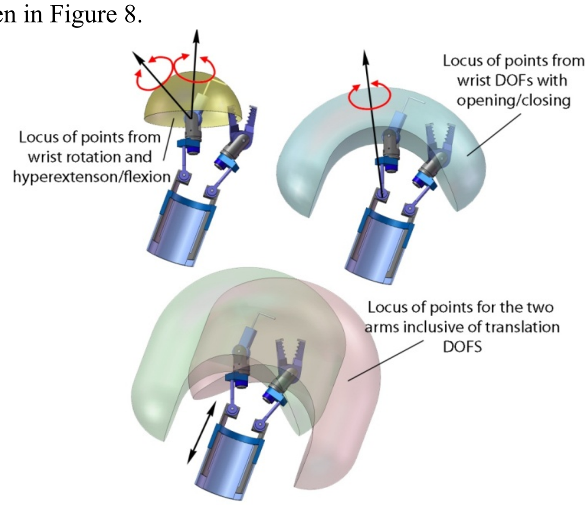

Figure 4: Workspace of prototype

The force that the joint exerts on the end effector is measured and can be seen in Table 1. The lowest force that can be generated is approximately 2.87N. This force is enough to hold and control the slippery and tough tissue during the procedure.

Joint Name	Force(N)
Opening/Closing	2.87
Rotation	3.29
End Effector	5.20

Table 1: Table showing the force of the joint at the end effector

C. *Actuator Housing*

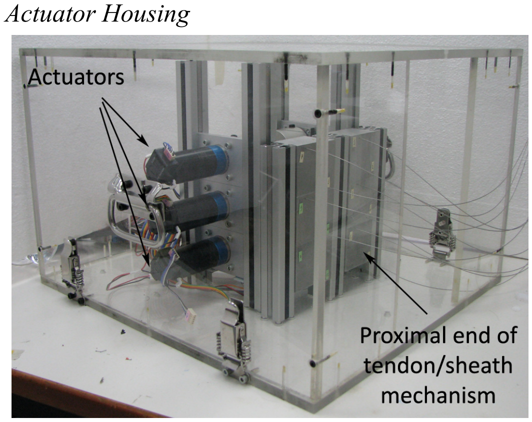

Figure 5: Actuator housing

The actuator housing is the interface between the actuators and the slave manipulator. The actuator housing consists of three components: the front plates for securing the sheaths, the side plates for securing the actuators and the rotating drums to secure and control the tendons. As shown in Figure 5, the plates are fixed onto a plastic plate by aluminum profiles. The actuator housing is designed to house the actuators together in a tight configuration to save space used in the operating theater as well as ease for transportation. Meanwhile each actuator is secured to a single module that can be removed from the housing separately and allow easy assembly or troubleshooting. Due to the small size, it can be positioned on top of trolleys and occupies little space in the operating theater.

D. *Master Console*

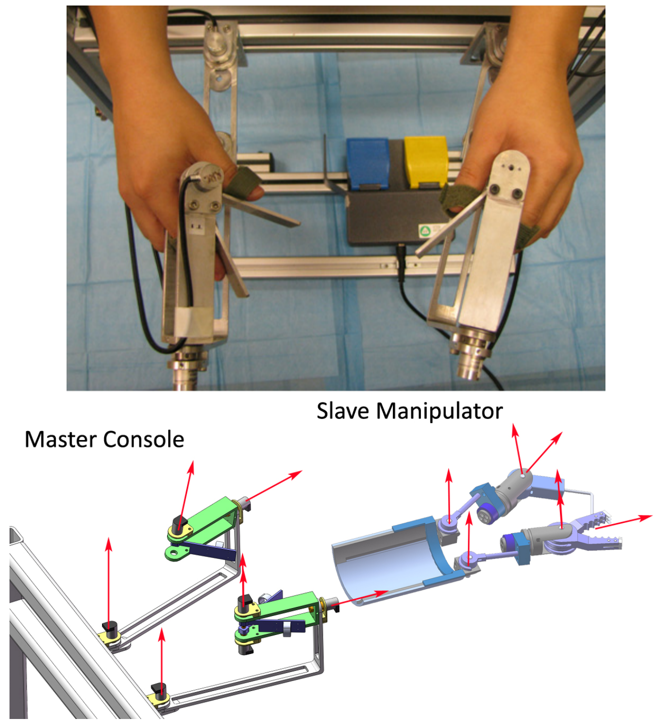

Figure 6: Master console

The master console is shown in Figure 6. This module of the robotic system reads in the surgeon's movement and interprets these signals to actuate the slave manipulator. It can be visualized as a multi DOFs joystick that maps the movement of the user to the end effector. The length of each link is adjustable to accommodate to the size of different users. For the translating DOF, it is controlled manually by the endoscopist by pushing and pulling the sheaths and therefore it is not reflected in the maser console.

The cauterizing or coagulating of the hook is controlled by pedals at the base of the master console. This makes it easy for the surgeon to perform coagulation and cauterizing without removing his hand from the handle. The overall size of the master console is small and only takes up approximately 30cm by 60 cm by 100cm in the operating theater.

E. *Computer Console*

Computer Console consists of a high-speed computer, motion controller and motor amplifier. The surgeon's hand movements are tracked by the encoder and sent to the computer for analyzing and scaling. Then corresponding command are sent to the electrical housing which contains the motion controller and motor amplifier, to control the actuator. These in turn drive the slave manipulator to move in the desired manner.

