Analysis and control of tendon-sheath actuation mechanism for a novel surgical robotic system

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ANALYSIS AND CONTROL OF TENDON-SHEATH ACTUATION MECHANISM FOR A NOVEL SURGICAL ROBOTIC SYSTEM

LOW SOON CHIANG

School of Mechanical and Aerospace Engineering

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Abstract

Current endoscopic tools are inserted along the body of a flexible endoscope to access the tissue of interest in the patient. Actuated manually by wire ropes at the proximal end, the tool is able to perform simple grasping and cutting tasks. However, these tools possess low number of Degrees of Freedom (DOF) and thus lack the dexterity and maneuverability to perform complicated tasks, like retraction and suturing of tissue, which are required in Natural Orifice Transluminal Endoscopic Surgery (NOTES) and Endoscopic Submucosal Dissection (ESD). A multi DOFs master and slave robotic system is therefore envisaged to better assist the endoscopist in performing these complicated procedures.

It is a requirement that the slave manipulator passes through a long, narrow and flexible channel of the endoscope to reach the distal end. Furthermore, due to size constraints, it would be appropriate to house the actuators at the proximal end which is situated outside the patient. As such, the tendon sheath actuation has been proposed for this application. However, shape dependent friction between the tendon and sheath results in undesirable characteristics such as loss of force, backlash, hysteresis and non linearity. For effective closed loop control of the proposed system, issues such as implementation of position control and haptics feedback have to be resolved. It is desired to find the end effector force and elongation of the tendon to control the system but it is not feasible to affix sensors at the end effector due to size constraint, practicability and sterilization issues.

It was proposed to utilize the knowledge of the force and position at the proximal end to perceive the distal end force and elongation of the tendon sheath. To realize this, theoretical analysis was conducted to find relations of parameters between the distal and

proximal ends of a tendon sheath. Using the analysis, new models and parameters for the effective coefficient of friction and elongation were established for the various phases of actuation. The hypotheses were tested with experiments and results showed an accuracy of 7% full scale error. Since there is a limit on the sensitivity of human perception, this error is low enough for the master slave application. This model estimates the distal end force and elongation of tendon sheath actuation with sensors situated only at the proximal end regardless of the shape of the sheath. This result is achievable provided the system has been initialized, the shape of the sheath remains constant and buckling of the sheath is restrained. The development of this novel model constitutes the academic achievement of this thesis.

Designs issues for the prototype such as the configuration of DOFs, the types of mechanism, maximizing the force to size ratio as well as considerations when used with the endoscope were studied. Based on these studies and the theoretical model of the tendon sheath mechanism, a two-armed, nine DOFs robotic prototype with a maximum force output of 5.2 N has been developed for NOTES and ESD. This robot has performed fifteen *ex vivo* and five *in vivo* animal trials for ESD as well as two *in vivo* animal trials for NOTES. The experimental results showed the time for performing ESD was reduced from a mean of 73 minutes to 23 minutes. No perforation of the stomach wall was observed and lesions were maintained as single pieces.

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Chapter 1 : Introduction

1.1: Background

Figure 1.1: Moving of the endoscope through the Gastrointestinal (GI) Tract [1]

An important breakthrough in the medical field is the invention of the flexible endoscope. Basically it allowed doctors to see the interior of the Gastrointestinal (GI) tract in the human body without the need of any incision. This is possible because fiber optics and miniature camera can be mounted onto a thin, long and flexible tube that can move along the winding passages of the human's natural orifice. The imaging devices on the flexible tube are able to light up the interior of the body, capture the images inside the patients' body and display it onto conventional television or monitor. This invention enables surgeons and doctors to monitor the interior of the patients' body in a reliable, safe, fast and non invasive manner. [2]. The side effect and risk of complication is so low that doctors recommend elder patients to get regular preventive checkup on their GI tract using endoscopy. The advancement in optics also opens up the possibility of Minimally Invasive Surgery (MIS) where more complicated procedures can be performed with small incisions made on the abdominal.

One particular type of endoscope for monitoring the stomach, throat and large intestine is the Gastro-Intestinal endoscope. This flexible endoscope can be used to inspect, diagnose and treat various pathologies in the upper or lower GI tract. A typical endoscope includes an ultra compact Charged-Coupled Device (CCD) camera, light source and a channel for infusing or withdrawing liquid or gas from the patient's body [3]. The tip of the endoscope is also steerable so that the endoscope is able to transverse through the winding channel of the GI tract faster, safer and giving less pain to the patient.

Figure 1.2: Olympus Gastrointestinal scope GIF-2T160 [3]

Another feature of the endoscope is providing tool channels for instruments to go through. At any time during the examination of the GI tract, endoscopists have the option of inserting tools or instruments from the proximal end of the tool channel that exit from the tool channel at the distal end and perform simple tasks and treatments. Nowadays, there are many commercially available tools that can perform a variety of treatments such as biopsy, polypectomy, stone removal, marking, haemostasis, injections etc [4]. The tools available are often simple one Degree of Freedom (DOF) devices mostly providing either grasping or controlling a steel wire in treating patients. When faced with a serious medical complication in the GI tract such as GI bleeding or Endoscopic Submucosal Dissection (ESD), existing endoscopic tools lack the dexterity to perform the treatments safely and reliably.

With the invention of the flexible endoscope, Natural Orifice Transluminal Endoscopic Surgery (NOTES) has become possible. 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 and perform an intra-abdominal operation [5]. In the abdominal cavity, the endoscope locates another internal organ that requires treatment and then proceeds with the necessary procedure. Lastly when the treatment is completed, the endoscope returns to the natural orifice, mends back the incision made before being taken out of the patient body.

Figure 1.3: Simplified diagram on NOTES procedure [6]

The advantages of using NOTES are many. Firstly there is a reduced risk of infection since the stomach is generally more antiseptic compared with the outside environment. Secondly, the stomach heals more quickly since it composes of the fastest growing cells in the human body. NOTES also allows the use of minimally invasive techniques to be used on obese patient whose abdominal wall is too thick to perform laparoscopy. Lastly and most importantly, it does not requires any incisions on the abdominal wall, thereby reducing pain, wound infections, cosmetics and speeding recovery [7].

However for NOTES to be used on human safely, many technical issues need to be addressed. In the white paper set by the leaders of American Society of Gastrointestinal Endoscopy and Society of American Gastrointestinal and Endoscopic Surgeons [8], some of the challenges and physical constraints are listed. A particular concern that is emphasis heavily is to close the incision at the gastric or intestinal site safely, securely and consistently. Presently many devices have been

developed to close back the wound made to the natural orifices but these methods are not safe, secure and consistent enough to use NOTES on the grand scale. Many experts felt that the ability for the endoscope to perform suturing is paramount since it is simple, reliable and do not have mechanical failure compared with other alternatives. If incision fails to be closed securely, it could lead to death. Currently, there is no commercialized product capable of performing suturing or other complicated procedures using existing devices.

1.2: Motivation

Figure 1.4: Artist impression on the master slave robotic system

As mentioned in the previous section, there is a limitation on the current tools for use with the endoscope. Although simple tasks can be performed with the available tools now, many important maneuvers for manipulating tissue are still impossible. For example, aggressive grasping of the tissue to expose and cut the tissue simultaneously is tentatively improbable with the tools available [8]. To perform suturing with the present commercial tools is also inconceivable.

An innovative solution is to develop a multi DOFs master-slave robotic system for use with the endoscope. The slave manipulator is fixed to the endoscope and it is small and flexible enough to be carried along with the flexible endoscope to perform technically demanding surgical procedures such as suturing and cutting. The movements of the slave manipulator are controlled by the surgeon handling the master console.

A benefit of using the robotic system compared with conventional methods is that it can retract the tissue out with the gripper before the hook cauterize. Due to the triangulation of the two arms as well as the ability to expose and cut the flesh, it offers a better vision for the surgeon in performing complicated operations. This is unlike the traditional method of using a cauterizing knife and poking it blindly into the lesion during ESD. Generally only experienced and qualified endoscopists perform ESD due to the difficulties and risks of the procedure. With the use of this robotic system, an endoscopist with lesser experiences can successfully perform the procedure in a safer, easier and faster manner. This not only has the potential to better treat the patients with ailments of the GI tract, it could also be used in NOTES setting as well.

However, in order for it to be ultimately used on human, the system not only has to work, it has to work well. The user must be fully aware of the environment and fully in control of the robotic system in order to realize the robot's full potential. To achieve this, it is necessary to sense the position of the end effector. Knowing this parameter makes it possible for the movement made to the master robot to have a desired relationship with the movement made by the slave robot. Otherwise the movements made by the slave would have backlash, non linear characteristics and hysteresis resulting in difficulty of control.

Another important parameter to be determined is sensing of the force at the end effectors. If this is known, force feedback to the surgeon could be achieved. Due to the limited depth perception from the endoscope, additional information during the procedure could aid the surgeon's judgment and results in a safer procedure. According to Wagner etc [9], the overall force applied on the human tissue and incursion into other sensitive tissue and structure reduces significantly with the use of force feedback. This results in a substantial reduction on the overall damage to the tissue.

If both position and end effector force are known, it could bring about easier, faster and safer manipulation during the surgery. Such a system in place could bring about a great step forward in GI therapeutic procedures and NOTES. In the future, such

robot assisted surgeries may replace many procedures which could only be performed in open surgery or MIS settings.

1.3: Objectives

The objectives of the PhD are separated into two areas. The first is to develop an approach to use the sensors at the proximal end to determine the distal end parameters while the second objective is the development of a master slave robot for ESD or NOTES. The following is an elaboration of these two main objectives.

- 1) To develop a possible means to predict the various parameters of the distal end by attaching sensors only at the proximal end.

Before embarking on the development of the robotic system, the problems associated with tendon sheath actuation have to be resolved. To build the proposed robot, long (approximately 2m) and slim (approximately 1mm outer diameter) tendons and sheaths have to be used. The tendons and sheaths thus face high friction between them and produce undesirable characteristics such as backlash, hysteresis and non linearity. This makes the distal end force as well as elongation of the tendon unknown. Due to the small size and flexibility of the slave manipulators, it is not possible to attach sensors at the end effector. This is because the size of the slave manipulator is less than 8mm in diameter, many sensors have to be used and it is difficult to sterilize these sensors for use on humans. Without the knowledge of these parameters, closed loop position control as well as force feedback cannot be achieved. Therefore the capability of sensing the parameters at the end effectors by utilizing sensors at the proximal end is critical for the robotic system. A good model of the tendon sheath system results in better safety and reliability when using the robotic system.

- 2) To develop a multi DOFs slave robotic system to perform ESD and NOTES.

There are limitations to the current conventional endoscopic tools that could be overcome by a multi DOFs master slave robotic system. Without robotic intervention, conventional ESD remains to be a difficult and time consuming procedure to perform with a high risk that could cause death. NOTES, a new surgical procedure, remains to be unviable due to the many challenges and limitations of

current conventional systems. Thus there is a motivation for the development of a robotic system to accomplish these tasks efficiently and effectively. Tentatively the robotic system is tasked to perform aggressive grasping and cutting with two robotic arms. One of the arms grasps onto a piece of tissue and exposes the site while the other arm does the cauterizing. This action is a step above the currently available tools and could be used for many procedures such as ESD and some form of NOTES.

1.4: Scope

On the distal end force and position estimation, the scope is limited to the use of tendon sheath actuation. The assumptions used for the estimation are based on the environment which the robot experiences during GI tract operation or NOTES procedure.

The estimation of the parameters is only considered when the sheaths do not experience extensive buckling. This is because the friction between the tendon and sheath increases tremendously and further pulling of the tendon at the proximal end fails to increase the distal end force significantly. Furthermore at this stage, the tendon sheath system is also more prone to failure.

The developmental contributions do not include the design of the master device, its requirements as well as how force feedback is provided to the human operator. This work is performed by another researcher working on the project and is therefore out of scope for the author of this thesis.

The robotic system trials is only limited to animals and not human. Only when the system reaches a high state of robustness, reliability and sterility, can the system be used on human beings. The desired task is to perform grasping, retracting and cutting actions which are required in many surgical procedures.

The robotic system is tentatively used on the gastrointestinal tract only. Although it is possible for the system to be used through other entry sites such as the vaginal, it is currently not within consideration in this report.

1.5: Organization of Report

The report contains seven chapters in total. They are organized as follows.

Chapter 1 introduces the background and motivation of this project. The objectives and scopes are also outlined along with the organization of the report.

Chapter 2 gives a literature review for the project. It consists of four main sections: robots for NOTES and surgery, endoscope and its treatment, the gastrointestinal tract and the DOFs for the human arm.

Chapter 3 describes the system architecture for the system. The design requirements, the brief description on tendon sheath actuation as well as the selection and criteria for the tendon and sheath are given in this chapter.

Chapter 4 described the theoretical modeling of the tendon sheath actuation for the distal end parameters prediction. Modeling is based on tendon and sheath with a fixed shape as well as a generic sheath of any shape. The experimental setup, initialization and the experimental results are also provided. In the discussion the limitation for the modeling and other potential applications are also given.

Chapter 5 discusses the different designs made for the system to fulfill the development objective of the project. It discusses the various designs possible as well as the evaluation for the components and the final prototype.

Chapter 6 The results for the use of the prototype in performing medical trials are given in this chapter. The procedures for the operations as well as timings for the trials are provided in the chapter. Overall 15 *ex vivo* and 5 *in vivo* animal trials have been performed for ESD and two *in vivo* trials for NOTES (Liver wedge resection)

Chapter 7 gives the current research progress and future works and conclusion for the project.

Chapter 2 : Literature Review

This chapter is the literature review for the robotic system and it is divided into four sections. In Section 2.1, a synopsis on the various surgical robots is given while Section 2.2 describes the endoscopes as well as the available treatments from it. The actual procedures for ESD and haemostasis are also provided in this section. Section 2.3 describes the gastrointestinal tract to understand the environment the robotic slave manipulator faces while in Section 2.4 the types and number of degree of freedom for the human arm is described. This study is important in order to build an anthropomorphic slave manipulator that is intuitive for human to control.

2.1: Robotic Surgical System

Figure 2.1: Schematics of the da Vinci surgical system ©[2008] Intuitive Surgical, Inc.

Robots had been widely used in many industries since 1970's. With the increasing advancement in computers, servomotors and sensors, robots are capable of performing more complicated tasks that cannot be achieved by men alone. In the late 1980's, the idea of using robots to perform surgery was conceived [10]. Using the industrial PUMA robot, the authors use it to position the fixture for the drills and

biopsy probes which are then inserted manually to the brain. However the idea of using robots for surgery gathers lukewarm response due to the general perception that robots should be operated away from human. [11]

Nowadays robots in the medical field come in all shapes, sizes and functions [12][13]. Robots are used for surgery [14], prosthesis [15] [16], surgery navigation systems [17][18], assistive robots [19], rehabilitation robot etc [20][21]. Due to the nature of the project, the focus on the literature review mainly focus on robots for NOTES as well as for MIS. The design and system overview of the surgical robots are also studied.

2.1.1: *Da Vinci Surgical System from Intuitive Surgical Inc*

**Figure 2.2: Patient side cart and different end effectors from the da Vinci surgical system
©[2008] Intuitive Surgical, Inc.**

The da Vinci surgical system is the first (1998) laparoscopic robot approved for use by the US Food and Drug Administration for use on more than 500 surgery procedures. More than 210 da Vinci systems had been used clinically throughout the world.

The da Vinci robot manipulator provides the seven DOFs (six DOFs for the positioning and orientation of the end effectors, one DOF for grasping) necessary for intuitive manipulation of the tool instrument. Since the slave manipulator has only four DOFs after passing through the incision, a two DOFs wrist is located at the distal end of the manipulator to restore its mobility [22]. The rest of the four DOFs actuation is provided from the patient cart of the robot. The slave manipulator made use of multiple wires for its actuation at the distal end of the manipulator. Due to the links of the slave manipulator being rigid and straight, most of the actuation is achieved with the use of tendon routing.

Intuitive Surgical provides many interchangeable end effectors that can pass through an incision as small as 6mm wide. The end effectors also contain sensors to provide basic force feedback to the surgeon [23]. This feature enables the surgeon to feel the resistance when the end effectors touch nearby tissue during the operation.

Figure 2.3: Design of one of its patented bending joint and gripper joint [23]

One of the joints that were patented by Intuitive was the bending mechanism that consists of multiple discs stacked together as shown in Figure 2.3a. The most distal disk is fixed to the end effector such as forceps. This design uses four or more wires to achieve bending of more than 90° but requires the device to bend in a relatively wider arc [24].

For the gripper that was patented by Intuitive, it made use of two wires to actuate each of its fingers. This not only allows the grippers to open the jaws up to 180° , it also gives the end effector another DOF similar to the flexion/hyperextension of the human wrist.

The da Vinci surgical system is one of the most famous commercially available surgical robots. However it is only used for laparoscopy where keyholes have to be cut into the human body to allow the end effector to work on the human body. It is not possible for it to be used in a NOTES or endoscopic settings since it is rigid and cannot follow the endoscope to travel through the winding human natural orifice.

This study however has similarities to the robot for NOTES and ESD and therefore was studied to learn about its strength and weaknesses.

Another complaint about the da Vinci surgical system is that it is too bulky, heavy and requires too much time to set up the system before it can be used. These problems make it less attractive to be used by surgeon during laparoscopy.

2.1.2: *Hyper Fingers Robotic System*

Figure 2.4: Master and slave robot of Hyper Fingers [25]

The design of the da Vinci system resembles the DOFS of the human wrist and the master system is designed to capture the motion of the human hand. Another type of design for the surgical robot resembles more of a snake than the hand. To control the slave manipulator, the user manipulates the master robot that is shaped like a pen.

This surgical slave manipulator developed by the Nagoya University in Japan has nine DOFs at the distal end [19]. The slave manipulator made use of four two-DOFs joints to make the slave bendable and capable to be able to perform surgeries at hard to reach sites. One of the key differences between the da Vinci system and the hyper finger system is that in the latter, all the DOFs are located at the end effector and none are at the base. Due to this reason, it is possible for it to be light and small enough to be mounted on a camera stand [26][25].

One of the most important joints in this robotic system is the two DOFs rotation joint at the end effector. It made use of a decoupled ring joint system as shown in Figure 2.5 that uses two wires to control each DOF. Since each axis and the corresponding wire-connecting points are located in the same plane, the DOF can be controlled independently from one another. This allows the joints to rotate independently at each axis thus making control easier and more effective. Moreover, the friction loss of the wire is very small due to the joint giving no folding effects onto the wire.

Figure 2.5: Decoupled ring joint design from Hyper Fingers [26]

For the gripper design of the manipulator, the mechanism shown in Figure 2.6 is used. A benefit of this gripper is that it needs only one wire to actuate the opening and closing of the jaws. In this design, the gripper can open up to 50° wide. However the total length of the gripper mechanism is long and the force it can grip is low, which makes it difficult for the surgeon to use.

Figure 2.6: Gripper of Hyper Fingers [26]

Similar to the da Vinci surgical system, this robot is meant for laparoscopy and cannot be used for NOTES or endoscopic procedure. However its design on the joints can be studied for possible applications in the project.

2.1.3: *ViaCath Robotic System*

Figure 2.7: The ViaCath robotic system [27]

So far, all the robots that were mentioned are used to perform MIS surgery. Tentatively, robots designed for use in NOTES can also be seen in the last two years. One of the robots for NOTES is the ViaCath robot [27]. It made use of a lot of hardware from a previous robot for laparoscopy, the Laprotek [28]. The attachment of the robotic arms to the endoscope can be seen in Figure 2.7. Basically the endoscope is attached with another carrier that also allowed the slave manipulators to go through.

Figure 2.8: Design of the slave manipulator of ViaCath [27]

The system consists of two 7 DOFs robotic arms with interchangeable tool tips. If the rotation and translation from the outside of the tube is included, the overall number of DOFs is nine. The design for the joint 4-6 can be seen Figure 2.9. The motion range of the joint 4-5 is approximately $\pm 40^\circ$.

Figure 2.9: Design of the joint in ViaCath [27]

Some of the flaws reported are that the motion of a link in the proximal joints could affect the motion of the distal one. This is because the cables for controlling the distal joint have to go through the proximal joints and any change in the bending radius of the proximal joint also bends the controlling cables of the distal joint.

Although it is reported that the DOFs of the slave manipulator follow the human arm, the position of the DOFs in Figure 2.8 does not appear so. The uses of many links make the slave long and may result in poor vision from the endoscope. The strength of the robotic slave as well as any medical procedure that it had accomplished is not reported. Tentatively the project is still within the research phase.

2.1.4: Endosurgical Operating Platform

Figure 2.10: The TransPort endosurgical operating platform [29]

A tool that has the potential for use in NOTES is the Endosurgical Operating Platform. This robot is not about robotic arms or gripper but on the interface between the robotic arms and the endoscope. It consists of an 18mm [30] diameter tube with

multiple lumens for conventional endoscope and other tools to go through. Once the site of interest is reached, the shape of the tube can be locked in place, providing a stable platform for surgery [29].

One of the benefits of this new operating platform is the ability to withstand higher stiffness against the force from the surroundings. This enables it to have a more stable platform to perform NOTES or other form of surgery compared with the endoscope. It also houses unusually large tool channels for developers to put in unconventional tools through to the distal end. The conventional endoscope only has at most two tool channels each at most 3.8mm in outer diameter. Meanwhile the endosurgical operating platform has four tool channels, two having an outer diameter of 4mm while the other two have an outer diameter of 6mm. Since the endoscope can be rotated within the tool channel, the orientation of the vision can be adjusted to ensure a good view. The air pressure that this device can provide is also much higher than convectional endoscope. These features make it more suitable to conduct NOTES compared with just the endoscope.

