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Master-Slave Robotic System for Therapeutic Gastrointestinal Endoscopic Procedures

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Abstract— **Flexible endoscopy is used to inspect and treat disorders of the gastrointestinal (GI) tract without the need for creating an artificial opening on the patient's body. Simple surgical procedures (like polypectomy and biopsy) can be performed by introducing a flexible tool via a working channel to reach the site of interest at the distal end. More technically demanding surgical procedures like hemostasis for arterial bleeding, or suturing to mend a perforation cannot be effectively achieved with flexible endoscopy. The proposed robotic system enables the endoscopist to perform technically demanding therapeutic procedures (currently possible only with open surgery) in conjunction with conventional flexible endoscopes. The robotic system consists of a master console and a slave. The latter is a cable driven flexible robotic manipulator that can be inserted into tool channel of existing endoscopes or attached in tandem to the endosopes. Together with the real time endoscopic view, the endoscopist would be capable of performing more intricate and difficult surgical procedures.**

Keywords— surgery, robotics, master-slave, endoscope

I. INTRODUCTION

Flexible endoscopy is used to inspect and treat disorders of the gastrointestinal (GI) tract without the need for creating an artificial opening on the patient's body [1]. The endoscope is introduced via the mouth or anus into the upper or lower GI tracts respectively. A miniature camera at the distal end captures images of the GI wall that help the clinician in his/her diagnosis of the GI diseases. Simple surgical procedures (like polypectomy and biopsy) can be performed by introducing a flexible tool via a working channel to reach the site of interest at the distal end. The types of procedures that can be performed in this manner are limited by the lack of maneuverability of the tool. More technically demanding surgical procedures like hemostasis for arterial bleeding, suturing to mend a perforation, fundoplication for gastrooesophageal reflux cannot be effectively achieved with flexible endoscopy. These procedures are often presently being performed under opened or laparoscopic surgeries.

With the invention of medical robots like the Da Vinci [2] surgical systems, clinicians are now able to maneuver surgical tools accurately and easily within the human body [3]. Operating from a master console, the clinician is able to control the movements of laparoscopic surgical tools real time. These tools (also known as the slaves) are designed with sufficient degrees of freedom to move according to the natural hand and wrist motion allowing the clinician to perform intricate procedures with minimal technical difficulties.

Thus far, master-slave surgical robotic systems like Zeus and Da Vinci are either completely rigid or do not have a significant length of flexible body [4]. The slave manipulators enter the human body by means of incisions on the body. In this paper, we propose a robotic system with flexible slave manipulators that could be attached directly to flexible endoscopes. Similar to a conventional flexible endoscopic procedure (e.g. gastroscopy), the 'robotic endoscope' bundle could negotiate the curves and bends in the GI to reach the desired position within the gut. This system empowers the surgeons to perform more difficult surgeries that are otherwise impossible with the conventional endoscopic tool.

II. OVERALL ROBOTIC SYSTEM

Figure 1 shows the proposed system layout whereby the endoscopist work on the master console while gathering visual feedback from the endoscope. A computer console will interpret the readings from the master console that will in turn give instruction to the slave robotic system to perform the treatment to the patient. This system allows complicated treatment to be performed with the added benefit of easy and intuitive control for the endoscopist.

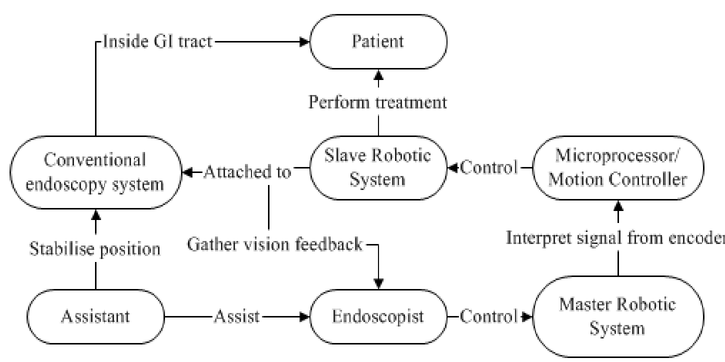

Figure 1. Proposed System Layout

III. THE SLAVE MANIPULATOR

The 3D model of the intended slave manipulator can be seen in Fig 2. In order for the surgeon to perform the necessary dexterous actions, the slave manipulators should possess a high number of Degrees of Freedom (DOF). The emphasis of the project is to make the slave manipulator to be as intuitive to control as possible. As such, the DOF and joints of the slave manipulator are modeled after a simplified human arm as shown in Fig 3. Altogether there are 5 DOF for positioning of the slave and an extra DOF for manipulating the end effector and the axis or rotation. Two slave manipulators are used instead of one since it can perform actions such as pulling and cutting of polyps or suturing bleeding sites. Furthermore two slave manipulators are more intuitive to use since they resemble the two human arms.