III. Results

Using MASTER, 15 *ex vivo* and 5 *in vivo* animal trials have been performed for ESD (Endoscopic Submucosal Dissection). The robot had also performed two *in vivo* liver wedge resection on animals through NOTES.

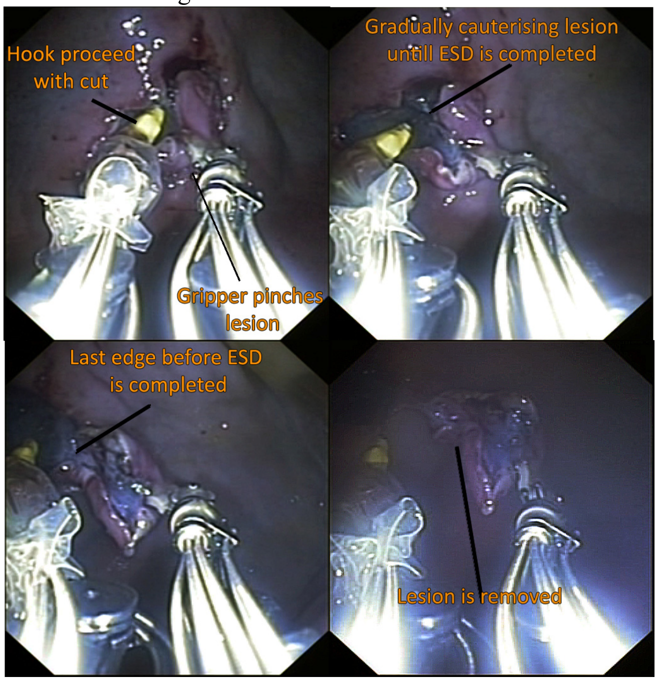

Figure 7: The view from the endoscope as it performed ESD

To allow the endoscope and the robotic system to be inserted with ease, an overtube has to be first inserted through the esophagus. The overtube also protects the patient from unintentional scratching by the slave manipulator. Some of the images captured from the endoscope during a real ESD trial are given in Figure 7.

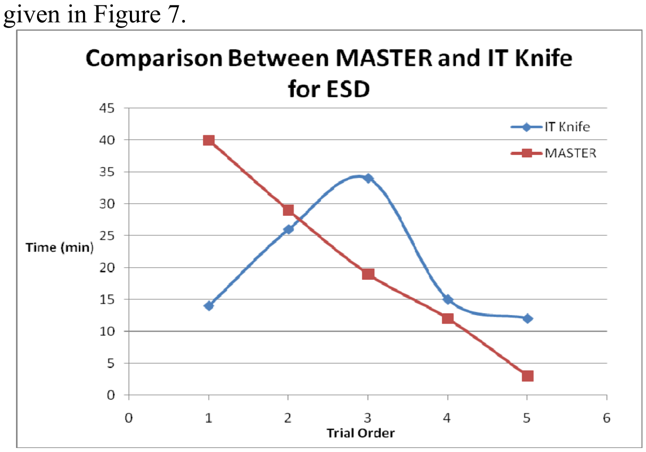

Figure 8: Comparison of time for ESD between MASTER and IT knife

For the 5 *in vivo* animal trials, the time taken by the robot to perform the procedure is compared with a conventional tool in the same animal. Two sites with approximately equivalent sizes are first marked on the animal stomach. For one of the site, it is removed with MASTER while the other one is removed with the IT knife from Olympus. The results from the 5 in vivo trials can be seen in Figure 8. Other important factors such as the perforations of the stomach, size is of the lesion, intactness of the tissue removed were also taken into considerations.

Initially the time taken using MASTER is longer than the time taken using conventional tool. However gradually with more trials, the effective time in performing ESD using MASTER is reduced to about 3 minutes in the fifth live animal. This result shows a relatively short learning curve for using MASTER and the potential of the robot in performing complicated surgeries such as ESD.

The robotic system also performed two transgastric liver wedge resections. First the robot performed gastrotomy and incised a hole through the stomach to the peritoneal cavity. The endoscopist then controls the endoscope to reach the desired site to perform the liver wedge resection. The grippers of the robot then hold onto the edge of the liver to provide tissue tension while the cauterizing hook proceeded with cutting out a piece of the liver. The liver resection process took approximately 9 minutes for the two *in vivo* animal trials. The dimensions of the liver pieces taken out are shown in Table 2.

	Time (mins)	Length (mm)	Width (mm)
Pig 4 (Robotic)	8.5	21	10
Pig 5 (Robotic)	8.2	14	8

Table 2: Timings taken for NOTES (Liver Wedge Resection)

Currently the robot is cleaned and sterilized before it is reused for another trial. In future it is foreseeable that the end effectors are disposable after a single use. Tentatively the slave manipulator is not designed for suturing and therefore the wound closure is performed with conventional tools such as the haemoclips.

IV. Conclusion

In this paper, the robotic system "MASTER" is presented. Multiple ESDs and even liver wedge resections have been successfully completed with MASTER. The results are compared with the conventional tools and it shows that MASTER has a fast learning curve can significantly reduce the operating time to complete ESD. This demonstrates the potential of our system in other application of NOTES.

For the future works, we will introduce haptics into our system to provide more feedback to the surgeons. It is also our objective to perform more complicated NOTES procedures like cholecystectomy and splenectomy with MASTER in future.

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