However this operating platform is in essence just an improved overtube for the endoscope to work in NOTES environment. It does not provide the necessary tools to perform the actual procedures of NOTES.

2.2: Endoscopic Procedure

This section discusses the latest tools that are available for use with the endoscope. Due to the desire for the endoscope to be small, the size of the tool channel is fixed to be only a few millimeters in outer diameter. The tools developed to be used with the endoscope are therefore limited because they have to be very small. That is why 50 years after the invention of the modern endoscopy, there are still many ongoing researches to improve on the tools for it.

Due to the nature of the project, the focus of the review is on the possible tools and its procedure to solve for gastrointestinal bleeding and submucosal dissection of the GI tract.

2.2.1: *Tools for Endoscopic Submucosal Dissection (ESD)*

Figure 2.11: Procedure for submucosal dissection [31]

This procedure aims to remove tumors from the human GI tract with the aid of the endoscope. The area that is removed could be substantially large if the tumor is large or multiple tumors grow near to one another. It is remarked that the tumor can reach an area of 85 mm in diameter [31]. To remove such a big piece of tissue from the stomach is not easy using current endoscopic tools. Furthermore, it is desired for the whole tumor to be in one piece since it reduces the risk of recurrence and also the sample can provide a clearer histological assessment [32].

The current procedures used are similar to one another except that the tool can varies. In [31], a thin type snare is used while in [32] a modified knife shaped tip is used. After the lesion is detected, the endoscopist marks the surroundings of the lesion with a cauterizing tip. The markings ensure the location of the lesion is still known after the endoscopist injects a solution to separates the mucosal and muscle layers. A knife or a hard snare can then be used to slowly cut away the surroundings of the marked area. This process is difficult and tedious since the endoscopist has to go one full circle around the lesion to cut it out. The process of removing the flesh below the lesion is difficult because some part of the lesion is cut loose and it could hinders the movement of the tool or blocks the vision of the endoscope. During cutting, the

depth of cut must not be deep enough to cause perforation or bleeding of the stomach. Due to the difficulty, the mean time taken to perform the procedure is 78 minutes and it can get to be as long as 540 minutes [32]. Moreover, 6-7% of the operations resulted in bleeding at the site and secondary treatments such as haemostasis have to be performed.

This is a trial and tested method used extensively on the human body after years of operations on the human body. It is also the steps that the surgeons are trained and skilled in. Therefore the above procedure is largely adopted by the robotic system to perform ESD as well.

2.2.2: *Tools for Gastrointestinal Bleeding*

Gastrointestinal bleeding describes every form of hemorrhage (blood loss) from the pharynx to the rectum. It has many causes; some of the more prevalent ones are hemorrhagic esophagitis and esophago-gastric varices. The degree of bleeding can range from nearly undetectable to acute, massive and life-threatening bleeding. Gastrointestinal bleeding is a cause for hospitalization and can cause death to the patient if no prompt treatment is given. In the case of serious bleeding, immediate resuscitation to establish hemodynamic stability (stabilize blood pressure) and prompt intervention to control the bleeding is critical in saving the patients' lives. Successful treatment to bleeding not only should stop the bleeding but also prevent re-bleeding from the same site.

Haemoclips

One possible and popular means to stop GI bleeding is the use of haemoclips. It consists of a clip that can be detached and strongly compress the openings of the wound together so the bleeding can be stopped. After using the clip, it is not necessary to perform another endoscopy treatment to remove the clip since it dislodges itself automatically after three weeks. Its advantages include no prior preparations necessary and it does not damage the nearby tissue during its usage. However to manipulate and control the clip is difficulty since it had to be clipped onto the right location and orientation. There are cases whereby the haemoclips are unable to be applied properly due to the difficulty in positioning and orientating the

clips. This problem is elevated if the bleeding site is difficult to be approached from the endoscope. It is a frequent practice to use several clips simultaneously to stop the bleeding [33]. The picture from Figure 2.12 shows the stomach after polypectomy, when the haemoclips are attached and the same site four months later.

Figure 2.12: The procedure of using haemoclips [34][35]

Heat Probe

One of the oldest methods to stop bleeding is by the process of cauterizing. This process is where heat that destroys and seals the bleeding vessel is applied to the tissue. A typical usage of cauterizing is by using a monopolar or bipolar forceps which try to isolate the bleeding vessel before compressing and heating it. One obvious disadvantage of using this method is the associated pain and redundant tissue damage to the patient body.

Another popular method for hemostasis is injection therapy. Injection therapy involves the use of several different solutions such as epinephrine, sclerosants and clot-producing materials such as fibrin glue are injected into and around the bleeding lesion. Some experts believe solution such as epinephrine works by decreasing the diameter of blood vessel and decrease blood flow to the area. This results in an increase chance of clog formation, thus stopping the bleeding. Although this type of

treatment is the easiest to perform, this method is not reliable as it has a high rate of rebleeding.

A common approach to stop bleeding now is the use of a combination of injection followed by cauterizing to stop the bleeding. First epinephrine injection is administered to the patient to stop the bleeding and temporarily provides a clearer view of the bleeding site to the endoscopist. After which the endoscopist applies the heater probe to the appropriate area and permanently seals the vessel by cauterizing. Much study has been conducted on the result of using these two methods together and it was found to have significantly reduced the amount of rebleeding and need of surgical intervention in the patient. Due to the effectiveness of this combination method, companies have come out with instruments that can inject and heat the tissue at the same time without the need to change the tools. Based on studies for peptic ulcer bleeding, a properly applied hemoclip has a similar result on the heater probe and injection method. If the bleeding site is at difficult to approach sites, heater probe plus hypertonic saline injection is preferred [36]. Even so, the possibility of rebleeding is still high and it is less reliable compared with suturing.

Eagle Claw

Suturing is the preferred method of all surgeons for haemostasis but it is tentatively unachievable in endoscopic procedure. Therefore a device that can suture in an endoscopic environment can bring tremendous potential application. That is the motivation for the design of Eagle Claw that can perform suturing in tandem with the endoscope [37].

The design of Eagle Claws and the steps involved in the suturing can be seen from Figure 2.13. First, the Eagle Claws have to be carefully positioned in front of the site that needs to be stitched. Then the surgeon can actuate one jaw in the form of a crooked hook that pierces through the flesh where the suturing is intended. At the tip of the crooked hook a suturing thread is attached with it. The tip is then locked onto another device that secures the suturing thread to it. With the help of the endoscope, this device can pull the suturing thread tight before dislodging itself onto the flesh. In this manner suturing has been implemented without the need for tying the knot.

Figure 2.13: The procedure of suturing using the Eagle Claw [37]

As can be seen from Figure 2.13, the securing of the thread relies on a mechanical device that pulls and secures the thread. Strictly speaking it is also no longer considered to be a bona fide suture but instead resembles the haemoclip that is a mechanical closure device. Although the design and procedure for the Eagle Claw look impressive, technically it is more complicated, bigger, troublesome and unreliable means to stop bleeding compared with the conventional haemoclip.

g-Prox Tissue Grasper

Another design that makes use of suturing threads is from USGI Medical Corporation and is commercially available. The basic steps to suture are largely similar to the Eagle Claw [38][39].

Similarly the endoscopic grasper has to position itself at the necessary site where the suture should be made. After the grasper had gripped the flesh securely, an off-axis needle driver shoots out an anchor through this gripped tissue. After the anchor is through, it is then inflated to stop it from slipping through the punctured hole. The steps are repeated for the other end of the anchor at another site. After this, the thread

between the anchors is tightened and this result in the first and second anchors compresses tightly together and closes the wound.

Figure 2.14: The procedure of suturing for the g-Prox Grasper [38]

Again this is not suturing as understood by the surgeon but more of a mechanical stopping device. It is however claimed to be a better system than the Eagle Claws since it does not have to leave the operation site to refill another set of anchors. The anchors can be loaded from the proximal end of the endoscope whereas the Eagle Claws have to be reloaded from outside. The view and positioning from the g-Prox is also better since it is tilted at a 45° instead of requiring it to be perpendicular to the site of interest.

2.3: Gastrointestinal (GI) Tract

The Gastrointestinal (GI) tract is a continuous tube that extends from the mouth to the anus. In short, it is the passage in the human body where it has a direct contact with the food as it travels from just being consumed to excretion. It consists of organs such as the mouth, most of the pharynx, esophagus, stomach, small intestine, large intestine and anus as well as accessory organs such as liver, gallbladder and pancreas [40] [41]. The accessory organs never come into contact with the food itself but produce secretions that aid digestion.

Figure 2.15: Organs and accessory organs of the GI Tract ©[2005] Terese Winslow & US Gov

The focus of the study of the GI tract is on the esophagus, stomach and large intestine because these are the organs where the gastrointestinal scope is to be used on. A brief study on the pharynx is also included since the GI scope has to move through the pharynx to get to the other upper GI organs. The small intestine however is not included in the study since it is too small and too distant to be used with the GI endoscope. The studies emphasis on the size, shape and possible movement of these organs so as to get a picture on the possible workspace, number of bends as well as the environment that the endoscope and the robotic slave manipulator has to work on.

2.3.1: Pharynx

The pharynx, also commonly known as the throat, is a cone shaped tube about 12.5 cm long and broader in the transverse than in the antero-posterior diameter. Its greatest breadth is immediately below the base of the skull (5cm), where it projects on either side and its narrowest point is at its termination in the esophagus. As can be seen, there is a gradual 90° bend from the mouth to the throat. At its upper end, it is continuous with the mouth and nasal passages, and connects with the ears via the

Eustachian tubes while the lower end of the pharynx is continuous with the esophagus. It is also connected to the larynx by an opening that is covered by the epiglottis during swallowing, thus preventing food from entering to the respiratory system. Food that was swallowed from the mouth will enter into the pharynx and into the esophagus by using muscular contractions of the oropharynx and laryngopharynx [42].

Figure 2.16: The pharynx and the surrounding organs © US Gov

2.3.2: Esophagus

Figure 2.17: Esophagus and the process peristalsis [40]

The esophagus is a straight 23-25cm long muscular tube and about 2.5cm in diameter that connects between the stomach and pharynx. Its main role is simply to carry the food from the pharynx to the stomach using contraction and relaxation of its smooth

muscle. Bolus, or food that was chewed and mixed with saliva, travel through the esophagus by using the process peristalsis, which is the muscle at the top part of the bolus contracting itself, pushing it downward while the muscle below the bolus relaxes, allowing it to move through. The esophagus inner wall is a layer of smooth muscles and covered with mucus or fluid to aid swallowing.

2.3.3: *Stomach*

Figure 2.18: The different parts of the stomach [41]

The stomach is an expanded section of the digestive tube between the esophagus and small intestine. It is J shaped with the right side of the stomach called the greater curvature and that on the left side the lesser curvature. The greater curvature is about 4-5 times longer than the lesser curvature and it is about 40 cm [41]. The most distal and narrow section of the stomach is termed the pylorus. As food is liquefied in the stomach it passes through the pyloric canal into the small intestine. When the stomach is empty, the stomach walls form folds called rugae and when it is full, it will stretch and straighten. To perform the necessary procedure on the GI tract or NOTES, the patient or animal has to refrain from eating for days to allow the stomach to be clean and free from food debris. As such, it is expected for the robotic manipulator to work on the stomach when it shows many folds on the mucosa. The slave manipulator has to work at four regions of the stomach namely the fundus, cardia, pylorus and the body. The walls of the stomach are expected to be lined with mucus and digestive fluids.

The shape and position of the stomach are so greatly modified by changes within itself and in the surrounding viscera that no one form can be described as typical [43]. On average the stomach can hold 2-3 litres of liquid, 30cm long and 15 cm wide at the widest point.

Figure 2.19: Stomach when it is empty, half full and full [43]

The stomach also performs gentle, rippling, compressing movements to the food about every 20 seconds. These mixing waves help to mix the food with the fluid secreted by the body to aid digestion and change it into a thin liquid called chyme. After every mixing wave a very small amount of the chyme is released into the duodenum, which is the first 10-20cm of the small intestine.

2.3.4: Large Intestine

Unlike the previously described organs of the GI tract, the large intestine is on the lower part of the GI tract. The function of the large intestines is mainly of absorption, production of certain vitamins, formation of feces and the expulsion of feces from the body. The large intestine is part of the GI tract where it started from the ileum to the anus. It is about 1.5 metres long and is largest at the cecum (6.25 cm in length 7 cm in breadth) and gradually diminishes in size to as far as the rectum.

A further dilation of considerable size occurs just above the anal canal. The normal large intestine went through a series of bends and can be divided into a few different sections. It started from the cecum, the shape of a large pouch, and its ends opens up to the ascending colon where it ascends up the right abdomen and reaches the under surface of the liver. After which it bends to the left and traverse across the abdomen to form the transverse colon and bends again downward to the pelvis region, forming the descending colon. Finally from the end of the descending colon it bends toward the direction of the anus and this forms the Sigmoid colon (about 50-55cm long).

Similar to the esophagus, the large intestine is also capable of peristalsis. It uses this action to push the colonic contents from the cecum into the rectum. When the endoscope is inside the colon, the colon performs peristalsis in an attempt to expel out the endoscope.

Figure 2.20: Layout of the large intestine [44]

2.4: Types and Number of DOFs for the Human Arm

It is desired to make the master, or control of the slave of the robot to be as intuitive and ergonomic as possible. To do so, the joints and the DOFs of the slave manipulator should be similar to the human arm as much as possible. In short, the slave should be designed to be as *anthropomorphic* as possible. To achieve this effect, a study on human arm movements and measurements are needed. This study is also useful for the design of future master devices that can capture the motion of the human arm with ease and comfort.

2.4.1: Shoulder Joint

Figure 2.21: Shoulder modeled as a ball and socket joint [45]

Of all the joints on the human body, the shoulder has the greatest range of motion. Although the shoulder joint can also translate, the shoulder is still commonly modeled as a ball and socket joint since this movement produces the greatest amount of movement of the arm. [45]

Figure 2.22: Range of motion for shoulder joint [46]

The range of motion of the shoulder varies among individuals. The people who tend to engage in sports such as baseball are found to have bigger movement from the shoulder joint while those who suffer from certain diseases will find their motion range restricted [47]. From [46], the typical range of movement of the shoulder joint

is described as seen in Figure 2.22. The shoulder can also rotate around its mechanical axis so that when the forearm is at a 90° angle with the body, it can turn laterally in a horizontal plane. It can also make inward rotation and cause the arm to turn medially.

2.4.2: Elbow and Forearm

Figure 2.23: Elbow modeled as a hinge joint and forearm as a pivot joint [45]

Due to the muscles attached and interactions between the bones, the elbow is capable of bending in one axis. As such, it is normally modeled as a simple hinge joint as shown in Figure 2.23. Due to the interaction of the 3 bones at the elbow, it allows another degree of freedom to occur at the wrist. This degree of freedom is commonly modeled as a pivot joint and it enables the wrist to perform supination and pronation. The range of motion of the extension/flexion of the elbow and the twisting of the forearm can be seen in Figure 2.24.

Figure 2.24: Range of motion of the elbow and forearm [46]

2.4.3: Wrist

Figure 2.25: Wrist modeled as a condyloid joint [45]

The hand and wrist owe their mobility to the large number of different joints and bones present. Basically, the wrist acts as a condyloid joint, meaning it can rotate up, down as well as left to right. Unlike a ball and socket joint, it does not allow twisting of the wrist. The twisting of the wrist is provided by the bones on the forearm and not on the bones on the wrist. The range of movement for the wrist can be seen in Figure 2.26.

Figure 2.26: Range of motion for the wrist [46]

From the study of the different joints on the arm, the human arm is therefore modeled as having 7 DOFs [48]. Using the joints as described by the classification above and the length of each joint, the arm and its associated DOFs can be modeled as shown in Figure 2.27.

Figure 2.27: Overall DOF of the simplified human arm

Chapter 3 : Design Requirements

In this chapter, the overview of the system as well as the design requirements and selection of the tendon and sheath is provided. In Section 3.1, it described the system architecture as well as each individual component of the system and their interaction with one another. In Section 3.2, it reports the necessary requirements for the robotic slave manipulator such as length, flexibility, size, force and vision from the camera. In Section 3.3 the introduction of the tendon sheath actuation is given and the considerations for the selection of the tendon and sheath are reported in Section 3.4.

3.1: Overview of the System

Figure 3.1: Overview of the system

The overall system architecture for the robotic system can be seen in Figure 3.1. It can be categorized into three different sections. On the left green column is on the human involvement in the system which consists of the endoscopist, surgeon and patient. The middle orange column is the conventional endoscopy system which is widely used for treating ailments at the GI tract while the right blue column is the components of the robotic system being developed.

Looking at the left column, the patient is to be treated with the endoscope and the robotic system. Both the slave manipulator and endoscope transverse along the

patient's GI tract to reach the site and perform the necessary operations on the patient. During this time, the patient is in a partially anesthetic state and can cooperate with the endoscopist and surgeon in moving his body for easier access of the endoscope.

The endoscopist handles and facilitates the positioning of the endoscope. His role is to introduce the endoscope into the patient and steer the endoscope until it reaches the right location in the GI tract to perform the necessary treatment. He also assists in the procedure by controlling the macro positioning and orientation of the endoscope during the medical intervention. The endoscopist does not have control over the master interface but instead have direct control of the endoscope.

The surgeon is the person that controls the master interface and operates the slave manipulator to perform the treatment. He does not control the endoscope but instead control the actions of the slave manipulator. Once the endoscopist had positioned the endoscope, the surgeon then controls the finer motion of the robotic slave to perform treatment such as cauterizing and marking on the patient GI tract.

Both endoscopist and surgeon have to communicate, cooperate and coordinate together in order for the surgery to be successful since the endoscope control the general position of the robot while the surgeon control the movements of the robot. This is important since the organs and site for operation are generally very large with respect to the view from the endoscope and therefore both macro movements of the endoscope and micro motions from the slave manipulator have to be simultaneous. Therefore it is important for both surgeon and endoscopist to understand the procedure to be worked on and communicate to each other effectively.

On the right column, the robotic system can be divided into four different parts, the master console, microprocessor, actuator housing and slave manipulator. The master console system is a specialized designed haptics device for the surgeon to manipulate and control the slave manipulator. It can be visualized as a custom designed multi DOFs joystick designed to follow the human natural DOFs for controlling the slave manipulator. Sensors that were attached to the master console sense the movement from the surgeon and send out the necessary information to the microprocessor. It also has actuators that can produce force feedback to the surgeon.

The microprocessor and motion controller interprets the signals from the sensors and gives out the right amount of motion for the actuators to move. The microprocessor also has to interpret the readings from the load cell at the proximal end and gives force and positioning feedback to the surgeon. This portion also includes the necessary wiring linking the computer, motion control card interconnection module, power supply, servo drivers, actuators and load cells.

The actuator housing consists of various electronics system and prime movers that receive information from the microprocessor component and actuates the slave manipulator accordingly. It also contains the load cells for the prediction of the end effector parameters. The actuator housing directly drives the slave manipulator which in turn performs the treatments to the patient.

For the design of the robotic system, the master console is only briefly described in the thesis. This is because the design of the master interface is the work of another researcher in the group.

3.2: Design Criteria

To fulfill the objectives, the design criteria for the robotic slave can be split into four requirements namely the length and flexibility of the slave manipulator, the size of the slave manipulator, the force the slave manipulator can generate and the vision from the endoscope. Each of the requirements is important by itself and if any of the requirements fails, the robotic system cannot be ultimately used on a normal human patient.

Other important design requirements such as accuracy of the positioning and effect of hysteresis are the work of another researcher and therefore not included in this thesis. What are included are only the requirements for the design aspect for the slave manipulator.

3.2.1: *Length and Flexibility of the Slave Manipulator*

Unlike the commercial da Vinci surgical robot, the intended slave manipulator must be long and flexible enough to follow the human GI tract. If the length is too short, it cannot reach the site of interest. If the flexibility is too low, it hinders the bending movement of the endoscope and also causes unnecessary pain during the procedure.

Since it is used together with the endoscope, a good reference for the amount of flexibility and length is derived from the endoscope itself. The length of the flexible segment of the slave manipulator should be significantly longer and more flexible than the used endoscope. In this way, the user can push the endoscope into the GI tract in the same manner he does it when there is no slave manipulator attached.

Figure 3.2: Types of endoscope attachment

Two endoscopes are chosen to be used with the robotic system, GIF-N230 and GIF-2T160. First the GIF-N230 endoscope from Olympus is chosen because it is the smallest endoscope for use on the human GI tract. The second endoscope GIF-2T160 is chosen because it possesses two tool channels instead of the conventional one tool channel. The size of the two tool channels is considered to be relatively large compared to the other endoscopes. The choice of which depends on how the slave manipulators are attached to the endoscope. If the sheaths are to be attached on the outside of the endoscope as shown in the right side of Figure 3.2, then the smaller endoscope is used to minimize on the size. If the sheaths transverse within the tool channel, then the GIF-2T160 endoscope is used since it provides a bigger space for putting the tendons and sheaths. The length and specification of the stated endoscopes are given in Table 3.1 [49].

Although the working lengths of the endoscopes are approximately 1.0 m, the length of the robotic system should be longer to prevent the actuators from interfering with the movements of the endoscopist when he is working with the endoscope. To do so, a clearance of space of approximately a forearm length should be given for the length of the sheath. Since the length of the human forearm from the elbow tip to the finger

tip is about 440-510mm [50], it is recommended for the whole length of the sheaths to be longer than 1500mm. If the length could be increased above 1.8m, it gives lesser movement hindrance to the endoscopist.