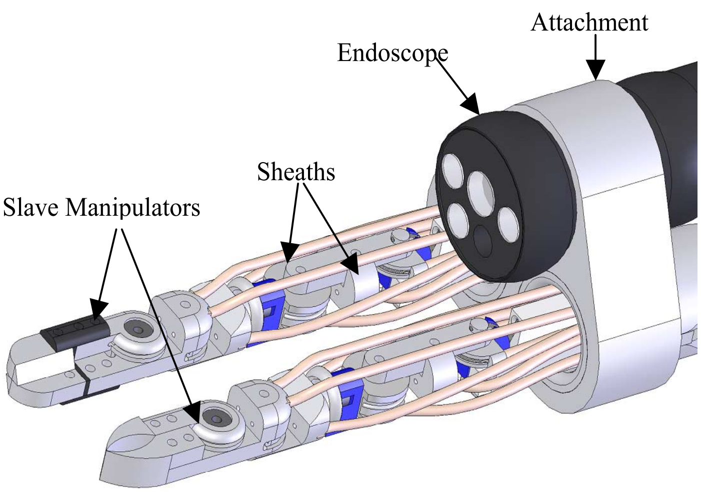

Figure 2. 3D model of slave manipulators attached with the endoscope

In order for the slave manipulator to be able to go through human GI tract, the slave manipulator has to be small yet flexible. Due to this unique requirement, tendon-sheath actuation is used. The prime movers are located outside the human body and it transmits power to the mechanism by pulling and releasing tendons in a sheath accordingly.

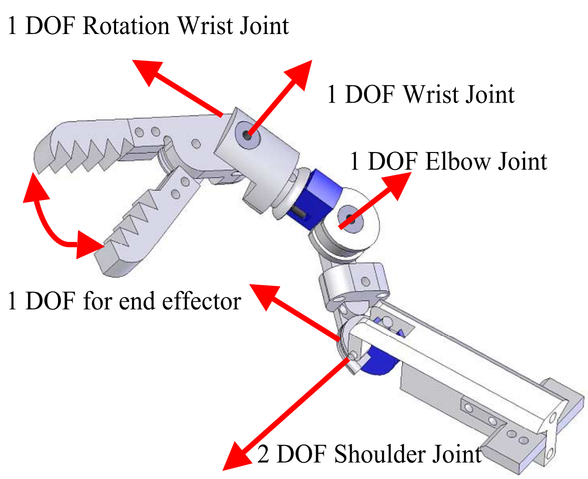

Figure 3. The degrees of freedom for one arm of the slave manipulator

The design of the mechanism is such that the two antagonistic tendons that control each DOF motion are independently actuated by one DC motor. In addition, the rotational displacement of each joint is directly proportional to the linear displacements of the tendon. These characteristics allow the serial slave manipulator to be controlled more easily. With the help of the software, the manipulator will not face singularity conditions in the prescribed range of motion for the manipulators.

Different types of end effectors have been designed to perform different types of actions during surgery. One of the tools includes electrodes that can perform monopolar cauterizing. The picture of the current developed prototype can be seen in Figure 4. Take note that the attachment that held the endoscope and manipulators is not fixed to the current prototype yet.

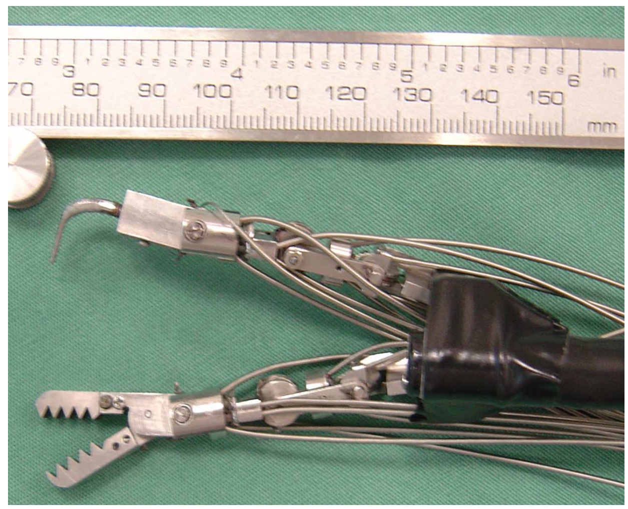

Figure 4. Picture of the current slave robotic system

To pass the endoscope and slave system to the desired site of the GI tract, an overtube can be used. Currently the size of the whole slave manipulator is approximately 25mm in diameter. Future developments will be on the miniaturizing of the slave manipulator till it is comfortable to be used on human beings.

IV. The Master Controller System

The ergonomic master device is built as a 6 DOF structure to control the 6 DOF slave mechanism. As the slave manipulators resemble the human arms, the anthropomorphic data of the surgeon's arm is used as the control parameters in order to give the surgeon better perception in performing the joint-to-joint control of the slave.

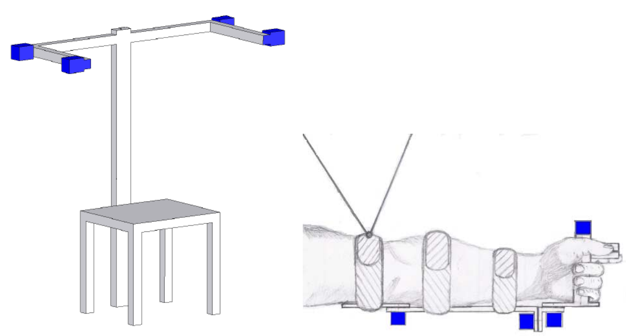

Figure 5. The whole schematic of the master setup (a) frame with two cable sensors for each arm (b) left arm with sensors attached

The schematic of the master controller is shown in Fig. 4. Two cable-actuated position sensors are used to measure the two contributing rotations of the shoulder joint that cause the up-down and in-out movement of the upper arm. Two optical rotary encoders are used to measure the flexion and supination-pronation movement of the elbow joint. Another similar encoder is used for flexion-hyperextension movement of the wrist, and the finger grip comes with an encoder inside the holder.

A virtual plane is formed using the reference of the shoulder joint with the two position sensors. The sensor locations can be modified to meet the required workspace that lies on one side of the plane. For the full range upper arm movement, additional sensor will be needed. As the comfortable workspace for the surgeon's upper arm lies in a quarter of a spherical space, two position sensors is sufficient to get the anthropomorphic data of one arm in that range.

The position sensors are located in such a way that the cables do not impose any disturbance on the surgeon's vision and movement. Furthermore the tensions of the cables facilitate the surgeon as a counterweight from his own arm moments, reducing the fatigue.

Assuming that the shoulder joint to be a ball and socket type, the point of cable-attached upper arm is determined by three spheres formed by upper arm length and two cable lengths. In Fig. 6, L_1 and L_2 are the two cable lengths and L_3 is the upper arm length.

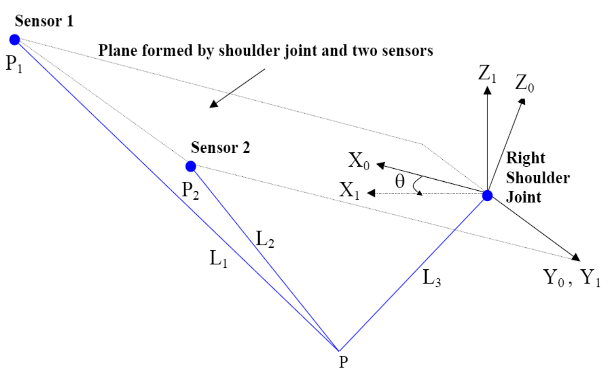

Figure 6. The location of cable-attached upper arm in two coordinate systems

In $X_0Y_0Z_0$ coordinate system,

$$\left({}^0P_x - {}^0P_{1x}\right)^2 + \left({}^0P_y - {}^0P_{1y}\right)^2 + \left({}^0P_z\right)^2 = L_1^2 \quad (1)$$

$$\left({}^0P_x - {}^0P_{2x}\right)^2 + \left({}^0P_y - {}^0P_{2y}\right)^2 + \left({}^0P_z\right)^2 = L_2^2 \quad (2)$$

$$\left({}^0P_x\right)^2 + \left({}^0P_y\right)^2 + \left({}^0P_z\right)^2 = L_3^2 \quad (3)$$

The point ${}^0P(x,y,z)$ below the plane can be solved from above equations and it can be transformed into $X_1Y_1Z_1$ by rotation matrix about Y-axis.

$$\begin{Bmatrix} {}^1P_x \\ {}^1P_y \\ {}^1P_z \end{Bmatrix} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{Bmatrix} {}^0P_x \\ {}^0P_y \\ {}^0P_z \end{Bmatrix} \quad (4)$$

${}^1P(x,y,z)$ can be used to calculate the shoulder joint up-down and in-out angles.