	GIF-N180	GIF-2T160
Distal end size	4.9 mm	13.2 mm
Working Length	925 mm	1030 mm
Viewing Angle	120°	120°

Table 3.1: Length and specification for the proposed endoscope

For the flexibility of the endoscope, it is mostly assessed based on the specification of the endoscope. Based on the study from [51], the flexural rigidity value of the endoscope can goes from 160 to 240 Ncm². The SI unit for flexural rigidity, or the force couple to bend a rigid structure to a unit curvature, is Nm². Generally the endoscope is considered to be stiff since it has to be pushed it into the GI tract without buckling or deformation. Thin and long tendons and sheaths generally have a greater flexibility compared with the stiffness of the endoscope and therefore does not pose any problems on the flexibility of the system.

3.2.2: *Size of Slave Manipulator*

The size of the slave manipulator affects the comfort, safety and even the feasibility of the use of the robotic system. If the size of the slave manipulator is too big for it to go through the GI tract, the system is considered to have failed.

Although it is obvious the smaller the system is the better it becomes, the robotic system is a real device which requires space. With a larger space allocation, the slave manipulator can possess higher DOFs, uses thicker tendon and sheath and can produces a higher force output to perform successful trials.

To find the requirements of the size for the slave manipulator, a possible reference is the commercially available Guardus overtube [52] for use during endoscopic procedure. It is a tube-like medical device that is inserted from the mouth and reaches into the stomach of a human patient. It is designed to protect the patient esophagus from mucosal shearing and tearing and it possesses an insufflation cap that allows inflation of the stomach as well as leakage of body fluids.

Figure 3.3: The Guardus overtube

The Guardus overtube has an outer diameter of 19.5mm, an inner diameter of 16.7mm and a length of up to 50cm. If the slave manipulator can go through the inner diameter of 16.7mm of the over-tube to work on the human patient, then its size is already appropriate for human use.

3.2.3: Force from Manipulator

To use the slave manipulator for ESD, each DOFs of the slave manipulator must generate enough force to manipulate the flesh. If there is insufficient force, the walls of the stomach cannot be and the robotic system is incapable of performing the allocated task. As mentioned before, increasing the force inevitably increases the size of the slave manipulator and therefore it is necessary to strike a balance between size and force.

Studies have been made by endoscopist and surgeon on the possible force output from the endoscope. One of the forces that are measured is when the endoscope is pushed. Experiments conducted with the Olympus GIF-2T100 reveal a pushing force of approximately 1.3N before the endoscope changes its bent shape [53]. From another study using a different endoscope GIF-140, the maximum pulling force from the endoscope is approximately 2.76N before it changes its original bent shape [54]. It is worthwhile to note that these values are given when there is a slight change in the shape of the endoscope when it is bent at the greatest angle.

To find the amount of force needed for the gripper, studies are made on the force exerted by manual laparoscopic manipulators. According to [55], the mean pressure

at the tip of a series of laparoscopic manipulators is 210 kPa. If the size of the grasper is 1.5mm by 8 mm, then the expected force exerted should be 2.52N.

It is recommended for the force output of the slave manipulator to be higher since the environment where the slave manipulator is working in is full of slippery mucus and the walls of the GI tract are smooth muscles that are stiff compared with other parts of the body. In [56], the maximum force used for a cutting and spreading experiments on the tissue should go higher than 3N.

3.2.4: Vision

Figure 3.4: Picture of GIF-2T160 endoscope and classical barrel shaped distorted image [57]

The vision from the endoscope is very important during the endoscopic procedure. The main purpose of an endoscope is to provide this sensory feedback that tells us what is happening inside the body. The location of the slave manipulator, the orientation of the slave manipulator, the abnormalities on the GI tract etc can only be known by seeing the vision from the endoscope. If the robotic manipulator blocks the vision excessively, then the endoscope cannot function as effective diagnostic equipment and cannot perform any procedure.

There is a need to understand the type of image that can be seen from the endoscope. The lens used by the endoscope is spherical and it causes a barrel shaped distortion as seen in Figure 3.4 [58][59]. Another problem with the vision is that the endoscope can only provides a two dimensional view. Coupled with the barrel shape distortion, the overall perception of depth is poor. As such the slave manipulator should be short so that the ends can be seen more effectively.

Figure 3.5: Amount of vision blocked by slave manipulator

According to the specifications given by Olympus in Table 3.1, the viewing angle of the two endoscopes that are used is 120°. Unless the slave manipulator is very close to the endoscope, it generally can see the end effector of the slave manipulators. However if the slave manipulator is very close to the camera, it can effectively block off a large portion of the view. Thankfully the camera of the endoscope is not centralized but located at one side of the endoscope and this allows some space for the slave manipulators to be located.

To calculate the amount of vision blocked by the slave manipulator, the formula below is used

$$\text{Amount of blocked vision} = 0.5 + \gamma/120$$

Where $\gamma = \tan^{-1}(\text{vertical distance between center of camera to top end of slave})/(\text{length of slave manipulator})$

Generally, for the prototype, as long as the robotic manipulator does not block more than 60% of the vision from the endoscope, it is considered as feasible for the trial purpose. It can also be seen from the formula above that the longer the slave manipulators are, the more vision it can block from the endoscope. It is also suggested that the slave manipulator to be capable of moving away from the view of the endoscope if desired during the procedure to restore the vision.

3.3: Mode of Actuation: Tendon Sheath Actuation

Figure 3.6: Mechanical and human tendon and sheath [43]

Tendon sheath systems generally consist of a hollow helical coil wire acting as a sheath and a cable within that acts as the tendon. It is named after the human anatomy of tendon sheath where the tendon is used to pull and control the motion of a joint while the sheath is used as a cover that encases and protects the tendon from friction especially [43]. When the tendon is pulled at one end, it slides within the sheath thereby allowing the pulling force to be transmitted to the other end of the sheath. A common example of a mechanical tendon sheath actuation is the Bowden cable that is commonly used in bicycle brakes.

Actuators that generate high power are usually bulky and heavy, making it unsuitable to be deployed on the slave manipulator. With tendon sheath actuation, the actuators could be situated away from the end effector thereby allowing it to be very small and light. The actuators generate the force to pull the tendon at the proximal end, making the tendon slide within the sheath and allowing the force to be transmitted to the distal end of the sheath. Depending on the choice of the tendon and sheath, the system can take up a long and flexible route of transmission as well as generate a large force at the end effector. Furthermore tendon sheath actuation does not require high electrical power or special chemicals at the distal end to actuate but instead uses simple structures such as helical coiled wires and stainless steel wire ropes instead. This allows the system to be used safely on human bodies since failure of any part of the tendon sheath system does not pose a catastrophic risk to the patient. This is why tendon-sheath actuation has found its way into many applications such as robotic hands and surgical robots [60][61][62][63][27].

Figure 3.7: Figure showing a real application of tendon sheath actuation [64]

Comparing with other modes of power transmission such as hydraulic, pneumatic and magnetic, tendon sheath actuation requires smaller size, generates greater force and is safer to be used inside the human body. They are also cheaper and simpler compared with these other modes of actuation. As such, tendon sheath actuation is used for the proposed robotic system.

However there are some downsides on the use of tendon sheath actuation. As the tendon slides within the sheath, some force is lost due to the friction generated between the tendon and sheath. This not only reduces the force at the distal end, it also create problems such as non-linearity, high friction, introduces dead zone, hysteresis and direction dependent behavior that is not desirable for control and sensing [65].

Generally speaking, the sheath for tendon sheath application does not need to be pre-shaped although it is recommended for it to be so in order for the system to bend in the desired manner. In the case of robotic system for NOTES, the robotic system has to negotiate through the curves and bends of the GI tract that deviates from person to person. Therefore it is not feasible to pre-shape the tendon and sheath for this application.

To use it for the robotic system, an understanding has to be established on the mode and type of tendon sheath actuation available. The control and characteristics of the actuation becomes different under different configuration.

3.3.1: *Tendon Routing vs Tendon Sheath*

There is another classification of tendon actuation that does not require the use of sheaths but instead depends on pulleys to reroute the direction of the tendon. This way, the problems linked with the friction problem is minimized and it brings about easier and more predictable control. Therefore many robots such as the Utah/MIT hand and the CT arm employ the use of cable routing for its actuation [66][67].

However for cable routing, for every change of direction of the tendon, there must be a pulley in place and a planned route for the tendon to go. In a robot with many DOFs, the amount of pulleys with the tendon makes it heavy, big, expensive and complicated. Since the pulleys are rigid, the whole mechanism is not completely compliant as well. Furthermore cable routing cannot be used for unpredictable bends such as the variation between the human GI tracts. Due to these disadvantages, tendon sheath actuation is used instead and it is more popular compared to the use of tendon routing.

Figure 3.8: Difference between cable routing and tendon sheath actuation

3.3.2: Actuators Configuration for Each DOF

Figure 3.9: Types of actuator configuration for tendon and sheath [68]

An interesting characteristic of the tendon is unidirectional. Unlike linkages, tendons can only stand a high tensile force but zero compressive force [69]. Therefore tendon sheath actuation generally requires two or more tendons to control one DOF. One tendon is used to rotate a joint clockwise and the other rotate it anti-clockwise. There are four different ways to provide the two forces at the distal end. They are the use of one actuator to drive one DOF (n), two actuators to drive one DOF ($2n$), cooperation between tendons ($n+1$) and finally using passive mechanism such as spring (n') [68].

For the n actuators to drive n DOF, it is commonly found in many applications since it is the simplest to implement [70]. Both ends of the antagonistic tendons are attached to opposite end of the actuator, which is a rotary motor as shown in Figure 3.9. As the motor rotates either clockwise and anti clockwise, it drives the tendons at the opposite sides of the joint and achieve control.

Figure 3.10: Problems of no or high pretension

However there is a need for high pretension of the tendons to prevent slacking of the tendons at high velocities. That means when the tendons are fixed to the actuators, the tendons have to be very taut. Otherwise whenever actuators changes direction, it has to move more to absorb the slack of the tendon before the joint starts to move. This is not suitable for applications that require a high velocity since the actuator require time to pull in the slackness of the tendon whenever it changes direction.

With a high pretension, the performance of the system inevitably degrades. This is because at a higher pretension, the intended pulling force has to overcome the co-contraction force at the other side of the joint before it moves. This reduces the possible force output of the tendon sheath actuation. Higher pretension also gives higher friction and backlash to the system. It should be noted that there is no such thing as an exact amount of pretension where it experiences no con-contraction force and no slacking throughout the whole movement range. If it is desired to have no slack in the tendons for all of the actuation force range, then it inevitably experiences a high pretension response on the other side of the tendon for some of the actuation force range.

On the $2n$ actuators for n DOFs, the characteristics are similar to using one actuator for each DOF except that the motion of the two sides of the joint can be decoupled from each other. Using two actuators for each DOF can also ensure that the opposite co-contraction force is zero or at a minimum if the force of the tendon can be known. The actuator that controls the loosening tendon just focus on releasing the tendon

until the force is low. In this way there is no slackness of the tendon yet the co-contraction force at the other end of the joint is minimal. This improves the performance of the system but the actuators housing becomes heavier, bulkier and harder to maintain due to the greater number of actuators. This is only true if sensors are used to determine the force of the tendons. Otherwise there is no way to know when to pull or release the tendons on the other actuator to minimize the co-contraction forces. The Utah/M.I.T hand uses this type of actuator configuration [66].

Figure 3.11: Using two actuators to ensure opposing side is at a low force

For the $n+1$ actuators for n DOFs configuration as seen in Figure 3.9, it utilizes a lower number of tendon sheaths for the same DOFs compared with the above two configurations. This configuration also uses up the least actuators with no pretension necessary for the tendons. This may be significant if the size of the end effector need to be controlled. Examples of robots using this type of configuration are [71][72].

However for this configuration of actuation to work, the DOFs have to be in the same plane and the DOFs are repeated and parallel. Furthermore for the DOF to be individually controllable, the tendon tensions have to be coordinated and controlled properly. This is difficult to achieve if there is insufficient sensors at the end effector.

In the fourth configuration, the tendon provides force at one end while the spring provides the opposing force to it. This configuration uses the least number of tendons and sheaths to actuate but at the cost of poorer performance due to a constant high co-contraction force from the spring. However in the case where the joint requires a high torque in one direction and a low torque in the other, the spring can be substantially weaker and the work done against the spring is low. That is why this configuration appears frequently for the actuation of robot fingers since it require a

greater torque to close the finger to hold objects while a much weaker force to open up the fingers [73].

Figure 3.12: Using n actuators with restoration spring [73]

As can be seen from the above descriptions of the different types of configuration for tendon sheath actuation, all of them have their weaknesses and strength. Depending on the DOF, a suitable type of configuration has to be chosen and used for the actuation of a joint.

3.4: Design Guidelines Based on Selection of Sheath

To ensure the success of the robotic slave manipulator, the selection of tendon and sheath is of utmost importance. The choice of the tendon and sheath directly affects the size, length and strength of the slave manipulator and determines the success of the robotic system. If the tendon and sheath has desirable characteristics, then it can be thinner, longer and yet produce a high force at the distal end. Otherwise not only is the force low, the tendon can break frequently during usage. Therefore a study is made on the tendon and sheath.

3.4.1: Size of Sheath

Figure 3.13: Change of bending radius with buckling

Before designing the slave manipulator, the size and type of tendon and sheath has to be decided first. If the sheath is bigger, it brings about advantages such as the use of bigger tendons and thicker walls. When bigger tendons are used, the strength of the tendon is greater and the force that the joint can exert is greater. If thicker walls are adopted, the buckling of the sheaths reduces and the maximum force of the slave manipulator increases. In Figure 3.13, the figure on the left shows the sheath when it is under a low force and exhibits no buckling while the figure on the right shows the same sheath under a high force and it buckles extensively. When it buckles extensively, multiple small bends are formed. It resembles a high order buckling of a column which curved to the left and right. The reason why the sheath can withstand higher order of buckling is because the tendon within the sheath still supports the integrity of the structure. The arrows in the figure show the approximate bending radius as well as the center of the curvature. It is practically difficult to know the exact bending radius and center of curvature for the shape of the sheaths.

If extensive buckling occurs, the force transmission decreases because the bending radius reduces and this increases friction between the tendon and sheath. Since the loss from friction becomes higher, the force transmission of the tendon and sheath becomes poorer. There is why there is a limit to how much the tendon and sheath can transmit the force even though they are far below their breaking load.

However if the size of the sheath is too big, the design of the slave manipulator is going to be big as well since it has to allocate space for inserting the sheath. Therefore a compromise has to be reached regarding the size of the sheath.

3.4.2: *Types of Wires for Sheath*

Figure 3.14: Deflection for round coil sheath and flat coil sheath

To preserve the stiffness and inner diameter of the sheath without increasing the size of the sheath, it is suggested to use flat coil spring instead of the traditional round coil spring. The biggest motivation is its ability to have thin wall thickness yet withstand deflection. This is because the flat coil requires more deformation of the wire coil to deflect compared with the round coil. [74]. This ensures the overall size of the sheath is small, internal diameter is big and stands buckling. However flat coil sheaths are substantially more expensive and harder to find. Another factor to consider is that if the sheaths are too stiff, it is harder for the joints closer to the base to actuate. This is because the joint not only has to overcome the force from the load to move, it also have to change the shape of the sheaths as well. This force can be substantial if the number of sheaths involved is high and the sheaths are stiff.

3.5: **Design Guidelines based on Selection of Tendon**

For the tendons, there is a need to choose between two different types of ropes: stainless wire ropes or plastic spectra fibers (ultrahigh molecular weight polyethylene). The stainless steel wire ropes can come in either just the wire ropes or coated with a plastic such as Teflon. Each type has its own strengths and problems that need to be studied. Five considerations are taken to decide on which tendons to use. The coefficient of friction between the surfaces, the strength of the tendon with respect to the size, resistance to abrasion, flexibility and the size of the tendons.

3.5.1: *Coefficient of Friction between Sheath and Tendon*

Material	Coefficient of Friction
Steel on Steel	0.74-0.78
Polyethylene on Steel	0.2-0.22
Teflon on Steel	0.04-0.13
Teflon on Teflon	0.04

Table 3.2: Coefficient of selected material

The first consideration is the coefficient of friction between the tendon and sheath. If the friction between the surfaces is high, the loss of force is also subsequently higher. Four different coefficient of friction are compared namely polyethylene on steel, steel on steel, Teflon on steel and Teflon on Teflon [75]. The value of the coefficient of friction is taken from the table of friction between the materials.

As seen, the friction between steel - steel is much higher compared with spectra fiber - steel and Teflon - steel combination. When a steel wire rope is used on the steel sheath, it produces the highest friction among the three. The use of lubrication can help to reduce the friction substantially but due to the sheath being porous, it also adhere dirt. This not only worsens the friction between the tendon and sheath but also increases abrasion. Therefore lubrication is not recommended to be used for this application. The use of Teflon coating however is encouraged because it produces the lowest friction between the tendon and sheath.

3.5.2: *Maximum Breaking Load*

The next important factor is the maximum load the rope can bear before it breaks. Using the information from [76][77], Figure 3.15 is plotted. From it, for the same outer diameter, spectra fiber offers more strength than steel wires. This is consistent with the claims made by Innovative textiles that make the spectra fibers. Although the force the tendons can endure appears to be high, in choosing the size of the wire or fiber it is recommended to use a tendon with a safety factor of ten [78]. That means the recommended effective force the tendons could give is effectively ten times lower. Even though the force it give is not high, there are limited options available since the size has to be small.

Figure 3.15: Comparison of breaking strength between spectra fiber and steel rope

3.5.3: Resistance to Abrasion

The breaking load of the tendon can be misleading since it could be reduced significantly due to the effect of abrasion. According to studies, the strength of the fiber and steel ropes can be reduced as much as 50% when it is placed over an edge [79]. Abrasion can cause the catastrophic breaking of the tendon even though the force it tolerates is lower than its breaking strength. This problem is particularly severe in the project since the tendons go through particularly sharp edges before bending to a large angle at a high tension. The use of protective coating over the wires can significantly solve the problem of abrasion and therefore is highly recommended to be used to reduce the problem caused by abrasion.

3.5.4: Flexibility of Tendon

Figure 3.16: Kinks and hockles formed after repeated usage at a low bending radius

A problem with the use of steel wire rope is their flexibility. Unlike spectra fibers, wire rope has a specified minimum bending radius and if it is exceeded, the wire experiences fatigue at a faster rate. It also forms kinks which affect the actuating of

the joints. The recommended minimum bending radius is 50 times the rope diameter [78]. In the case of the slave manipulator, due to its small size it is not possible to provide this bending radius. If a protective coating is applied, the effect of fatigue is reduced [78]. In the case of spectra fibers, it is very flexible and therefore is not a problem.

3.5.5: *Size of Tendon*

Next the size of tendon has to be chosen for the slave manipulator. As shown in Figure 3.15, the larger the size of the tendon, the more force it could accept before breaking. The size however is determined by the inner diameter provided by the sheath. The size of the tendon should be significantly smaller than the sheath to provide the clearance for lesser friction. This is known as fill ratio and it is recommended it is lower than 53% by the National Electrical Code (NEC) [80]

$$\text{Ratio} = \frac{d^2}{D^2}$$

Where d represent the diameter of the tendon used while D represents the inner diameter of the sheath. The above ratio is the same as the proportion of area covered by the tendon over the area of the hole of the sheath. If this fill ratio is exceeded, the friction increases significantly [81].

Figure 3.17: Crimp and Teflon coated wire rope compared with a ruler

From the following information, the best type of tendon to be used is actually steel wires coated with Teflon. This is because it provides the least friction, highest

resistance to abrasion and moderate flexibility without kinking. However ultra small tendons coated with Teflon is hard to find and the cost is high. If it is unavailable, spectra fibers can be used instead which promise reduced friction, higher strength and good flexibility compared with traditional steel ropes. However for spectra fibers, failure due to abrasion can be a serious problem.

Chapter 4 : Tendon Sheath Analysis

This chapter discusses on the mode of actuation used for the robotic system, namely the tendon sheath actuation. This chapter discusses the method of making use of the tendon sheath characteristics to sense the end effector force and elongation for haptics feedback. Section 4.1 introduces the motivation of using the modeling of tendon and sheath for the distal end effector approximation actuation. Section 4.2 is on the theoretical modeling of the characteristic of the tendon sheath actuation and the prediction of the distal force and elongation during the various phases of the actuation. Section 4.3 shows the experimental setup to verify the result and Section 4.4 is on the experimental result for the prediction of the force and elongation. Lastly Section 4.5 presents the discussion on the limitation of the modeling.

4.1: Motivation for Tendon Sheath Modeling and Analysis

Tendon and sheath actuations are used by two different categories. One category is on the use of robotic hands/arms while the other is on robotic surgical system. Tentatively most of the studies made on the tendon sheath actuation are based on applications on robotic hands and arms. For their applications, they installed many sensors at the end effectors and using their readings, the robotic hands and arms can move autonomously to perform the necessary task. Torque control and position control of the robotic hands are reported to work satisfactory for their application [82][83].

For the application of the development of the robotic system for surgery [27][84], generally there is no autonomy. It is a master-slave robotic system and the surgeon is directly in control with all the end effector movement. The use of force and position sensing at the end effector is critical to the operation of the surgical robotic system. However it is difficult to put sensors at the end effector compared with robotic hands. This is especially true for robots to be used for NOTES or ESD application. Three distinct differences between robotic hands and surgical robots for NOTES are mentioned that makes it difficult to mount sensors at the end effector, namely physical restraint, sterilization and practicability.

The size available for the robotic hand can be described as putting sensors onto fingers in a life-size arm while for NOTES type of surgical robots it is described as putting sensors on arms inside a life-size finger. It is difficult, if not impossible to mount force or position sensor at the end effector. Just allowing two 0.5mm wires to send back the electrical signals to the base is already a difficult task due to the small size ($<10\text{mm}$) and high mobility ($>3\text{DOFs}$) of the mechanism. Furthermore to effectively sense the necessary forces on the end effector, many sensors have to be employed making the task of design worse. Even if the sensors can be mounted, the design of the end effector will not be efficient compared with a design without sensors. Efficiency is the output force of the mechanism with respect to the size of the end effector. The end effector is also expected to experience large forces in all possible directions as it is inserted through the body and connected thin wires may tear off easily.

In the use of the robot for surgery, not only is the environment harsh due to it being filled with enzymes and fluids with varying viscosities from the human body, the sensors and all its connectors have to be sterilized effectively before it can be used on human. At the present, sensors for haptics are always placed outside the human body for safety purposes. Research conducted on surgical robots is mainly used for Minimally Invasive Surgeries (MIS) and consists of a rigid rod to attach their end effectors to outside the human body. They also use cable routing actuation which does not experience significant friction from the proximal end to the distal end. Sensors are therefore placed on the rigid shaft or cables outside the human body for haptics feedback [23][85]. This is possible since keyholes are cut into patients' body. In the case of surgical robot for NOTES, it needs to be flexible in order to go through the human natural orifice. It cannot have a rigid shaft to attached sensors to in order to go through the natural orifices. Therefore tendon sheath actuation has to be used and the distal and proximal end force differs greatly due to the high friction between the tendon and sheath. Another means of sensing the parameters at the end effector without attaching physical sensors has to be developed in this case.

Due to sterilization and mechanical wear and tear, it is likely the end effectors are designed for single use. It is therefore impractical to attach many miniaturized and

sophisticated sensors at the end effector that is disposed off after a single use. However if the sensors are attached to the housing, it do not have to be disposed off after a single use since it does not need to be sterilized nor does the mechanism experienced significant wear and tear.

As such, it is necessary to develop a method to predict the parameters without attaching sensors at the end effector. This can increase the performance and safety of the robot when it is used inside the human body.

4.1.1: Force Feedback

The system used for the project is a master slave robotic system. The motion of the slave manipulator is completely controlled by the surgeon and therefore there is no autonomy for the motion of the slave manipulator. Hence is it imperative for the surgeon to get the right and necessary information to make the best decision in carrying out the task. Although the endoscope provides the necessary vision for the surgeon, there is still some important information about the slave manipulator that he does not know. An example is the force that the slave manipulator exerts on the surroundings. Due to the limited depth perception from the 2D image, the surgeon cannot tell if the slave manipulator is pushing at the wrong place excessively. Some possible examples are the two arms unintentionally pushing against one another or when the arms push against the walls of the stomach excessively. This is a problem since the tendons could become damaged due to the high tension or it cause unnecessary damage to the patient body.

To solve this problem, force feedback from the slave manipulator to the master system is proposed. With force feedback, the surgeon can feel the force that the slave manipulators are exerting on the surroundings. This ensures the surgeon does not cause unnecessary trauma to the patient body and also ensures the robotic system does not break down easily. The surgeon can also perform the procedure in a faster, safer and more consistent manner.

4.1.2: Elongation

The use of tendon sheath actuation has a problem. Due to the high tensile force the tendons experienced, it elongates. Similarly due to the high compressive force the

sheaths experienced, the sheath inevitably compresses. The amount of deformation of both the tendons and sheath is not obvious since there is a high amount of friction between the tendon and sheath. Some of the tension and compression force is lost because it is used to overcome the friction between them. The amount of friction between the tendon and sheath also cannot be known easily since this friction is dependent on the bending radius of the tendon and sheath. This bending radius varies greatly between trials and different human and there is no efficient way to measure this bending radius effectively.

Due to this phenomenon, there is no way to know the amount of tendon that is pulled at the distal end and this becomes an open loop positioning control. To control the system, the surgeon has to use vision from the endoscope intensively and has to move the master robotic system according to the desired movement of the slave. This can result in the orientation of the hands of the surgeon to be completely different from the orientation of the slave. Ideally, the slave manipulator should follow the orientation of the surgeon hand instead. That way, the surgeon can visualize the slave manipulator to be his hand and perform the operation more intuitively. If prediction on the elongation of the tendon could be achieved, then the control of the positioning system becomes a close loop system and the slave can follow the orientation of the surgeon hand. The control can then become more intuitive, efficient and the surgeon only needs to go through a shorter learning curve in order to use the robotic system.

4.1.3: Methodology

Tentatively, there is no way to determine the values of these parameters without the need of any form of sensors or special mechanism at the end effector. However there is no space constraint at the proximal housing end of the tendon and sheath and most conventional sensors can be mounted there. Therefore it is proposed to model the tendon and sheath analytically and using the model to predict the end effector parameters given the sensors readings at the proximal end. Although the values predicted from the model pales in comparison with an actual sensor, the control of the robotic slave is by the surgeon who faces limitation in human perception and a

primary vision feedback to guide him. This is basically the approach of the author to predict the parameters at the end effector given the proximal end readings.

4.2: Analysis of Tendon Sheath Mechanism

4.2.1: Tension study of tendon and sheath

In the following, we assume the sheath is bent with a constant radius of curvature as seen in Figure 4.1. In our model μ is the friction coefficient between the sheath and the tendon, N is the normal force the sheath is exerting on the tendon in this unit length, T is the tension of the sheath, C is the compression force experienced by the sheath, T_{in} is the tension at one end of the sheath, R is the bending radius of the tendon, x is the longitudinal coordinate from the housing end of the sheath to the present location, F is the friction between the tendon and the sheath in this unit length. To simplify our model, μ can be assumed as the dynamic friction coefficient when the tendon is moving within the sheaths.

Figure 4.1: Modeling of a small section dx of a tendon and sheath

Using the force balance equations on the tendon for a small section dx , based on studies from [82][83].

$$T d\alpha = -N, d\alpha = dx/R, F = \mu N \text{ and } dT = F$$

$$\frac{dT}{dx} = -\frac{\mu}{R} T$$

$$T(x) = T_{in} e^{-\frac{\mu}{R} x}$$

4.1

Equation above appears often in literature [65][82][83] and it highlights the fact that the tension of the tendon decreases exponentially as either length increases, bending radius decreases or friction increases.

Next, the force balance equation is applied on the sheath. For both tendon and sheath, the forces N and F are equal and opposite since they are reacting against each other. Since the tendon thickness is close to the inner diameter of the sheath and the segment of tendon sheath is negligible, the angle of both tendon and sheath can be assumed to be the same. Therefore we have

$$C=-T, dC=-dT \quad 4.2$$

The compressive force measured at the proximal end of the sheath is the same as the tension measured from the tendon at the same end. This result can be easily verified by experiments.

Figure 4.2: Simplified model of the sheath compared with a generic sheath

The theory presented so far applies only to sheath and tendon with a fixed curvature throughout its length, as shown in Figure 4.2(i). In general, the sheaths are free to move and the curvature is different throughout the whole length, as shown in Figure 4.2(ii). This can be modeled as a sheath having n sections, each having a different radius of curvature R_1 to R_n and a displacement of x_1 to x_n from the housing. In this case equation 4.1 becomes

$$T(x)=T_{in}e^{\frac{\mu}{R_1}x} \quad (0<x<x_1)$$

$$T(x) = T_{in} \left(e^{-\frac{\mu}{R_1} x_1} e^{-\frac{\mu}{R_2} (x - x_1)} \right) \quad (x_1 < x < x_2)$$

$$T(x) = T_{in} \left(e^{-\frac{\mu}{R_1} x_1} e^{-\frac{\mu}{R_2} (x_2 - x_1)} e^{-\frac{\mu}{R_3} (x - x_2)} \right) \quad (x_2 < x < x_3)$$

...

$$T(x) = T_{in} \left(e^{-\frac{\mu}{R_1} x_1} e^{-\frac{\mu}{R_2} (x_2 - x_1)} \dots e^{-\frac{\mu}{R_{n-1}} (x_{n-1} - x_{n-2})} e^{-\frac{\mu}{R_n} (x - x_{n-1})} \right) \quad (x_{n-1} < x < x_n) \quad 4.3$$

To predict the tension at the end of the sheath, expression 4.3 can be simplified as

$$T_{out} = T_{in} e^{-K} \quad 4.4$$

Where $K = \mu \left(\frac{x_1}{R_1} + \frac{x_2 - x_1}{R_2} + \dots + \frac{x_n - x_{n-1}}{R_n} \right)$ and it represents the effective friction

between the tendon and sheath. It is important to note that, if the sheath does not change its shape, K is a constant. It is impossible to determine x_i and R_i , but there is a way to make use of this equation as described in the following.

4.2.2: Elongation study on tendon and sheath

Another relevant parameter is the elongation of the tendon and sheath system under a specified force. The study is initially applied to a sheath with a fixed bending radius then it is applied to a generic sheath. Being e the tendon elongation and E the combined stiffness of the tendon and sheath, we have

$$e(x) = \frac{T(x)}{E} \quad 4.5$$

where the tendon tension varies with x . To obtain the total elongation, equation 4.5 must be integrated over the length of the tendon sheath system, thus obtaining

$$e_{total} = \frac{1}{E} \int_0^x T_{in} e^{-\frac{\mu}{R} x} dx \quad 4.6$$

This is actually the area under the graph of the tension distribution T divided over the constant E . The analytical solution is

$$e_{total} = \frac{T_{in}R}{E\mu} \left(1 - e^{-\frac{\mu}{R}x} \right) \quad 4.7$$

Another expression is

$$e_{total} = \frac{R}{E\mu} (T_{in} - T_{out}) \quad 4.8$$

The last expression is true only if R is a constant.

T_{out} is the tension experienced by the tendon at the end effector. This result is slightly different from the other works reported in literature [82][65] for two main reasons. First, pretension is not required. Then, it does not make the assumption that the force is evenly distributed within the sheath. When the system is used, it starts with low pretension. In this case, two actuators are used to control one DOF instead of the traditional one actuator per DOF. This also simplifies the modeling of the problem, since only one tendon undergoes a tension at any given time.

The above derivation is used when both the tendon and sheath have a constant bending radius. If the sheath is modeled as having n sections, each having a different radius of curvature R_1 to R_n and each having a displacement of x_1 to x_n , then

$$e_{o1} = \frac{R_1}{E\mu} (T_{in} - T_{o1})$$

$$e_{o1} = \frac{T_{in}R_1}{E\mu} \left(1 - e^{-\frac{\mu}{R_1}x_1} \right) \quad (x=x_1) \quad 4.9$$

Where e_{o1} is the elongation at $x=x_1$ and T_{o1} is the tension at $x=x_1$. Similarly

$$e_{o2} = \frac{T_{in}}{E\mu} \left[R_1 \left(1 - e^{-\frac{\mu}{R_1}x_1} \right) + R_2 e^{-\frac{\mu}{R_1}x_1} \left(1 - e^{-\frac{\mu}{R_2}(x_2-x_1)} \right) \right] \quad (x=x_2)$$

...

$$e_{total} = \frac{T_{in}}{E\mu} \left[R_1 \left(1 - e^{-\frac{\mu}{R_1} x_1} \right) + \sum_{i=2}^n R_i^{-\mu \sum_{j=1}^i (x_{j-1} - x_{j-2})} \left(1 - e^{-\frac{\mu}{R_i} (x_i - x_{i-1})} \right) \right] \quad (x=x_n) \quad 4.10$$

$$e_{total} = M_e T_{in} \quad 4.11$$

$$\text{Where } M_e = \frac{1}{E\mu} \left[R_1 \left(1 - e^{-\frac{\mu}{R_1} x_1} \right) + \sum_{i=2}^n R_i^{-\mu \sum_{j=1}^i (x_{j-1} - x_{j-2})} \left(1 - e^{-\frac{\mu}{R_i} (x_i - x_{i-1})} \right) \right]$$

M_e represents the effective elongation constant of the tendon and sheath system. It is a constant if the shape of the tendon and sheath remains constant.

The relationship of K and M_e with T_{in} is expressed in Figure 4.3. The straight line curve represents the actual tension distribution for a generic sheath at T_{in} . The dotted line represents the approximate solution coming from equation 4.4 as displacement x increases. The value of M_e is proportional to the area under the straight line curve and it is an indication of tendon sheath deformation. In the experimental setup section, the approach to find K and M_e will be discussed in detail. It should be noted that just the approximated values for the force at the two ends are relevant for control.

Figure 4.3: Graphical representation of M_e and K

By approximating the original curvature to the one characterized by K , the relationship between M_e and K can be retrieved by evaluating the area underneath $T_{in}e^{-K}$ multiplied by L/E

$$M_e T_{in} = \frac{T_{in} L}{EK} (1 - e^{-K}) \quad 4.12$$

$$e^{-K} = -\frac{M_e E}{L} K + 1 \quad 4.13$$

It can be seen that M_e and K are dependent on each other and the value of M_e is enough to give an approximation of K and vice versa. There is no readily available solution for equation 4.13 and numerical methods, such as Newton-Raphson or the Golden Section method, must be used.

However, this result is relevant only when the system undergoes a pulling phase. In the case the tendon is just released after being pulled, the system does not immediately go into the release phase. It instead undergoes a transitional phase from pulling to releasing.

4.2.3: Pulling to Release Phase

Figure 4.4: Gradually reducing T_{in} and the tension distribution within the sheath

Figure 4.4 shows the tension distribution within the sheath as the housing force is gradually reduced. The first effect of a decrease in T_{in} is a reduction of the tension within the sheath, while the tension at the end effector is not affected. Let X' be the distance from the proximal end where the highest amount of tension within the sheath. As T_{in} decreases, X' moves further from the proximal end closer to the end effector. Only when X' reaches the end of the sheath, then T_{out} starts to decrease. This is the so called “backlash” of the tendon sheath system.

During the transitional phase, it is noticed that T_{out} remains the same until T_{in} reduces to T_{in5} as shown in Figure 4.4. Therefore

$$T_{out} = T_{in0} e^{-K} \quad 4.14$$

Where T_{in0} is the highest point of the tension recorded at the housing before it starts to loosen.

Differently from tension, the elongation varies during the transitional period. The area under the tension distribution curve is proportional to the elongation of the tendon and sheath and it undergoes relevant variations. This change in the area can be observed under the shaded graph of Figure 4.4.

The elongation of the tendon during the transitional phase may be derived in two steps. First, the displacement X' must be calculated. The second step is to evaluate the elongation under the shaded areas A and B of the curve. To perform this step, we take advantage from the curvature approximated by K . Let L be the length of the whole sheath, we can write

$$\begin{aligned} T_{in} e^{\frac{K}{L} X'} &= T_{in0} e^{-\frac{K}{L} X'} \\ \ln T_{in} + \frac{K}{L} X' &= \ln T_{in0} - \frac{K}{L} X' \\ X' &= \frac{L}{2K} \ln \frac{T_{in0}}{T_{in}} \end{aligned} \quad 4.15$$

When $X'=L$, $T_{in}=T_{in0}e^{-2K}$ is the force that the tension at the housing side has to release before T_{out} reduces. This value can also be calculated and used online in order to infer if the system is still working within the backlash region.

Now a way to calculate the elongation coming from area A of Figure 4.4 is presented. Let A be the area underneath the tension distribution from $x=0$ to $x=X'$

$$Area A = \int_0^{X'} e^{-\frac{K}{L} x} dx$$

$$Area A = \frac{L}{K} \left(1 - e^{-\frac{K}{L} X'} \right) \quad 4.16$$

Similar to the derivation of equation 4.6, the elongation under Area A is given by the area of the curve multiplied by the highest tension in A, divided by E . In this case, the highest tension within A is $T_{in} e^{\frac{K}{L} X'}$. The resulting equation becomes

$$e_A \approx \frac{T_{in} L e^{\frac{K}{L} X'}}{EK} \left(1 - e^{-\frac{K}{L} X'} \right) \quad 4.17$$

The elongation caused by area B is proportional to the area under the curve from $x=X'$ to $x=L$.

$$Area B = \frac{L}{K} \left(1 - e^{-\frac{K}{L} (L-X')} \right)$$

$$e_B \approx \frac{T_{in} L e^{\frac{K}{L} X'}}{EK} \left(1 - e^{-K \left(1 - \frac{X'}{L} \right)} \right) \quad 4.18$$

The combined elongation for the two areas become

$$e_{total} \approx \frac{T_{in} L}{EK} \left(2e^{\frac{K}{L} X'} - 1 - e^{-\left(-K + \frac{2KX'}{L} \right)} \right) \quad 4.19$$

Sub $X' = \frac{L}{2K} \ln \frac{T_{in0}}{T_{in}}$ into the equation above, we obtain

$$e_{total} \approx \frac{L}{EK} \left(2\sqrt{T_{in0} T_{in}} - T_{in} - T_{in0} e^{-K} \right) \quad 4.20$$

All the unknowns for equation 4.20 are known and thus elongation can be found.

4.2.4: Release Phase

Figure 4.5: Change of housing tension in release phase

If T_{in} keeps decreasing after the transitional phase from pulling to release, the tendon sheath goes into the release phase. As T_{in} decreases further, T_{out} starts to decrease as well. The method to derive the end effector force and the elongation is by changing the side that is “pulling” to be at the distal end instead of the proximal. Looking at Figure 4.5, assuming the sheath maintains the same shape,

$$T_{out} = T_{in} e^K \quad 4.21$$

For simplicity, Figure 4.5 shows the tension distribution when the sheath is in the pulling, end of backlash and releasing phases.

For the elongation, equation 4.11 can be used by substituting the value of T_{out} instead of T_{in} into the equation. The value of T_{out} is from equation 4.21 and the solution for the elongation can be seen in the following

$$e_{total} = MT_{in} e^K \quad 4.22$$

4.2.5: Release to Pull Phase

Similar to the transition from pulling to release, the tension at the end effector remains the same throughout the whole phase.

$$T_{out} = T_{in0} e^{-K} \quad 4.23$$

Where T_{in0} is the lowest point of the tension recorded at the housing before it starts to increase. To find the elongation during this phase, X' needs to be found.

$$T_{in} e^{-\frac{K}{L} X'} = T_{in0} e^{\frac{K}{L} X'}$$

$$X' = \frac{L}{2K} \ln \frac{T_{in}}{T_{in0}}$$

4.24

Figure 4.6: Gradually increasing T_{in} and the tension distribution within the sheath

The shaded area A and B is calculated as before.

$$\text{Area } A = \frac{L}{K} \left(1 - e^{-\frac{K}{L} X'} \right)$$

4.25

$$\text{Area } B = \frac{L}{K} \left(1 - e^{-\frac{K}{L} (L - X')} \right)$$

4.26

However the point with the highest tension for area A and B are different. Looking at Figure 4.6, the pulling point for area A is at T_{in} while for area B it is at $T_{out} = T_{in0} e^{-K}$

Then approximate elongation is therefore

$$e_{total} \approx \frac{T_{in} L}{EK} \left(1 - e^{-\frac{K}{L} X'} \right) + \frac{T_{in0} L e^K}{EK} \left(1 - e^{-K \left(1 - \frac{X'}{L} \right)} \right)$$

$$e_{total} \approx \frac{L}{EK} \left[T_{in} - T_{in} e^{-\frac{K}{L} X'} + T_{in0} e^K - T_{in0} e^{\frac{K}{L} X'} \right]$$

4.27

Sub $X' = \frac{L}{2K} \ln \frac{T_{in}}{T_{in0}}$ into the above

$$e_{total} \approx \frac{L}{EK} \left[T_{in} - T_{in} e^{\ln \sqrt{\frac{T_{in0}}{T_{in}}}} + T_{in0} e^K - T_{in0} e^{\frac{1}{2} \ln \frac{T_{in}}{T_{in0}}} \right]$$

$$e_{total} \approx \frac{L}{EK} \left[T_{in} - 2\sqrt{T_{in} T_{in0}} + T_{in0} e^K \right] \quad 4.28$$

With this equation found, the force at the end effector and elongation of the tendon and sheath are found for all the different phases when the system is used.

4.3: Experimental Setup for Verifying Theoretical Prediction

In order to verify the theoretical aspects derived in the previous section as well as to determine the accuracy of the prediction, physical experiments have to be performed. This section therefore describes the experimental setup as well as the process of initialization necessary to determine the parameters for the subsequent prediction.

4.3.1: Physical Experimental Setup

At the housing, or proximal end, two Faulhaber 2642W024CR DC servomotors with a gear head of 30/1S 134:1 ratio are placed. The two tendons, that are used to control one DOF, are fixed to the two actuators separately. These actuators are set to position control and each of them uses the rotary optical encoder HEDS-5540 A14 attached to the actuator to measure the angular rotation. The combined resolution of the encoder with the gear head is 67000 lines per revolution. At the end effector side, or distal end, another actuator is used under torque control. Its main purpose is to simulate the load that the end effector can apply to the environment. It also has the same rotary encoder attached to the actuator to measure the amount of movement made by the system. In the middle, two tendons and sheaths are used together with an overtube to prevent buckling. The forces at both ends of the system are measured with donut shaped load cells LW-1020 from Interface. Although they measure the compression experienced by the sheaths instead of the tension from the tendons, the result is similar to measuring the tension force at the same end, as shown in equation 4.2. The elastic modulus of the tendons must be known beforehand either from the supplier or measured with a simple stiffness test. The tendons used are Asahi 0.27mm 7X7 Teflon coated wire rope with a length of approximately 2m while the sheath is

Acetone flat wire coil with outer diameter of 0.8mm and inner diameter of 0.36mm with a length of 2m. The bending radius for the sheath and tendon is about 30cm.