The mobility range of the master is constrained only at the upper arm by the virtual plane formed by the shoulder joint and two cable sensors. The other joints accommodate the full range of motion of the surgeon.

V. Software Control

A dedicated computer software is programmed to control and interface the slave and master robotic system. First it takes in real time readings from each encoder of the master device to determine the motion geenrated out by the user. This data is processed and appropriate signals are sent out to actuate the respective motors to bring about the required movements of the slave. The system framework adopts a 2-layer architecture. The bottom layer is the hardware control module that uses low-level drivers for hardware control. The top-layer modules are the kernel algorithms, which perform the signal processing to compensate for backlash and noise disturbances (more details in Section 7).

VI. Preliminary Experiment

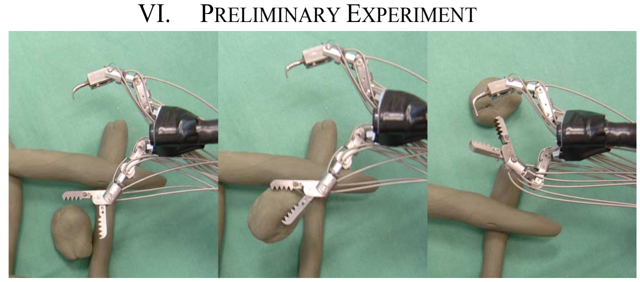

Figure 7. Using the robotic system for pick and place tasks

In vitro experiments with the master-slave system have been conducted in carrying out some tasks. By manipulating the master, users are able to manipulate the slave to carry out pick and place action as well as grabbing and cutting a soft object. In future animal trials will be conducted to verify its functionality. During experimentation, it is found that the mechanism is capable of producing at least 0.8N for each DOF.

VII. Discussion

One of the biggest problems in the tendon-sheath driving robot system control is the nonlinear characteristic due to the friction between the tendon and sheath [5]. As a result, delays and movement hysteresis are noticeable and can be seen in the below relationship

$$\delta(L) = \frac{T_0 L}{EA}\frac{\exp(\lambda) - \lambda - 1}{\lambda} \quad (5)$$

Where T_0 is tendon-pretension, L is the length of the tendon-sheath, E is Young's modulus, A is the cross section area of tendon, λ is a non-dimensional parameter and indicates the total friction force acting on the tendon under unit tendon-tension [2]. We can regard $\delta (L)$ as a kind of backlash for the tendon-sheath driving system. For any tendon-sheath driving system, L, E and A can be considered as constant. λ can also be considered as a constant if the curve of the tendon-sheath does not vary much. From (5), the backlash length is only a function of the cable tension T_0. To improve the performance of the system, a pretension device is introduced so that the tendon is always in tension. The modified mechanism from [6] can also minimize the problem of wire elongation after repeated use.

The pretension is set in such a way that the tension change during robot movement is trivial compare to the pretension, so that backlash length $\delta (L)$ can be considered as a constant.

To further reduce the movement delay of the slave the software will record the movement of each slave joint, whenever a direction change is detected, additional actuator displacement is used to compensate for the backlash. Experiments have been designed and performed to obtain the appropriate backlash compensation displacement for each joint. Using this method the delay of the slave can be reduced by up to 0.5 second. The system can be improved in future with the modelling of the system as well as making use of force sensors on the slave robot.

VIII. CONCLUSION

A master slave robotic system that can enhance gastrointestinal endoscopic procedure has been designed and built. The developed slave robotic system consists of a long and flexible body that allows it to follow the endoscope through the human natural orifice. This characteristic has the potential to allow treatment such as suturing to be performed on the patient without the need of any incision. A user was able to apply the master-slave system to perform tasks such as grabbing and cutting as well as pick and place. Future animal trials are planned using the developed system.

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