Figure 4.7: The Schematics of the Experimental Setup

The rationale of using two actuators for a single DOF is to ensure only one tendon is providing a tension at a given time, while the antagonistic tendon is left loose. This provides the highest possible force from the tendon since it does not have to work against the other taut antagonistic tendon.

The shape of the sheath can be different and the result for the prediction should remain accurate provided the shape remains the same after initializing. For the experiment, the angular velocities of the actuators are deliberately set as low. This is because the application is for the robotic system for ESD and NOTES, the amount of length necessary for actuating the whole motion range of a joint is very short. In many cases, the full length of tendon that needs to be actuated for the whole motion range of the joint is less than 40mm. Furthermore it is likely the user moves in a slow and deliberate manner during the surgery since abrupt and fast movement can hurt the patient during the operation. Therefore the effects of high angular speed of the actuator are considered as negligible.

4.3.2: Necessary Steps for Prediction

After the end effector reaches the site where it is designated to work, the global shapes of the tendon and sheath are fixed. The experimental procedure then goes as follows. First, it is necessary to determine the values of K and M_e for this particular shape of the sheaths. To do so, initialization is required. The actuator at one end of the DOF pulls one end of the tendon until the slave reaches the end of its motion. This is the point where further pulling of the tendon at one side of the joint does not result in a change of the rotation angle, as shown in Figure 4.8. Regarding the actuator at the other side of the DOF, it must minimize the pulling force to prevent interference with the initialization procedure. This is possible since it is controlled by a separate actuator and it can read the load cell on its side, thus deciding either to pull or release the tendon accordingly.

Figure 4.8: Limit of motion for a simple revolute joint

Even when the joint at the distal end reaches the limit of its motion, the actuator on the pulling side can still continue to pull in the tendon at the proximal end. This length that is pulled can only come directly from the deformation of the tendon within the sheath. Using equation 4.11,

$$M_e = \frac{e_{out}}{T_{in}}$$

e_{out} is obtained from the rotary encoder reading from the proximal end while T_{in} is the force obtained from the load cell of the pulling side at the proximal end. The

value of M_e can then be derived from the process of initialization while K can be obtained from equation 4.13,

$$e^{-K} = -\frac{M_e E}{L} K + 1$$

With these two values, the elongation and force at the distal end can be easily approximated, since both elongation and force at the distal end are a simple function of T_{in} . This is repeated for the opposite direction of the DOF as well to capture the specific value of M_e and K . During initialization, the user must prevent the slave from touch any object in the environment. After initialization, the user can start to use the master slave robotic system as desired and both the end effector force and the elongation can be computed using the derived K and M_e values

An assumption is made regarding the use of constant values for K and M_e . After the system has reached the target site, the user no longer moves it around and the shape of the sheaths is regarded as fixed. In this condition, constant values for K and M_e can be used with negligible position and force errors. In the case the user needs to change the system position, the robotic system would require a quick initialization to compute the new values for K and M_e again.

4.4: Experimental Result

The system is then tested by either torque control of the actuator at the distal end or allowing the distal end to push against a hard object or spring. The result when the slave is pushing against a hard non-deformable object is shown in the following.

First of all, the setup is initialized to obtain K and M_e . The experiment is then performed with three profiles as shown in Figure 4.9. In the first profile, the actuator pulls the tendon until it reaches a limited force of approximately 20N on the housing. In the second phase, the tendon is released at the housing to about 5N, while in the third phase, the tendon is pulled again back to 20N. These last two steps test the pull-to-release, release, release-to-pull and pulling phases and check the approximation level with the actual reading. In Figure 4.9, the curves on the top are the readings from the housing load cell while the dotted curves on the bottom are the readings from the end effector load cell.

Figure 4.9: The phases of pulling and releasing that is studied

The comparison of the end effector force with the predicted force is shown in Figure 4.10. The results are broken up into three phases. The graphs on top are the plots of actual vs. predicted end effector force, while the graphs below are the actual vs. predicted elongation plots. The continuous lines in full are the actual sensed values, while the dotted lines are the predicted values.

For this experiment, the maximum full scale error is approximately 7%, while for the elongation, it is approximately 3%. The higher error in the force reading is due to the fact that the value of M_e is found and then used to deduce K . Overall the average full scale error is less than 2%.

Figure 4.10: The results of the actual force/elongation vs predicted force/elongation

4.5: Discussion

Figure 4.11: Buckling of sheath

Another important point to note is that at a high force, the sheath may buckle. This dramatically changes the shape of the tendon and sheath and the value of K and M_e varies instead of remaining constant. As such, the prediction of the force as well as the elongation will not be accurate at high forces. The buckling of the sheath is shown in Figure 4.11.

To counter this problem, the buckling of the sheath is restrained using an overtube for all the sheaths. Due to the size of the overtube and the combined stiffness of the sheath within, it restrains the buckling of the sheaths to ensure it does not affect the estimation of the necessary parameters. Figure 4.12 shows how the overtube tightly constrains the sheaths and prevents them from buckling.

Figure 4.12: Over tube with the loaded sheaths

Although this method is capable of sensing both the elongation and end effector force, it can be applied just in the case where there is little or no change in the sheath shape after initialization. The greater the shape of the sheath changes, the worse the prediction becomes. If a great change of the shape of the sheath is suspected, it is recommended to reinitialize the system again to obtain updated values for M_e and K . If the application force on the sheath undergoes regular displacements, then this method should not be used. However, if the application is not critical and does not require high accuracy, then small changes in the shape of the sheaths during usage can be tolerated.

The force predicted at the end effector is already the combined force the joint experienced. Therefore, it can directly be scaled to the master controller without the need of any further calculation or conversion.

This method can also be used for predicting the end effector parameters for any robotic arm having relatively constant sheath shapes. This offers an additional advantage of locating the sensors away from the end effector. This reduces the inertia of the end effector and allows the robotic hand to work in extreme environmental conditions, whereby sensors at the end effector would fail.

4.6: Conclusion

The mathematical modeling of the tendon and sheath for the force at the end of the sheath, as well as overall elongation, are described in the chapter. Using the analytical approach, important values such as K , M_e and E/L for predicting end effector force and elongation are identified. The method to find these values is explained and the results are verified experimentally. Using this method, the end effector force and elongation can be predicted without a sensor attached. The

required assumptions and important considerations to take note of are also given in the discussion section. Other possible applications on using the modeling are also provided in the discussion.

Chapter 5 : Development of the NOTES Robotic System

This chapter is about the actual development of the NOTES robotic system. Section 5.1 is the design outline for the slave manipulator and discusses the difference between the proposed robotic systems with other conventional MIS systems. It also describes the routing of the tendon and sheath as well as the configuration of DOFs for the slave manipulator. In Section 5.2, the possible slave designs for the various components are given as well as their pros and cons. In Section 5.3, the various joints from Section 5.2 are evaluated and the components for the final prototype are chosen. Section 5.4 describes the final slave manipulator as well as provides its technical specifications such as its size and length. Section 5.5 describes the other components of the robotic system that were designed and the conclusion for the chapter is given in Section 5.6.

5.1: Design Outline for Slave Manipulator

5.1.1: Introduction

The main novelty of the proposed robotic system is on the design of the slave manipulator and it deviates from the other commercially available MIS robot due to the differences in their applications. MIS robots are mainly used for laparoscopy and require an incision on the abdominal wall of the patient to access the peritoneal cavity. In this case, the link between the end effectors and actuators can be straight and rigid, therefore allowing the use of tendon actuation without the sheath. Tendon actuation without sheath produces considerably lesser friction and thus smaller deviation in force between the distal end and proximal end of the slave manipulator.

Another difference is that the supporting base of most MIS robots is situated outside the human patient. The number of DOFs at the end effector can therefore be reduced to as low as two or three while the supporting base generates the other DOFs outside the patient's body. This reduction of DOFs at the end effector corresponds to a reduction in the complexity at the end effector of the slave. The MIS robot also naturally has the necessary triangulation necessary for performing the various

procedures because the entry keyholes incised into the patient can be planned and separated far from each other.

The proposed robotic system is used in tandem with the flexible endoscope to treat patients. In this case the link between the end effector and actuators has to be very long and flexible thereby making it impossible to be used by normal tendon actuation. Instead, tendon sheath actuation has to be used and this introduces high friction and great deviation in the forces between the distal and proximal end. The proposed slave manipulator also does not possess a base that is situated outside the patient body. This means that all the joints for the necessary DOFs have to be within close proximity to the end effector and this result in a more complicated design compared with conventional MIS robots. The arms from the slave manipulator are also expected to be bundled closely to the endoscope in order for the overall size to be small. If the two arms are straight and close to one another, it blocks the view and is not dexterous enough to treat the patient. The arms thus have to open up at the base before closing in at the tip to offer triangulation and this force each arm to possess multiple links. Due to these differences, the designs and requirements for the MIS robots and proposed robotic system are vastly different.

Chapter 4 of this report presents the theoretical prediction of the force at the distal end as well as elongation of the tendon. This gives the assurance that haptics and position control is achievable and therefore the robotic system can be feasible in fulfilling the stated objectives. It can also be known that no extra space is required for fixing sensors at the end effector. At this stage, the development of the slave manipulator can focus solely on actuation and not on allocating space for sensors.

Types of Requirements	Minimum Requirement	Desired Requirement
Length	1.5m	>1.8m
Size	19.5mm	<16.7mm
Force	2.76N	>3N
Vision	>60% blocked	Able to move arms away at will

Table 5.1: Table of design requirements

The design requirements for the slave manipulator are also given in Chapter 3.2 and it is summarized in Table 5.1.

To design the slave manipulator, it is necessary to determine the space set for the tendons and sheaths as well as the configuration of DOFs that the slave manipulator should possess. These are important to determine the components and joint needed for the slave manipulator.

5.1.2: *Tendon and Sheath Routing*

The first task for designing the robotic manipulator is determining the amount of space for the tendons and sheaths. If the space provided for these components is large, more DOFs can be planned. Likewise if the allocated space is small, the number of DOFs that can be implemented is low. The amount of space for the tendon and sheath is dependent on how the tendon and sheath is routed with the endoscope.

As stated in Section 3.2.1, there are basically two ways, one is for the tendons and sheaths to transverse along the outside of the endoscope and the other is for the tendons and sheaths to transverse within the tool channels of the endoscope.

Figure 5.1: *Tendons and sheaths outside the endoscope or within tool channel*

If the tendon and sheaths are outside the endoscope, as seen in the right figure of Figure 5.1, there are lesser constraints in the sheath number and sizes. This allows the use of more DOFs or larger tendon and sheath for greater dexterity and strength. The sheaths can also be allocated further away from the camera and improves the vision from the endoscope. On the other hand, if the tendons and sheaths are allocated within the tool channels, it is smaller and easier for the endoscopist to handle the endoscope. It also makes the system more airtight since there is a seal at the proximal end that reduces the air leak from the porous sheaths.

In the end, size is the most critical specification for the robotic manipulator and therefore the allocation of the tendons and sheath within the endoscope is chosen. If the size is too big for human application, even if it can produce a high force and dexterity, it is not feasible to be used on human beings.

Since it is decided for the tendons and sheaths to transverse through the tool channels, the endoscope used for the robotic system is the Olympus 2T160 endoscope. The size of the tool channels is then 2.8mm on the left size and 3.9mm on the right side. Due to the small size of the tool channels, there is a great restriction on the amount and size of the tendon and sheath for the robotic manipulator. Therefore the configuration of DOFs has to be carefully selected.

5.1.3: *Types of DOFs and Components for Slave Manipulator*

Figure 5.2: DOFs of the proposed slave manipulator

The next decision for the design of the slave manipulator is on the number and types of DOFs it should possess. Due to the severe restriction on the space for the tendon and sheath, the DOFs it should possess should be as low as possible. On the other hand if too little DOFs are designed for the slave robotic system, it cannot perform the necessary procedure due to the lack of dexterity. Therefore it is desired to find out the least number of DOF necessary for the slave manipulator in performing the task of ESD and NOTES.

The first component necessary for the slave manipulator is the base. This base has to be firmly attached to the endoscope and provides a stable platform for the two arms to work on. If the base is not securely fastened onto the endoscope, the forces made by the arms only rock the slave manipulator about the base instead of working on the patient.

Next, the types of DOFs for the slave manipulator were determined. In this case, the decision on the DOFs is basically task driven as well as minimizing the total amount of DOFs.

If the arms are located in front of the endoscope's camera, they inevitably block the view from the camera. On the other hand if the robots are too spread out from the center of the endoscope, the overall size of the system becomes big and it cannot be put in easily and safely into the human body. Therefore to solve this conflicting requirement, a DOF is allocated for it to be closed in when it is inserted through the human's natural orifice and the arms open up after it reaches the site of interest. In this manner it also provides the effective triangulation for the robot during the procedure as well as another DOF for controlling the robot in performing the procedure.

Another DOF for the two arms of the robotic system is the translation of the arms forward and backward. This DOF resembles the endoscopic tools used during the operation whereby tools can be pushed in or pulled out during the procedure. Without this DOF, the endoscopist not only has to manipulate the endoscope to face the site of operation, it also has to adjust the distance from where the robotic arms should work. This results in a more difficult procedure that took up more time and efforts. With the translating DOF, the endoscopist only has to control the endoscope to face the site of the operation and the robotic manipulator can move forward and backward to work accordingly. In this way the difficulty and operational time are reduced.

Another advantage of such a DOF is that it is controlled by pushing and pulling the sheaths attached to the slave manipulator. This utilizes the push-pull cable actuation and do not use up any space allocated for the sheaths for the other DOFs. This is

similar to using available conventional tools for the endoscope and therefore experienced endoscopists can use it with ease.

The rest of the DOFs for the proposed manipulator resemble the DOFs for a simplified human wrist as described in Section 2.4. It has a supination/pronation DOF followed by the hyperextension/flexion of the wrist. Due to the similarity, it is easier to visualize the movements of the slave manipulator and the user can control it naturally with his hands. The supination/pronation joint ensures the gripper or hook of the slave manipulator is able to rotate to a right orientation before it grips the tissue or cauterize the site. This ensures the gripper hold the tissue at most effective angle as well as ensuring a neat cut from the hook. For the hyperextension/flexion joint, it is used to provide the second part of the triangulation formed by the opening/closing DOF. This forms the latter part of triangulation for the slave manipulator so it can ensure a good view from the endoscope that is not blocked by the robotic arms. The DOF also adds to the dexterity of the slave manipulator in performing its task.

Number	Types of component
1	Base
2	Translation joint
3	Opening/closing joint
4	Supination/pronation joint
5	Hook
6	Gripper

Table 5.2: Required components for slave manipulator

In order to perform the task of ESD or NOTES, it is necessary for the robotic manipulator to be able to cut and grip at the same time. Therefore one of the end effector is proposed to be in the form of a cauterizing hook while the other is in the form of a gripper. This follows the conventional tools available to perform the various medical procedures in laparoscopy. In order for the gripper to open and close, the last DOF is allocated as the opening and closing of the gripper. Due to the size of the right tool channel of the endoscope being bigger, the left arm is in the form of the

cauterizing hook while the right arm is in the form of the gripper. From above study, it was decided to design the components listed in Table 5.2

5.2: Listing of Designs with Morphological Chart

After determining the necessary components for the slave manipulator, the possible designs for the various components are brainstormed, designed, fabricated and tested. One of the greatest difficulties on the designing of the slave manipulator is that the size is too small. In order for it to fit into the size requirement, the outer diameter of the whole slave manipulator has to be below 16mm. Therefore the parts for the robot must be designed to be simple in order for it to be fabricated using conventional machining. The morphological chart for the various designs of the robotic slave manipulator can be seen in Figure 5.3.

	Options		
Attachment of base to endoscope	Using screws	Using flexible band	Using flexible tape
Sliding mechanism	Guiding pin prismatic joint	Restraining surfaces prismatic joint	
Type of mechanism for Opening/ Closing joint	Hinge pulley	Spine mechanism	Deformable shaft

Rotation joint	<p>Rotation joint with edge</p>	<p>Rotation joint with fillet</p>	
Hook	<p>Translation hook</p>	<p>Normal hook</p>	
Attachment to hook	<p>Hook held by locating pin</p>	<p>Hook held by screw threads</p>	<p>Hybrid pin and screw</p>
Gripper	<p>Single tendon with slot</p>	<p>Duo fingers different layered</p>	<p>Duo fingers same layer</p>

Figure 5.3: Morphological chart for design of slave manipulator

The detailed study on the various items inside the morphological chart is discussed in the following sections.

5.2.1: *Attachment of the Slave Manipulator to the Endoscope*

The “base” is the first component of the slave manipulator and it provides a stable platform for the arms to work. The first task is therefore to determine the possible means to secure the base of the slave manipulator to the endoscope. The amount of space available for the base is limited. The outer diameter of the 2T160 endoscope is 13.3mm and the desired size of the endoscope with slave manipulator is less than 16mm in order to use the overtube. This only gives 1.35mm wall thickness on each side of the endoscope to work with.

Other than the size requirement, the slave must be detachable from the endoscope easily and it does not damage the endoscope in any way. It also must be secured firmly to the endoscope and can resist the force made by the arms of the slave manipulator. Otherwise even if the arms of the slave manipulator can produce a high force, it cannot be effectively applied on the environment because the base shifts around the endoscope’s tip. Another important consideration is the tip of the endoscope is steerable itself. If the length of the base for the slave manipulator is too long, it hinders the movement made by the endoscope.

Screw

This design makes use of two screws to tighten the base to the endoscope as seen in Figure 5.4. The tightness of the attachment is adjustable by tightening or loosening the screws and this is one of the most traditional means of making mechanism detachable. The screws can provide a very strong holding force onto the endoscope thereby providing a secure platform for the slave manipulator to work on.

Figure 5.4: Conventional detachable mechanism with screws

However since only 1.35 mm space is provided on each side of the wall, there is not enough space to put in the screws or tap in the threads. Even if M1 screws are used, the allowance for the thread of the screw, screw head and length make the whole system bigger than the inner diameter of the overtube.

Flexible band

Figure 5.5: Making use of a flexible tube for fixing cap base

A custom made stretchable plastic tube can be used to hold the base to the endoscope. The flexible band works like a long stretch of rubber band that covers the base and

endoscope by holding it with its deformation potential force. This method uses up little space compared with screws however the strength to stabilize the base is limited. This is because for the flexible band to fit in with ease, the flexible band cannot be very tight but slightly loose. Unless a very long length of flexible tube is used, it is not strong enough to stabilize the cap to the endoscope. On the other hand, if the flexible tube is too long it hinders the steering capability of the endoscope tip.

Flexible tape

This method uses a flexible tape with slight adhesive properties to secure the base of the slave manipulator to the endoscope. In this manner the size of the whole system remains small and the slave manipulator can be easily attached and detached from the endoscope without damaging it. A key difference between the usages of flexible tape with flexible band is that the flexible tape can be stretched and applied tightly to the endoscope without any gap. Thus this results in a high stabilizing force that can withstand the forces from the movement of the arms.

Figure 5.6: Using a insulating tape for holding cap base

5.2.2: Design of the Translation Joint

The first joint for the slave manipulator is the translation joint. It is required for it to slide smoothly forward and backward yet uses up as little space as possible. As mentioned in the previous section, the available size for the wall thickness of the translation joint and base is 1.35mm. It also has to ensure that the other DOFs are constrained during the translation joint so that its movement is smooth and

predictable but not shaky. The design should also prevent the translating joint moving too far and slipped out of the base.

Guiding Pin Prismatic Joint

One possible design for the sliding mechanism can be seen in Figure 5.7. It made use of a guiding pin to allow only the grey link to translate in the Z axis while restraining the other DOFs. The design also has a stopper to prevent the translating link from moving out of the base.

Figure 5.7: Guiding pin mechanism for translation joint

However the space that this design requires is high. To allow the whole system to be able to fit into the overtube, the size of the wall is approximately only 1.35mm thick. Even if 0.5mm diameter guiding pins are used, the remainder wall thickness on each side of the pin to work on is less than 0.5mm and can be too weak and too difficult to be fabricated.

Restraining Surfaces Prismatic Joint

Figure 5.8: Restraint surfaces mechanism for translation joint

Another possible design for the prismatic joint can be seen in Figure 5.8. Instead of using guiding pins to restraint the other DOFs, the mechanism makes use of multiple surfaces to ensure it only slides forward and backward in a steady manner. Although this design is more complicated and more difficult to assemble, it wastes lesser space compared with the guiding pin design. The required thickness for this mechanism is only 1mm and is therefore lower than the required 1.35mm in order for it to go through the overtube.

5.2.3: Design of the Opening/Closing Joint

Figure 5.9: Types of linkages on actuation of joints

Generally, in order to actuate bending motion using tendon and sheath, there are three different designs options available. One of them is making use of tendons to bring about deformation of a deformable central shaft as seen in Figure 5.9. The second make use of multi spine-like mechanism joined octagonal to one another and the last one is using pulleys. The choice of the type of linkages is important since it sets the general design and performance for the slave manipulator. Therefore an in depth study on the three designs options are conducted to select the best possible design option for the slave manipulator.

Deformable Shaft

For the deformable shaft, it made use of a flexible and slightly compressible material as the central shaft. At the internal side of the shaft, many rings are situated on the four sides of the wall where a tendon can run through it. Without any pulling of the tendon, the shaft is at a neutral position. When a side of the tendon is pulled, it compresses or folds the material between the rings resulting in a shorter side to the shaft. This action causes one side of the shaft to be longer than the other side and it bends. Using this actuation, it can perform 2 DOFs movement and this is widely used for designs of the endoscope [86][87].

This form of actuation takes up very little space in the whole tube and it is useful for miniaturization. This is particularly true since it does not use up any space in the center and therefore able to accommodate other devices through it. Generally, in order for it to bend, the length of the deformable shaft has to be long enough. However if the length is too long, the moment caused by the horizontal force is much higher than the moment caused by the pulling tendon due to the difference in the perpendicular distance. This means that with the same tendon force pulling the shaft, it can only exert a much smaller force horizontally. Furthermore there is a loss of force in deforming the shaft.

The mathematical solution of the force pulled by the tendon, force it exerts laterally and deflection is given in the equation below [88]

$$\delta = \frac{k^2 x^2 (L \cot \alpha - e)}{2} - \frac{k^2 x^2 \cot \alpha}{6}$$

Where α is the angle of the resultant force, e is the distance from the center of the shaft to the connection of the tendons, δ is the deflection of the beam, L is the length of the flexible region and $k^2 = \frac{F \sin \alpha}{EI}$. E is the young modulus of the material, I is the moment of inertia and F is the magnitude of the force exerted on the shaft. However the assumption is that amount of deformation has to be small in order for the equation to be valid.

Figure 5.10: Definition for equation of buckling with eccentric loading [88]

Since this type of design is to provide force as the shaft deflects, it is necessary to find out the force it can exert over the force the tendon had pulled. Let $L=40mm$ and the corresponding values of EI and e is shown in Figure 5.11. The value of the vertical force is fixed as 1 while the horizontal force varies from 0 to 1. The amount of deflection the deformable shaft experience as horizontal force varies can be seen in Figure 5.11.

Figure 5.11: Graph of deflection of deformable shaft with increasing horizontal force

Initially the values of the deflection are at a negative value because the allocation of the length e provides a clockwise moment and a deflection to the right. As the horizontal force giving an anti clockwise moment increases, the deflection increases till it pass 0 and reaches positive values.

It can be seen that if the horizontal force is increased from 0 to 1, when e is set as 5mm and the tendon pulls at 1 N, it can only generate 0.13 N horizontal force. This is actually the ratio of the height of the deformable shaft compared with the thickness of it. The stiffness and shape of the material does not affect this efficiency but it affects the amount of deflection the shaft made. This made it harder for this mechanism to start deflecting because the stiffness of the shaft is higher than the other designs. To improve on the efficiency the distance of the tendon from the middle has to be increased but this inevitably increases the size of the mechanism.

Spine Design

Figure 5.12: Design of the endoscope bending mechanism [89]

For the spine design, the amount of force the mechanism can produce is calculated. Figure 5.12 shows one of the joint from the design of an endoscope mechanism for bending [89] and it is similar to many designs of flexible sheath actuated by tendon.

For studying its force capability and check for singularity, a coordinate system is set for one of the link as shown in Figure 5.13. The origin of the analysis is at the pivot of the joint and the XY coordinate frame is set up as shown in the black lines. When the joint rotates anti-clockwise, the angle that it had rotated is set as θ . Consequently

as the joint rotate in a clockwise manner, the angle it rotates is $-\theta$. When the joint is upright as shown in Figure 5.13, the angle is 0.

For each tendon involved in the actuation of the joint, there are two points of interest. One of them is the point where it originates from (now known as originate point) while the other point is the location when it is fixed to (now known as end point). Basically it is the point where the tendon comes out from the base of the mechanism to the point where the tendon is fixed to the rotatable joint. Let the coordinate of the originate point on the right side of the mechanism be (X_0, Y_0) and the end point be (X, Y) . Subsequently on the other side the coordinate is $(-X_0, Y_0)$ and the end point is $(-X, Y)$. Let L_1 be the length of tendon on the right side of the mechanism while L_2 be the length of tendon at the left side of the mechanism.

As the joint rotates θ angle, the originate point remains the same while the end point location changes. By using matrix transformation, the coordinate of the right end point after an arbitrary rotation θ is

$$\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} X\cos\theta - Y\sin\theta \\ X\sin\theta + Y\cos\theta \end{pmatrix}$$

Figure 5.13: Coordinate system set for spine mechanism

Since the originate point remains the same after rotation, and assuming the tendon never touches the hinge at the pivot, then the length L_1 becomes

$$L_1 = \sqrt{(X_0 - X\cos\theta + Y\sin\theta)^2 + (Y_0 - X\sin\theta - Y\cos\theta)^2}$$

$$L_1 = \sqrt{X_0^2 + Y_0^2 + X^2 + Y^2 - 2X_0(X\cos\theta - Y\sin\theta) - 2Y_0(X\sin\theta + Y\cos\theta)} \quad 5.1$$

On the left side of the mechanism, since it is symmetrical, the length of L_2 can be found by substituting X_0 as $-X_0$ and X as $-X$ into the above equation.

$$L_2 = \sqrt{X_0^2 + Y_0^2 + X^2 + Y^2 - 2X_0(X\cos\theta + Y\sin\theta) - 2Y_0(-X\sin\theta + Y\cos\theta)} \quad 5.2$$

Let's substitute a *hypothetical* dimension of 3 mm, 4 mm, 3 mm and -4 mm respectively as X , Y , X_0 and Y_0 . The resulting equation becomes

$$L_1 = \sqrt{50 + 14\cos\theta + 48\sin\theta} \quad 5.3$$

$$L_2 = \sqrt{50 + 14\cos\theta - 48\sin\theta} \quad 5.4$$

And the graph of L_1 and L_2 against θ is plotted as seen in Figure 5.14.

Figure 5.14: Length of L_1 and L_2 against θ for the hypothesis dimension from -55° to 55°

From the figure, it can be seen that the rate of change of L_1 and L_2 are not constant. If the length L_1 and L_2 are pulled and released accordingly at the same velocity, the joint rotates with a different angular velocity. Furthermore to rotate the joint, the amount of tendon released at one side is not the same as the amount of tendon pulled at the other side. From the figure, as the joint rotates from 0.4 rad to 0 rad, the amount of tendon released by L_1 is 1mm while the amount of tendon pulled by L_2 is approximately 1.3mm. This makes the system experience higher slackness or tautness of the tendon during the rotation which is undesirable for control.

To quantify the effectiveness of the design of the joint to give out torque, the effective perpendicular distance from the pivot is to be found. It uses the simple formula $T = \text{Perpendicular distance} \times \text{Force}$ and the value of the perpendicular distance is directly related to the force provided by the tendon to the effective torque it can give to the joint.

To calculate this value, the distance from a point to a line is to be found using the formula. The point of interest in this case is the center of rotation while the line is the straight line between the originating point and end point of a side of the mechanism.

$$\text{Perpendicular distance} = \frac{|y_1 - mx_1 - b|}{\sqrt{m^2 + 1}} \quad 5.5$$

where (X_1, Y_1) is the coordinate of the point of interest, m is the gradient of the line and b is the y-intercept of the line. In the case of this analysis, the coordinate of the point is the origin and therefore both X_1 and Y_1 are zero. The gradient m is actually the gradient of the straight line between the originate point and end point at the particular rotation θ is found. The gradient is found by using the standard formula change in Y over change in X

$$m = \frac{(X \sin \theta + Y \cos \theta) - Y_0}{(X \cos \theta - Y \sin \theta) - X_0} \quad 5.6$$

The y-intercept b can be found by substituting a point into the equation of the line $y = mx + b$. Since the tendon originating point (X_0, Y_0) does not change, $b = Y_0 - mX_0$.

The resulting perpendicular distance becomes

$$d_1 = \frac{|Y_0 - mX_0|}{\sqrt{m^2 + 1}} \quad 5.7$$

The higher the value of d_1 or d_2 , the greater torque the joint can generate given the same force. As seen from the diagram, the force it can generate is the weakest when the top hinge is tilted to the opposite side of the tendon.

Figure 5.15: Perpendicular distance d_1 and d_2 with respect to θ

This design, similar to the deformable shaft design, requires a long length of the manipulator in order for it to work. This can be undesirable since a longer slave corresponds to a loss in dexterity and the slaves can hit the walls of the GI tract easily. However the range of motion can go higher than 180° with the use of multiple linkages. The problem of loss of force transmission can also be averted by restricting the motion that one of the joint can make. However this inevitably increases the cost and complexity of the system. This system also has a variable rotational speed and force with respect to θ and therefore is less predictable than one with a constant rotational speed and force regardless of θ .

Hinge Pulley

For the design with the hinge pulley, the coordinate is given as seen in Figure 5.16. To analyze the length and velocity of the tendons on each side, the approach for analyzing the spine mechanism is used with a slight modification. Previously the tendon are not guided on any other surfaces and the length of the tendon is the difference between the coordinates of the originate and end points. Now the rounded pulley acts as a guide for the tendon and the tendon direction and movement had changed. The length has to be broken into two regions. One is the point where the tendon follows the guide while the other is the point where the tendon leaves the guide towards the originate point. The dimensions of $X=0\text{ mm}$, $Y=2.2\text{ mm}$, $X_0=1.5\text{ mm}$ and $Y_0=-4\text{ mm}$ and the radius for the rotating pulley be 2.2 mm is used for the

analysis. First the location of the point where the tendon does not follow the guide is calculated.

Figure 5.16: Coordinate System set for hinge pulley configuration

Looking at the right diagram of Figure 5.16, the angle which the tendon made with the base can be split into angle A and B . Using geometry,

$$A = \tan^{-1} \left(\frac{Y_o}{X_o} \right) \quad B = \sin^{-1} \frac{Y}{\sqrt{X_o^2 + Y_o^2}} \quad 5.8$$

Next the angle θ_0 at which the joint has to rotate for it to reach the point where the tendon ceases to follow the guide is found. At the specified point where it just ceases to follow the guide, the end point forms a straight line with the originate point. Therefore

$$\tan(\pi - A - B) = \frac{(X \sin \theta_0 + Y \cos \theta_0) - Y_o}{(X \cos \theta_0 - Y \sin \theta_0) - X_o} \quad 5.9$$

Since θ_0 is the only unknown in the equation, it can be solved. Using the above dimensions, the answer of $\theta_0 = -100.44^\circ$ or -1.753 radians is found. The length of tendon from the originate point to the point it first ceases to follow the guide is found using equation 5.1 to be $L_0 = 3.66 \text{ mm}$. The length of tendon is then simply

$$L_I = r\theta + L_0$$

$$L_1 = 7.519 + 2.2\theta$$

Similarly,

$$L_2 = 7.519 - 2.2\theta$$

The effective perpendicular distance for the hinge joint is simply the radius of the pulley for the hinge pulley design. The result for the analysis of length and perpendicular distance is shown in Figure 5.17. As can be seen, the rate of change for the length L_1 and L_2 and d_1 and d_2 are the same regardless of the rotation of the joint.

Figure 5.17: Analysis of the length and perpendicular distance of hinge joint

From the analysis, it is found that the hinge joint offers more predictability, steady force output as well as greater range of movement for one of the joint. The angle of rotation now goes from -100° to 100° which is higher than the -55° to 55° of the spine design. The force is also consistent throughout the whole range of movement and these two features offer predictability for the user.

Conclusion on Selection of General Design for Slave Manipulator

Therefore for the design of the slave device, the hinge pulley design is chosen. This is because this design can provide the highest force, predictability as well as shortest length compared with the other design. It also provides a highest range of rotation within a certain stipulated length. Using the hinge pulley design, ball bearings can also be conveniently used which can reduce the friction cause by friction substantially. This is also the design chosen by a lot of commercial and research

surgical robots. [90]. This study also help in determining what are some of the important details to look out for during the designs of the subsequent joints.

5.2.4: Design for Supination/Pronation Joint

Figure 5.18: Difference in opening/closing joint and supination/pronation joint

The supination/pronation joint is different from the opening/closing joint in that the axis of rotation is parallel with the tendon direction. For the opening/closing hinge pulley design, the axis of rotation is perpendicular to the tendon pulling direction and therefore the tendon can be attach directly to the pulley after it exit from the originate point. In the case of the supination/pronation joint, the axis of rotation is parallel to the tendon pulling direction instead. In order for the tendons to provide a turning moment to the pulley, the tendon has to bend 90° after exiting from the originate hole as seen in Figure 5.18.

Figure 5.19: Comparison between normal drilled hole, countersunk hole and rounded edge

Due to the high bending angle, the tendon rubs against the edge of the tendon hole and it experiences high abrasion. This could caused the strength of the tendon to experience fatigue at a much higher rate and his strength could be reduce by more than 50% as stated in Section 3.5.3.

To reduce on the abrasion on the tendons, the edge which the tendon bends toward must not be too sharp. A solution to this is to countersink the hole or place a rounded edge near the exit of the hole as seen in Figure 5.19. If the slave mechanism is designed to let the tendon bend only at a low angle, countersunk hole is good enough in reducing abrasion. If it is desired for the tendons to bend at a high angle such as 90° , the rounded edge near the hole is more effective in reducing abrasion.

Two possible ideas on adding the rounded edge near to the originate hole of the tendon are thought out. One of them is the making use of a ring of rounded edge around the pulley as seen in Figure 5.20. In this way, the tendon always faces a smooth rounded edge as it is actuating the supination/pronation joint.

Figure 5.20: Rotation joint with ring of rounded edge and rounded fillet

Another possible design is making use of a protruding fillet near the tendon originate point as shown in Figure 5.20. In this case the tendon do not faces a sharp edge since the fillet ensures it bends gradually. However an advantage of using a rounded fillet is that it saves more on space compared with the rounded edge design. The space it wastes using the rounded edge is a small strip in front of the originate point of the tendon while the space wastes by the rounded edge is a whole ring as seen in Figure 5.21. Therefore the design of the rounded fillet generally saves more on the space compared with the rounded edge. It should be noted that the rounded edge of the

former design cannot be too narrow otherwise the tendon can slip below this edge and get caught between the pulley and rotation base, causing tendon jam.

Figure 5.21: Space wasted between external ring and fillet near tendon originate point

5.2.5: Design of Cauterizing Hook

The next component of the slave manipulator is the cauterizing hook. There are three roles which the hook component has to fulfill. First the hook needs to perform the hyperextension/extension movement of the wrist. Second it must withstand the high electrical current from the cauterizing machine and cut the desired site as efficient and effectively as possible. Lastly it must be electrically insulated from the rest of the slave manipulator to prevent unintentional cauterizing of the patient.

Figure 5.22: Design of the hyperextension/extension joint of the hook

After the study on the different types of actuation for bending in Section 5.2.3, the pulley hinge design is carried on the hook's hyperextension/extension movement.

This is because from the study it was found to be more predictable, shorter and wider range of movement compared with the other actuation means. A possible design for the hook can be seen in Figure 5.22.

Figure 5.23: Design of the translation hook

It is however possible to add another DOF to the hook component for it to perform the procedure with ease. If the hook is capable of performing translation movement forward and backward, the extra dexterity can perform the procedures easier. This is because the surgeon only needs to position the hook behind the flesh that is to be cut and then pulls the hook in to provide the tissue tension. A possible design for the translation hook can be seen in Figure 5.23. It made use of a single tendon and sheath to actuate one DOF and using a spring for it to return it back into position.

Although the translation hook had an increase DOF, the length of the hook component increases substantially. This is especially true if the length of the stroke is long. A longer slave manipulator not only makes it easier to hit the walls of the stomach and get trapped, it also reduces the amount of force that the lower joints can exert to the environment. This is because the force that the joint can exert on the end effector is a ratio of the joint effective perpendicular distance with the distance of the joint to the tip of the end effector. Therefore a longer slave manipulator is not desirable since it reduces the much needed force at the end effector. This design also makes it harder for it to be insulated securely.

Figure 5.24: Ratio of effective perpendicular distance to tip of end effector tip

Another role played by the hook is the ability to cauterize yet insulate the rest of the slave manipulator from the high voltage at the hook. The hook must also be fastened securely enough to prevent it from coming off or rotates about the base. This is because the force exerted by the hook can be high and the shape of the hook inevitably provides a high turning moment to twist itself. Furthermore during cauterizing, the temperature of the hook can reach up to several hundred degrees Celsius and it can melt normal plastic.

Figure 5.25: Method to fix cauterizing hook to base

The possible designs for holding the hook can be seen in Figure 5.25. For the left design, it makes use of locating pins to fix the DOFs of the cauterizing hook. A hole is drilled within the cauterizing hook and is fixed to the base by using a locating pin. A problem using this method is that the drilling of the hole inside the hook and base is required to be very precise. Otherwise the hole drilled through the hook and hook

base is not in a straight alignment and the pin cannot fit into the two components. This difficulty is increased if the pin must only be slightly smaller than the hole in order to prevent the hook from being shaky.

Another possible means to secure the hook to the base is by making use of threading on both the hook holder and hook. To prevent the hook from rotating, adhesive is added to the groove and top of the screw holder to bind the two pieces together. The problem of such a method is that if the force the hook experienced is high, it could overcome the bonding strength of the adhesive and turn the hook.

The last possible design is the use of both screw and locating pin. The hook and hook holder are both threaded and there is a hole for both components to fit in a locating pin. In this way the hole for the locating pin can be made significantly larger than the pin. However for this design, the size of the screws threads on the hook must be pretty big in order to drill the hole for the locating pin.

In order for the base to stand the high temperature from cauterizing, the material for the hook holder is chosen to be ceramic. This is because ceramic is not only inert to the human body, it is also an electrical insulator, possess a very high melting point and had high hardness. Tests had been conducted before on the engineering plastic as an insulator before however it is found to melt during prolonged cauterizing.

5.2.6: *Design for the Gripper*

For the gripper, its role is to perform the hyperextension/extension movement of the wrist, open and close the jaws of the gripper and also the design of the teeth of the gripper to hold grasp tissue better. The hyperextension/extension motion and the opening/closing of the jaws are discussed collectively since the design can incorporate both motions at the same time.

Figure 5.26: Figure showing the single tendon controlled gripper

Three different possible designs are discussed for the motion of the gripper. Since the closing force is required to be much higher than the releasing force of the gripper, the first design on the opening/closing of the gripper is by using the n' actuator for n DOFs configuration as can be seen in Figure 5.26.

On each arm of the gripper, it is attached to two pins. One pin is at the side and the other is at the middle pin which is controlled by the sole tendon and spring. Due to the slot on the gripper and the side pin, as the middle pin moves up and down, it opens and closes the gripper. When the tendon pulls down, it acts against the spring and force the middle pin to translate down as shown in Figure 5.26. When the tendon is released, the spring is then freed and it forces up the middle pin.

Figure 5.27: Design of gripper controlled by a single tendon

Although the gripper can be actuated with a single tendon and sheath, the force that is produced by the joint is weak because it has to overcome the force from the spring. The design is also less intuitive compared with the other designs because each individual jaws cannot be controlled.

Figure 5.28: Grippers having two layers of pulley hinge joint

Another possible design is utilizing two pulley hinges arranged in a layered manner to control the opening and closing of the gripper. The first hinge pulley layer rotates two jaws of the gripper simultaneously while the second hinge pulley layer only rotates one jaw of the gripper. The illustration showing the first and second layer for the gripper can be seen in Figure 5.28.

Figure 5.29: Single layer pulley hinge design for gripper

Lastly the two jaws of the grippers can be designed to have the same layer and both acts as a single pulley hinge joint. In this case, the overall length of the gripper had become shorter and it is more intuitive to be controlled compared with the gripper joint at two different layers.

On the design of the gripper teeth, the various existing MIS robotic end effector are studied. There are many different shapes and sizes for the gripper, each is specially designed for holding a particular type of tissue as well as amount of tissue to be gripped. For example, if the flesh is very slippery and stiff, the teeth of the jaws should be slightly sharper in order to hold it properly with slipping. On the other hand if the flesh is easily torn and loose, a flat but coarse gripper is more appropriate. Some of the available shapes for the gripper can be seen in Figure 5.30

Figure 5.30: Possible gripper design from da Vinci instrument catalogue [91]

In the case of procedure on the wall of the stomach, it is very slippery and stiff. It is also desired for the slave manipulator to just pinch a bit of the flesh and not the whole length of the jaw in order for it to handle it with ease. Therefore the cobra teeth gripper is chosen and it is designed to be able to grip the flesh of the stomach as well as possible.

Figure 5.31: Chosen cobra teeth design for shape of gripper

5.3: Evaluation of Design Options

After the various types of joint are proposed and the advantages and disadvantages are discussed, a matrix evaluation table is made based on the following criteria.

- 1) ***The amount of force the gripper can exert or withstand.*** With a higher force, the slave manipulator can control the environment with greater ease compared with a weaker slave manipulator.
- 2) ***The required size for the design.*** The slave manipulator must be able to be small in order to go through the natural orifice of the human easily for it to work on.
- 3) ***The predictability of the design.*** This is the robustness of the design and whether it is prone to any possible failures.
- 4) ***Length of the design.*** The longer the length is, the more cumbersome it becomes and the lesser force can be produced from the lower joints.

Types of Joint	Force	Size	Predictability	Length	Total
Base: Screws	3	1	2	2	8
Base: Flexible tube	1	2	1	1	5
Base: Flexible tape	2	3	2	2	<u>9</u>
Translation: Guiding pins	2	1	2	2	7
Translation: Restrained surfaces	2	3	2	2	<u>9</u>
Opening: Deformable shaft	1	3	2	1	7
Opening: Spine mechanism	2	2	1	2	7
Opening: Pulley hinge	3	1	3	3	<u>10</u>
Rotation: External ring	2	1	1	2	6
Rotation: Rounded fillet	2	3	3	2	<u>10</u>
Hook: Translation	3	1	1	1	6
Hook: Normal	1	3	3	3	<u>10</u>
Hook holder: Locating pins	3	2	1	3	<u>9</u>
Hook holder: Threads	1	1	3	2	7
Hook Holder: Hybrid	2	3	2	1	8
Gripper: Single tendon gripper	1	2	1	2	6
Gripper: Two layered gripper	2	1	2	1	6
Gripper: Single layered gripper	3	3	3	3	<u>12</u>

Table 5.3: Table showing the matrix evaluation of the various components

The table is formed with information based on analytical studies and also tested by actual designing, fabricating and verifying its performances. Experiments are also conducted on several components of the slave manipulator fixed together in order to determine the effect of interactions between the various joints. The effect of stiffness from the higher sheaths to the lower joints, the combined length effect to the lower joints, the workspace the end effectors can move and the vision to the endoscope can only be known if a multi-DOFs experimental platform is built and tested. These experiments are mainly simple tests such as looking from the view from the endoscope as well as estimating the force output with a force gauge.

For the chosen opening/closing joint, supination/pronation joint and hyperextension/extension joint, experiments were first conducted to determine the

force it can produce as well as the accuracy of the distal force and elongation predictions. The translation joint is not included in this study because it is controlled manually and its force output depends directly on the force exerted by the surgeon himself. The translation joint also do not use the prediction studies because it is not actuated by using tendon sheath actuation but instead by pushing and pulling the sheaths.

5.3.1: Maximum Force

A series of experiments were conducted to test the maximum force the joint can exert by itself and at the end effector. Force is one of the most important specifications for the slave manipulator and the experiments can check if the force that the joint produces is enough to fulfill the minimum required force for the project.

The experimental setup shown in Figure 5.32 is used to check the force from the various joints. The joint is clamped in position and fixed as per normal with tendons (Asahi 0.27mm 7X7 Teflon coated wire rope with length 2.2m) and sheaths (Acetone flat wire coil outer diameter 0.8mm inner diameter 0.36mm with length 2m) to a housing module with an actuator (Faulhaber 2642W024CR DC servomotors, gear head of 30/1S 134:1 and rotary encoder HEDS-5540 A14) There is also a loadcell (Interface washer type load cells LW-1020) located at the actuator front plate to measure the compression of the sheath. On the slave end of the manipulator, the movement from the joint is stopped by a Mecmesin AFG 100N force gauge that is also clamped in position and set to compression mode measuring maximum force. The bending radius of the sheath was fixed at approximately 30cm.

The experiment starts by actuating the end effector to push against the force gauge. The end effector keeps pushing the force gauge until the loadcell at the proximal end reaches 20N, which is the determined safe force limit for the slave before the tendon and sheath is damaged excessively. The reading of the force gauge is then recorded at the moment when the proximal load cell just registered a reading above 20N. A total of ten experiments are conducted for each joint.

Figure 5.32: Experimental setup for measurement of maximum force of joint

The max force of the joints can be seen in Table 5.4. As can be seen the weakest force at the joint is at the supination/pronation joint with approximately 3.57N while the forces from the opening/closing joint is comparable to the hyperextension/extension joint at 5.16N and 5.37N. The lower force output from the supination/pronation joint is because it has to bend more than 90° before actuating the pulley and this increases the friction it experienced substantially. The high standard deviation can be explained by the difficulty in measuring the force at the same position of the slave manipulator during the experiment.

Joint Name	Force (N)	Standard Deviation
Opening/closing	5.16	0.20
Supination/pronation	3.57	0.12
Flexion/hyperextension	5.37	0.15

Table 5.4: Maximum force from various joint at the joint level

Another series of experiments are conducted on the output force at the end effector. This is because the combined length and stiffness of sheaths from the other DOFs can affect the force output from the particular joint. The experiment setup is similar to Figure 5.32 except that the whole slave is assembled with all the tendons and sheaths fixed to its respective actuator housing module. The force gauge then measures only at the tip of the end effector and not just slightly above the joint. A total of ten experiments are conducted on each joint.

The max force of the joints at the end effector end can be seen in Table 5.5. As seen the weakest force of 2.87N is produced by the opening and closing joint while the

highest force of 5.37N is produced by the end effector joint. The reason why the opening/closing joint is reduced tremendously is because it is much further away from the end effector and it has to overcome the stiffness of the sheaths from the other joints.

Joint Name	Force (N)	Standard Deviation
Opening/closing	2.87	0.13
Supination/pronation	3.29	0.14
Flexion/hyperextension	5.20	0.12

Table 5.5: Maximum force from various joints for intermediate prototype

According to Section 3.2.3, the minimum required force for the joint is approximately 2.76N and the forces from these joints fulfill this requirement. However it is recommended for the force to be above 3N, this cannot be achieved with the current slave robotic system due to the reduction in the size to fit into the Guardus overtube. Nevertheless the weakest joint has cleared the minimum required force for the system.

5.3.2: Distal End Force Accuracy

To confirm the accuracy of the force at the distal end with the prediction from the modeling, a series of experiments with the experimental setup shown in Figure 5.33 is performed. The actuators, load cells, sheaths and tendons used are the same as the experiment setup described in Section 5.3.1.

Figure 5.33: Experimental setup to confirm accuracy of force at distal end

Two tendons are wound antagonistically around the slave manipulator as it is usually done in normal application. One of the tendons goes through a sheath and attached to an actuator. The tension of the tendon is then recorded by the loadcell (Interface washer type load cells LW-1020) at the proximal end as shown in Figure 5.33. The other antagonistic tendon is fixed tightly to another distal end load cell directly with the cable without any sheath. When the actuator at the proximal end pulls on the tendon, it tries to rotate the joint. However this rotation is halted by the antagonistic tendon fixed to the distal end loadcell. This force used to prevent the rotation of the slave manipulator is recorded and this is the force which the slave manipulator actually exerts on the environment. This is compared with the predicted force from the reading at the proximal loadcell.

Figure 5.34: Experimental data on distal end force estimation with prototype joints

The data provided from the trials are given in Figure 5.34. The blue lines are the actual readings from the distal end load cell while the red lines represent the prediction from the modeling. Since the pulling force from the actuator and load cell

acts within the same perpendicular distance from the joint's center of the rotation, the tension force at the end of the sheath should be the same as the force recorded on the distal end load cell. The experiment is repeated to obtain three different set of readings for the three joints. From the data, the average error is approximately 0.2N with a standard deviation of 0.0534N for approximately 8N from the distal end force. The worse prediction comes from hyperextension/extension joint with an average error of 0.27N while the best performing prediction is the supination/pronation joint with an average error of 0.14N. The average full scale error is thus approximately 2.5%.

5.3.3: Elongation Accuracy

Similarly, the accuracy of the positioning of the slave manipulator has to be performed with an experiment using the experimental setup shown in Figure 5.35.

Figure 5.35: Experimental setup to confirm accuracy of position at distal end

The experimental setup is similar to the one performed on force accuracy of the system except it focuses on the prediction on the elongation. For this experiment, the slave manipulator has two tendons that were wound around the slave manipulator. One of the tendons is still connected to the tendon and sheath that is in turn attached to the proximal end with a load cell and actuator. This time the other tendon goes around a low friction high resolution rotary encoder (Faulhaber 3863A024C with gear ratio 3.71:1 and encoder HEDS-5540 A12). Whenever the actuator pulls the tendon and sheath, it rotates the slave manipulator which in turn rotates the rotary

encoder. In this way, the amount of rotation the slave manipulator moves can be recorded by the reading from the rotary encoder and verified with the predicted position result. Resistive force is applied to the slave manipulator directly as can be seen in Figure 5.35. The reason for it is to ensure the tendon do elongates before it rotates the slave manipulator. The experiment is conducted with three different load settings. The result of the experiment can be seen in Figure 5.36. Three experiments are made on each of the joint.

Figure 5.36: Experimental data on elongation with prototype joints

The blues lines of the graph represent the actual elongation of the tendon while the red lines represent the estimation using the modeling. The grand average of the error is approximately 0.523mm with a standard deviation of 0.297mm for the range of 18 to 23mm and the average full scale error is about 2.3%. The worse prediction comes from hyperextension/extension joint with an average error of 1.02mm and the best

prediction is from open/close joint 2 with average error of 0.24mm. As seen from the result, the positioning error is low for the tendon sheath system.

After the three sets of experiments are conducted on each of the joint, the final prototype for the slave manipulator is designed and built. The details of the prototype can be seen in Section 5.4.

5.4: Final Prototype of Slave Manipulator

After the experiments are conducted on the various joints and tested to have passed the requirements, the design of the various components of the slave manipulator are further enhanced and fabricated as shown in Figure 5.37.

Figure 5.37: Overall view of slave prototype

This prototype is a two-armed, nine DOFs slave manipulator that is tendon sheath actuated. Using this prototype, 15 ESD *ex vivo* trials are completed as well as two *in vivo* ESD trials on live pigs. It is also successful in performing two liver wedge resections on two live pigs using this robotic system. The design and the breakdown of its components can be seen in Figure 5.37. For this prototype, there are seven motorized DOFs of the slave manipulator which are controlled by the surgeon while two non-motorized DOFs which are controlled by the endoscopist. The types of components chosen for the design of the prototype are summarized in Table 5.6.

The overall size of the slave manipulator is approximately 16mm when the arms are straight and it can be easily pushed through a Guardus overtube (Refer to Section 3.2.2). Therefore the size of the endoscope and slave manipulator of this prototype is already suitable for use on human beings. During the procedure, the overtube is first inserted into the upper GI tract to reach the stomach and the slave manipulator just transverse within this overtube to reach it. This makes it easy for the slave manipulator to be inserted and taken out as well as protecting the patient from possible scratching by the slave manipulator.

Types of Components Required	Chosen Design for Components
Attachment to base	Flexible Tape
Translating Joint	Restraining Surfaces
Opening/Closing Joint	Pulley Hinge
Rotating Joint	Rounded Fillet
DOFs for Hook	Normal Hook
Attachment to Hook	Locating Pins
Gripper	Single Layered Gripper

Table 5.6: Chosen design for prototype

The length of sheaths used is 2m which is much longer than the length of the endoscope. This makes it more comfortable and easier for the endoscopist to control the endoscope. The length of the slave manipulator in front of the endoscope is 40mm and the thickness of each arm is approximately 6mm. For this prototype, a 0.27mm outer diameter stainless steel wire coated with Teflon from Asahi is used while the sheaths are 0.9mm Asahi stainless steel flat coil sheaths. The Teflon coated

tendon reduces the friction of the system and is more resistant against abrasion and kinking.

Using the information of the length of each links as well as the configuration of the DOF, the workspace formed by the two arms of the slave manipulator can be seen in Figure 5.38. The blue and red space is where the end of the arms can work on. As can be seen the workspace for both arms are relatively big and can reach in front of the endoscope to perform treatment to the patient.

Figure 5.38: Workspace of the prototype

The vision from the endoscope is good because the arms can open up at the base before closing in at the interested site with the hyperextension/extension DOF. The results from using the intermediate prototype are discussed in detailed at Chapter 6.

5.5: Design for the Other Components of the Robotic System

Other than the slave manipulator, there are other components of the robotic system that need to be designed and fabricated. This includes the actuator housing, microprocessor and master console. However the description of the design for the

master console is not included in this thesis because it is the work of another researcher in the project.

5.5.1: *Actuator Housing*

Figure 5.39 shows the picture of the actuator housing used for the prototype. The main function of the housing actuator is to contain all the actuators used for holding the tendons and sheath at the proximal end. To achieve that, it requires a side plate to hold the actuator where it pulls the tendon and a front plate to provide the compression force to the sheath. For each actuator, a rotating drum is fixed to its shaft to increase the amount of speed the actuator can pull as well as a means to secure the tendon efficiently and easily to the actuator.

Figure 5.39: Actuator housing for the subsequent prototypes

Some of the features important for the actuator housing are overall size, bundling of the sheaths and ease of assembly. If the size of the actuator housing is small, it is easier to position it in the operating theater of the hospital as well as transportation to and fro from various locations. If the sheaths of slave manipulator are bundled closely at the proximal end, the effective length of sheaths which the surgeon can use is increased and the endoscopist can use the robotic system with greater ease. If the design is such that it facilitates assembly, then it is faster and easier to change the tendons of the slave manipulator after prolonged usage.

Figure 5.40: Assembly of housing for subsequent prototypes

Therefore for the actuator housing, it is designed for the housing of each DOF to become a module of its own. In this case the user can fix one DOF at a time to the slave manipulators easily since he can assemble it without any space interferences. When all the DOFs are fixed onto each individual module, it slides into the housing frame which has the suitable rod and surfaces to ensure each module is properly constrained and do not have any unnecessary movement. The frame also orientates each module so that the sheaths converge out closely to one another and they can be bundled together after a short distance from the front plate. The overall size of the actuator housing is small and can be put on small tables or trolley.

5.5.2: Control

Figure 5.41: Flow chart of two parallel processes for the control

To implement the force feedback and position control, two orthogonal independent control loops are carried out as shown in Figure 5.41. When implementing the position and force control to the user, a simple PID control is used to control the position of the end effector. When the difference between the actual predicted position and user input is calculated, the value is fed through the PID which produces the signal that is to be sent to the actuators. The PID values are determined by tuning the system experimentally. Though the PID control method is not optimized in terms of speed, accuracy and robustness, it provides a simple means to control the end effector of the system. The command “JG” from Galil motion control is used in the program for the PID control and its function is to move the actuator at a specified constant velocity set by the programmer.

Figure 5.42: Flowchart of program for second prototype

For the force feedback, it is calculated and implemented separately from the position control since they are mutually independent. If the scale of the force at the distal end

is calibrated well enough, it can prevent the user from over pulling the tendon and sheath. The loop for force feedback is simply reading the force from the load cell at the proximal end and utilizes the modeling to estimate the force at the distal end. This force is then multiplied with a scale calibrated from experiment and feed directly to the voltage limit of the actuator at the haptics master controller.

Figure 5.43: Connection diagram for interconnection module

The electrical connections for the various components of the system are connected in this module too. The specialized motion controller provides the interconnection module where all the necessary wires can be connected together. Figure 5.43 shows the wiring necessary for one DOF. Care has to be taken to ensure all the wirings are fixed to the right position. Otherwise errors are received and the wires can even be burnt.

Figure 5.44: Electrical housing to safely hold the electrical connections

To allow easier transportation of the electrical circuitry, a separate casing is made to house it. In the past, whenever the system had to be transported to another location,

the different components of the electrical system have to be taken apart and the wirings have to be re-fixed. Due to the high number of wires, it is time consuming and easily causes errors in connecting back the wires. This can result in the actuators running wildly and even wires being burnt.

With the electrical housing, it provides a stable platform where the wirings to the other parts of the system can remain fixed permanently. The necessary wires that need to be linked with the other components are bundled into thicker multi-strands connectors and cables so that they become the only cables to fix during assembly and transportation.

5.6: Conclusion

The designs for the robotic system is being discussed in detail over this chapter. The morphological chart as well as the evaluation matrix for the various designs was given as well as the final prototype for the slave manipulator, actuator housing and microprocessor. The results on using the prototype are given in Chapter 6.

Chapter 6 : Medical Experimental Results

This chapter describes the experimental results obtained with using the robotic slave manipulator mentioned in Chapter 5. Section 6.1 discusses on the medical trials performed for ESD and Section 6.2 discusses the experiments conducted on NOTES (liver wedge resection). The procedures for each type of trials are given in detailed as well as the experimental results on live animals are given. A total of 15 *ex vivo* animal trials for ESD, 5 *in vivo* animal trials for ESD and 2 *in vivo* animal trials for NOTES had been conducted in total. The conclusion of the chapter is given in Section 6.3.

6.1: Medical Trials on ESD

Figure 6.1: The experimental setup inside Advanced Surgical Training Center (ASTC)

Since a new tool is invented for ESD and NOTES, a novel procedure had to be planned in order for the slave manipulator to perform the trials in safely and with ease for the patient. Discussions are held with experienced surgeons and endoscopist and the various steps necessary for the procedure is conceptualized and tested. The detailed steps of the new procedure are given in the later sections.

With the new slave manipulator, intensive experiments were conducted to verify the feasibility of the robotic system. Together with the help of experienced endoscopists, 15 *ex vivo* ESDs and 5 *in vivo* ESDs had been performed successfully on pigs. Before the trials, practices sessions with *ex vivo* pigs' stomachs were conducted with

the surgeon to establish the necessary steps for the ESD. It also let the endoscopists understand the capability and limitation from the endoscope and the robot.

Due to it being a prototype working on animals, the robots are tentatively just cleaned thoroughly with soap, water and brush and subsequently reused for further trials. In future the slave manipulator could be designed to be disposable after a single use to ensure it is sterilized effective for human patient.

6.1.1: Procedure for ESD

The finalized steps for robotic ESD are given as follows. The figures provided are the actual view recorded from the endoscope during one of the ESD.

Figure 6.2: Marking lesion with needle knife

Firstly, the endoscopist has to spot the lesions where the ESD should take place with a normal endoscope. When the surgeon has located the lesion, he proceeds with marking of the surroundings of the flesh with a conventional needle knife set at coagulating mode. This is to ensure both the endoscopist and surgeon are clear about where the procedure is worked on and do not cut too excessively or too little.

Figure 6.3: Injection into the submucosal layer

Next the endoscopist uses an injector to inject saline at the lesion to separate the muscle and mucosal layer. This procedure is to ensure the tool does not overcut into the muscle layer and cause excessive damage and bleeding to the patient. The saline is also colored with Methylene Blue for better vision clarity during the subsequent procedures.

After the injection, the normal endoscope is taken out and replaced with the robotic slave system. Both the endoscopist and surgeon then try to perform the peripheral cut on the lesion. This cut is performed using the robotic system to cut a complete circumference around the lesion. This makes the lesion region loose from the surrounding and therefore easier to be manipulated by the robot. The peripheral cut also ensures the cut is localized within the region and not cut excessively into the other healthy site.

Figure 6.4: Peripheral cut at the left edge

For this procedure, the endoscopist and surgeon try to position the hook slightly above the lesion before the hook pokes into the lesion using electro-cautery. Once the hook is through, the endoscopist then moves the endoscope and the hook to cauterize along the left side of the lesion. During this time, the surgeon has to move the hook if necessary to facilitate the peripheral cut.

Figure 6.5: Peripheral cut at the right edge

For the right side, the surgeon rotates the hook 180° as shown in Figure 6.5 before cutting the top to right side of the lesion. The cut is made at the same manner by the endoscopist controlling the movement of the endoscope and the surgeon coordinating with the orientation and movement of the hook.

After the peripheral cut, the endoscopist and surgeon has to go around the lesion and ensure that the peripheral cut for the whole circumference is complete. If there is a site which is still attached to the lesion, the surgeon then try to finish the cut with the hook. This step is important since any remaining ridges on the lesion can cause the subsequent steps to be more difficult.

Figure 6.6: Real cut for the procedure

After the peripheral cut is complete, the endoscopist proceeds with the actual removal of the lesion. The slave then go to the top left hand corner of the lesion and

the gripper grasps onto the former. This exposes the flesh below the mucosal layer and the hook can proceed with cauterizing the lesion off. If there is a need, the endoscopist can relocate to another location for the slave manipulator to work on. The surgeon keep cauterizing until the whole lesion is cut loose from the stomach. If there is bleeding, the hook can acts as a coagulator to seal the blood vessels.

Figure 6.7: View of the site after ESD

The view of the site after the procedure can be seen in Figure 6.7. No perforation of the stomach is observed and the marked lesion is cleanly removed. ESD procedure had been successfully performed with the robotic system.

6.1.2: Actual Results for ESD

Figure 6.8: Actual lesion removed during ESD

The actual lesion can be seen in Figure 6.8. It is in one complete piece and the size is substantial. Table 6.2 shows the summary of the results for the fifteen *ex vivo* animal trials and five *in vivo* animal trials performed by the system.

Experiment Number	Lesion Dissection Time (min)	Tissue Size(mm)	
		Length	Width
Lesion 1A	10	50	40
Lesion 1B	41	40	30
Lesion 1C	48	32	28
Lesion 2A	48	27	20
Lesion 2B	22	23	18
Lesion 2C	15	46	25
Lesion 3A	8	25	21
Lesion 3B	26	40	27
Lesion 3C	41	45	28
Lesion 4A	7	50	26
Lesion 4B	24	37	33
Lesion 4C	9	30	26
Lesion 5A	22	48	26
Lesion 5B	25	39	26
Lesion 5C	12	29	24

Table 6.1: Result from 15 *ex vivo* ESD animal trials

	Lesion Dissection Time (min)	Length (mm)	Width
Pig 1 (Conventional)	14	29.1	22.2
Pig 1 (Robotic)	40	38.6	25.2
Pig 2 (Conventional)	26	50.2	33.0
Pig 2 (Robotic)	29	33	30
Pig 3 (Conventional)	34	34.7	32.9
Pig 3 (Robotic)	19	42.8	25.7
Pig 4 (Conventional)	15	21.8	17.2
Pig 4 (Robotic)	12	33.0	29.8
Pig 5 (Conventional)	12	28.4	22.9
Pig 5 (Robotic)	3	28.8	22.9

Table 6.2: Result from 5 in vivo ESD animal trials

Figure 6.9: Comparison of timing between robotic surgery and conventional tool for ESD

From the results shown, it is observed that initially the robot took much more time in performing ESD compared with conventional methods. However gradually after more practices, refinement of the procedure and improved communication between

the endoscopist and surgeon, the time taken for the procedure had reduced to 3 minutes compared with 12 minutes from the conventional ESD. The average size for the lesion is about 35.24 mm by 26.72 mm. The procedure also shows no complication, perforation and the sample lesion taken out is in one piece. This study was performed on live pigs and the results show the method is feasible and can be an improvement in performing ESD.

6.2: Medical Trials on NOTES

In a separate experiment, the robot was also used to perform liver wedge resection on the live pigs. This is a feasible study on using the robotic system to perform NOTES. The procedure for performing NOTES is discussed below.

6.2.1: Procedure for NOTES

After the system gain access into the live pig's stomach, the endoscopist tries to establish the position and orientation of the stomach before using the robot to perform gastrotomy. Gastrotomy requires the robot to cut a hole through the stomach wall to access the peritoneal cavity of the pig.

Figure 6.10: Gastrotomy of the stomach

Once the system is inside the peritoneal cavity, the robot faces the liver and proceeds with the liver wedge resection. The endoscopist determines the site where the cut should take place. The cauterizing should begin close to the edge of the liver instead of the edge to ensure there is a tension at the top end of the cut tissue. During this procedure the gripper has to grasp the edge of the liver to provide tension for the

cauterizing cut to be effective. The surgeon and endoscopist then try to cauterize the liver till only the top and bottom edges are left.

Figure 6.11: Performing liver wedge resection

After they ensure the cut in the middle is complete, the two edges are then cut. The surgeon can choose to cut the top edge or bottom edge to complete the liver resection. In the first trial, the endoscopist and surgeon chose to remove the top edge first before cutting through the bottom edge.

Figure 6.12: Final cut to complete lever wedge resection

With the gripper still holding the cut liver wedge, the hook then proceeds with the coagulating of the liver surface to stop the bleeding. The surgeon then removes the robot from the pig and retrieves the liver wedge for analysis. The perforated cut on the stomach wall can then be mended using conventional methods such as haemoclips etc (refer to Section 2.2.2).

Figure 6.13: Coagulating bleeding with robotic system

In all, two experiments had been conducted on the liver wedge resection on live pigs. Since there is no conventional means to perform transgastric liver wedge resection there is no comparison for the robotic system. The liver wedge taken out during the trial for pig 4 is shown in Figure 6.14.

Figure 6.14: Actual liver wedge removed during NOTES

6.2.2: Actual Results for NOTES

A table showing the results for the two trials for NOTES can be seen in Table 6.3. The time taken to cut through the stomach, cut off the liver wedge and coagulating took approximately 8-9 minutes.

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

Table 6.3: Table showing result on time taken for liver wedge resection and size

6.3: Conclusion

The medical trials the robotic system had performed are given in details in Section 6.1 and 6.2. Basically 15 *ex vivo* animal trials and 5 *in vivo* animal trials had been conducted for the ESD procedure. In addition two *in vivo* animal trials for NOTES on liver wedge resection were also performed.

From the animal trials, it can be concluded that the robotic system had met its objectives on performing ESD on live animals successfully. The system offers an alternative method to perform complicated endoscopic surgical procedures with the added advantages over conventional methods. The robotic system also shows great potential to perform new surgical procedures that are otherwise not possible with conventional endoscopic tools.

Chapter 7 : Conclusions and Future Works

This final chapter gives the conclusions and future works for this thesis. Section 7.1 lists the contributions made by the author towards the development of the robotic system. It discusses the modeling of the tendon and sheath actuation, the design and development of the robotic system and lastly the animal trials that have been performed. Section 7.2 is on the possible future works for the robot and lastly, Section 7.3 discusses the conclusions of this thesis.

7.1: Summary of Contributions

The summary of contribution is segregated into three sections. The first section is on the modeling of the tendon and sheath mechanism. The second portion describes the development for the robotic system and the last section is on the animal trials that were performed by the robotic system.

7.1.1: Modeling of Tendon Sheath Mechanism

Figure 7.1: Flowchart for academic contribution

Tendon sheath actuation has many desirable characteristics crucial for the development of the proposed robotic system such as small size, high power transmission, no dangerous chemicals and power involved and capable of possessing a long and flexible route of power transmission. However there is a high shape dependent friction between the tendon and sheath and this results in power loss, hysteresis and non linearity etc. These factors make it difficult to sense forces at the

distal end as well as elongation of the tendon. Without this knowledge, it would not be possible to implement haptics feedback and close loop position control. Force feedback and close loop position control are critical in allowing the user to steer a robotic manipulator in an intuitive and safe manner.

Previous works on tendon sheath studies are mainly on largely applications such as robotic hands. The focus of these studies is on achieving autonomous torque control of the joint by attaching joint torque sensors at the distal end of the robot. This is possible since space is not a major constraint in the application of robotic hands.

In the case of the proposed master slave robotic system to perform NOTES, it is not viable to affix sensors at the distal end of the robot. This is because the proposed robotic system requires more DOFs for a smaller size and the sensors also have to be sterilized effectively to be used on human. Furthermore it is conceivable that the distal end of the robot has to be disposed off after a single use. All these factors reduce the appeal of having multi miniature, expensive and sophisticated sensors at the distal end. If the distal end force and elongation of the tendon are known, then closed loop position control as well as force feedback could be achieved.

Related models of tendon sheath actuation are only on sheaths with a constant bending radius [65][82][83]. Bending radius of the tendon and sheath has a great influence on the friction between them and it alters the distal end force and elongation. In the application to robotic surgery, this change in shape is almost impossible to be maintained or measured practically.

The study on tendon sheath actuation is expanded to include a sheath with a variable shape. The shape is now modeled as a sheath with multiple different lengths each with different bending radius. The shape factors affecting the friction are then separated and identified as parameter K . K can also be described as approximating the varying and changing shape of the sheath to be one with a constant bending radius. This is possible since only the tension and elongation at the proximal and distal end of the sheath are important. The study is also adopted for the modeling of the elongation of the tendon. The shape factor affecting the elongation of the tendon is then separated and identified as M_e . By approximating the bending radius of the

sheath to be one characterized by K , the relationship between K and M_e is found and knowing one constant gives the other.

So far the modeling and use of K and M_e applies only when the tendon is pulling the distal end. When the tendon starts to release, the earlier modeling becomes invalid and its distal end force and elongation deviates rapidly. In order to know the distal end forces and elongation at all the possible phases of actuation, different models have to be developed at these phases. These different possible types of actuation modes are then identified namely pulling phases, pull to release phase, releasing phase and release to pull phase. The models of the tension and elongation within the various phases were built and the formulas to determine the various elongations were derived. With the values of K and M_e , the distal end force and elongation can be estimated for the various phases with these formulas. The models are verified subsequently by experimental data.

After the models and formulas are established, it is necessary to find a way to obtain K and M_e online for the distal end estimation. This is necessary since the shape is a variable and cannot be determined until it had pass through the human natural orifice. After that then the shape of the sheath is considered to be relatively fixed and only then can the value of K and M_e be determined. The process of initialization is then introduced. This process involves making the joint at the distal end rotates till it reaches the end of its motion. The actuator continues to pull the tendon after this stage and the length of tendon pulled is actually the elongation from the tendon. Working backwards, the value of M_e and K are then derived for this particular shape of tendon and sheath and can be used for the estimation subsequently.

A series of actual experiments are conducted to validate the models and formulas for estimation of the end effector force and elongation. The experimental setup consists of force and displacement sensors at both end of the tendon and sheath. The estimation based on the sensors reading at the actuating end of the sheath is then compared with the actual reading from the distal end of the sheath. The detailed experimental setup and the analysis of the results are disclosed in the thesis.

After a series of experiments, the results show that the full scale error for the approximations is approximately lower than 7%. These hypotheses and formulae for the estimation are credible and can be used for distal end force and elongation predictions. Since there is a limit on the sensitivity of human perception, this error is low enough for the master slave application.

Using this method, the distal end force and elongation could be approximated using only sensors attached at the proximal end. To achieve these results, initialization has to be conducted. To obtain the appropriate value of K and M_e , the shape of the sheath should remain largely the same after initialization and buckling of the sheaths has to be restrained during actuation.

With the completion of the theoretical studies, it is concluded that no sensor is necessary to be fixed at the end effector. Therefore during the design phase, there is no need for sensors at the end effectors. As such, the design of the slave manipulator emphasizes on providing optimal actuation without the implementation of sensors for force feedback or position control.

7.1.2: *Development of Robotic System*

On the development of the robotic system, it is intended for one arm of the robotic system to perform aggressive grasping and exposing the site while the other arm performs tissue removal. Currently the available tools cannot perform this action because they have limited DOFs and lack triangulation. If the robotic system could realize these actions with ease, many complicated procedures such as ESD on the stomach or removal of malignant growth from other organs could be executed faster and with lesser technical difficulties.

A list of requirements for the prototype to fulfill is discussed. The length of the sheaths, the flexibility, the force it can exert, the size of the whole system and the vision from the endoscope is studied and listed in the thesis. Only with all these requirements fulfilled can the robotic system be viable for surgery.

Figure 7.2: The flowchart for the design and development for the prototype

The research conducted on the selection of the tendon and sheath is also shown. The use of suitable tendon and sheath is critical to the success of the prototype and it inevitably determines the amount of force, size and DOFs the robotic system possesses. At the end of the study, it is recommended to use Teflon coated stainless steel wire ropes and stiffer flat coil sheath for the robotic system.

The physical constraints as well as the configuration of the DOFs for the robotic system are investigated. Due to the limited space of the tool channels, the DOFs are set as nine for the two arms combined. The opening/closing DOFs allow the slave manipulator to close in when it is inserted into the patient and opens up after it reaches the site. This allows a small overall size for the slave manipulator yet capable of providing a clear vision to the endoscope after the arms open up. It also has a translation DOF that resembles a conventional tool and reduces the difficulty of orientating the endoscope. The third DOF resembles the supination/pronation joint of the human wrist and this DOF is critical in orientating the gripper or hook at the right angle before it execute the necessary procedure. The fourth DOF mirrors the flexion/hyperextension DOF of the wrist and it form the second part of triangulation whereby it can close in to the site of operation after opening up from the base. Lastly an additional DOF is allocated for the opening and closing of the grippers to hold onto tissue. This configuration would allow for grasp and cut actions, which is well suited for performing ESD asnd NOTES.

The various components of the slave manipulator are then set and the various possible designs for each component are discussed. A morphological chart for the various designs options is provided and it summarizes the various feasible designs for the slave manipulator.

The various designs are each evaluated and compared before the design of the prototype was finalized. Analysis has been performed to determine the type of mechanism used for the bending DOF. It compares the theoretical performance between deformable shaft, spine design and pulley hinge. From the in-depth investigation, it is decided that the pulley hinge is the most suitable in terms of predictability, range of motion and strength for the robotic slave manipulator. The problem and ways to reduce abrasion of the tendon are also discussed.

A matrix evaluation table highlighting the various factors critical to the success of the robotic prototype is presented. Various experiments were conducted to test the various joints of the prototype and the results are furnished. The experiments include the verification of the theoretical studies and the maximum force each of the joint can exert at the end effector. It is found to produce approximately 2.8N for the weakest joint and maximum force of 5.2N for the strongest joint. The series of experiments also show that the errors for the estimations of the force and elongation are 0.2 N and 0.523 mm respectively. Therefore it has fulfilled the design requirements previously stated.

The prototype based on the finalized components has been developed and reported in the thesis. It is a two-armed master slave robotic system with a total of nine DOFs. It is able to be attached to the tip of the endoscope and the tendon and sheaths transverse through the two available tool channels for easier handling. The left arm is in the form of a cauterizing hook while the right arm is a grasper. The cauterizing hook can conduct the electrical power from the conventional cauterizing machine yet is carefully insulated from the rest of the slave to prevent unintentional cauterizing. The gripper also has in place intermeshing teeth at the tip for it to be competent enough to grip on the slippery and tough stomach tissue. It has a length of 2m, flexible enough not to hinder the movement of the endoscope, produce at least 2.8N force at the joint yet small enough to go through a commercially available overtube.

It also does not block the view from the endoscope excessively by allowing the slave manipulator to open up at the base and close in at the tip during the procedure.

7.1.3: *Animal Trials*

Since this is a novel endoscopic tool, a new procedure was planned to utilize the robot in performing the relevant tasks for ESD and NOTES. Discussions were held with experienced endoscopists and surgeons to finalize a procedure that is safe and could be performed with ease to minimize patient's risk and their recovery.

To perform ESD, first the lesion has to be marked by heat probes and the mucosal and muscle layers are separated with injection. Next a peripheral cut is made to the lesion with the robotic manipulator. This involves cutting a ring outside the marked lesion. After that, the gripper grasps the lesion to expose the site and the hook cuts into it. The gripper can release and change the site to grasp until the whole lesion is cut off and taken out of the patient body. If there is excessive bleeding, the hook can coagulate and seals the blood vessels.

To perform NOTES such as liver wedge resection, the robotic manipulator first has to make an incision on the stomach wall with the gripper and hook. Once the incision is made, the endoscopist then pushes the whole system through the incision to reach the peritoneal cavity. Next, the endoscopist locates the site to perform liver wedge resection and adjusts the position and orientation of the endoscope accordingly. Once it reaches the site, the gripper grasps the liver and provides tissue tension while the hook cuts the lesion. The edge of the liver is left intact first so the whole liver wedge does not become too flabby during the cut. When the cut in the middle of the liver wedge is completed, the slave manipulator proceeds with the cutting of the edges. Once the liver wedge is cut loose from the liver, the hook can proceed to coagulate and seal off the bleeding before the whole system is taken out of the body.

Using the robotic system, 15 *ex vivo* ESD and 5 *in vivo* ESD on live pigs have been completed successfully. The lesion removed is in one piece and there is no perforation of the stomach wall. The time taken initially for the trials is approximately 40 minutes but subsequently reduces after more practices. With the fifth pig, the time required for a successful ESD was reduced to 3 minutes. The

results also show the time for performing ESD was reduced from a mean of 73 minutes to 23 minutes. The average size for the lesion taken out using the robotic system is about 35.24 mm by 26.72 mm.

The robotic system also performed two NOTES procedure (transgastric resection of liver wedge) on live pigs as well. The timing taken to perform the whole procedure is approximately 9 minutes for both trials. The average size of the liver taken out is approximately 17.5 mm by 9 mm. These medical experiments show the feasibility of the robotic system to perform procedures such as ESD and NOTES.

7.2: Future Work

On the development of the robotic system, several possible future directions are proposed.

Currently for estimating the distal end force and elongation, the modeling requires the slave manipulator to initialize before every use. This is time consuming and the robot cannot be controlled during this period. However initialization is necessary since a process must exist to obtain the value of K and M_e after it undergoes a shape change. It would be advantageous to have an initialisation method that takes lesser time, and then the robot could continuously calibrate itself. In this way, K and M_e are always relevant, the error can be reduced and no time is wasted during initialization.

Although the study is for the proposed robotic system, it could be used for other fields such as robotic hand and rehabilitation robot. For robotic hand, if the model is adopted it could eliminate the use of sensors at the distal end and reduce the cost, complexity, size and weight of the hand. Furthermore the hand could be used in hazardous environments whereby sensors could be damaged. The academic studies could be extended and customized to fit such applications.

The slave manipulator should be designed to be capable of being inserted and removed from the tool channel. In this way, the robot can change tools at any time during the procedure. This could aid the surgeon greatly since the robot can perform a variety of actions such as cutting, clipping or injecting without the need of removing the endoscope halfway during a procedure. This is important if the

intended task is complicated and requires a variety of actions to complete successfully.

Another possible improvement is for the slave manipulator to perform wound closure such as suturing. Currently the wound is closed by using haemoclips and this process faces problems such as difficulty in placement and a high possibility of rebleeding. In fact this is one of the main challenges of performing NOTES reliably as listed in [8]. If the robotic slave manipulator could perform suturing, then the wound could be secured reliably and this makes it safer for patient. The robot can also be used for treating other types of ailment such as GI bleeding etc.

7.3: Conclusion

Referring to the Section 1.3, the desired objectives for the thesis are

- 1) To develop a possible means to predict the various parameters of the distal end by attaching sensors only at the proximal end.
- 2) To develop a multi DOFs slave robotic system to perform ESD and NOTES.

For objective (1), models of the tendon sheath have been developed to be used with the current system in providing position control and force feedback. The models can work on sheaths of any shape and do not require any sensors at the distal end. The errors for the estimation are considered to be acceptable for implementation of haptics feedback. A major drawback of this prediction method is that initialization is required before the system is used and the shape of the tendon and sheath has to remain unchanged. The development of the model constitutes the academic achievement of this thesis.

For objective (2), a master-slave robotic system that could enhance the possible treatments for NOTES and GI endoscopy has been developed and tested. It had fulfilled the design requirement stated for the project such as length ($>1.5\text{m}$), flexibility (sheaths much more flexible than endoscope), size ($<16\text{mm}$), force ($>2.76\text{N}$) and vision (effective triangulation).

A new procedure for using the robotic system to perform ESD and NOTES is devised. Using the system, 15 *ex vivo* trials and 5 *in vivo* trials had been performed

successfully. The system is also used successfully in NOTES procedures. The current development brings the system closer to improving therapy for GI endoscopy as well as realizing the possibility of NOTES in humans.

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List of Publications and Awards

International Journals

S.C. Low, S.J. Phee, S.W. Tang, Z.M. Thant, K.Y. Ho, S.C. Chung, "Master-Slave Robotic System for Therapeutic Gastrointestinal Endoscopic Procedures", Encyclopedia of Healthcare Information Systems, Information Science Reference, Vol II (Jun 2008), pp.860-865. [Book Chapter]

S. J. Phee, S. C. Low, Z. L. Sun, K. Y. Ho, W. M. Huang, Z. M. Thant, "Robotic System for No-scar Gastrointestinal Surgery", The International Journal of Medical Robotics and Computer Assisted Surgery, Volume 4, Issue 1, Pages 15-22

K.Y. Ho, S.J. Phee, B.Y.J. So, S.C.S. Chung, "Robotic Manipulator for Natural Orifice Transluminal Endoscopic Surgery," Gastrointestinal Endoscopy, Vol. 65, Iss. 5, Apr 2007, pp. AB110.

International Conferences

S.J. Phee, S.C. Low, V.A. Huynh, A.P. Kencana, Z.L. Sun, K. Yang, "Master and Slave Transluminal Endoscopic Robot (MASTER) for Natural Orifice Transluminal Endoscopic Surgery (NOTES)", 31st IEEE Engineering in Medicine and Biology Society, Minnesota, USA, Sep 2009 (Submitted)

S.C. Low, S.J. Phee, Valdastrì. P, Menciassi. A, Dario. P, "Tendon Sheath Analysis for Prediction of Distal End Force and Elongation", IEEE Advanced Intelligent Mechatronics, Singapore, Jul 2009 (Submitted)

S.J. Phee, K.Y. Ho, A. Shabbir, S.C. Low, V.A. Huynh, A.P. Kencana, K. Yang, D. Lomanto, B.Y. So, S.C. Chung, "Endoscopic Submucosal Dissection of Gastric Lesions Using Through-The-Scope Intuitive Controlled Robotics-Enhanced Manipulator System", Video for display at ASGE Learning Center Digestive Disease Week, May 2009

K.Y. Ho, S.J. Phee, D. Lomanto, S.C. Low, V.A. Huynh, A.P. Kencana, K. Yang, M. Rasouli, S.C. Chung, "Natural Orifice Transgastric Endoscopic Segmental Hepatectomy Using Through-The-Scope Intuitive Controlled Robotics-Enhanced Manipulator System", Video for display at ASGE Learning Center DDW, May 2009

A.P. Kencana, S.J. Phee, S.C. Low, Z.L. Sun, V.A. Huynh, K.Y. Ho, S.C. Chung, "Master and Slave Robotic System For Natural Orifice Transluminal Endoscopic Surgery", IEEE International Conference on Robotics, Automation and Mechatronics, Chengdu, China, Sept 2008

L. Phee, K.Y. Ho, S.C. Low, Z.L. Sun, Z.M. Thant, V.A. Huynh, A.P. Kencana, "Robotic Manipulator for Natural Orifice Transluminal Endoscopic Surgery", 3rd Asian Conference on Computer Aided Surgery, Singapore, 1-2 Dec 2007

Z.M. Thant, S.C. Low, S.W. Tang, L. Phee, K.Y. Ho, S.C. Chung, "Ergonomic Master Controller for Flexible Endoscopic Gastrointestinal Robot Manipulator", Proceedings of the International Conference on Biomedical and Pharmaceutical Engineering, Singapore, 11-13 Dec, 2006, pp. 575 – 579

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Patents

S.J. Phee, K.Y. Ho, S.C. Low, S.W. Tang, S.C. Chung, “Surgical Robotic System for Flexible Endoscopy”, US Provisional Application no. : 60/785,985, 27 Mar 2006.

Awards

Project has received the Singapore National Academy of Science Award 2006 in recognition of research excellence in biomedical robotics engineering

“Video of the Week” at ASGE website titled “Natural Orifice Transgastric Endoscopic Segmental Hepatectomy Using a Through-The-Scope Intuitive Controlled Robotics-Enhanced Manipulator System” 2009

“Video of the Week” at ASGE website titled “Endoscopic Submucosal Dissection (ESD) Using a Computer Controlled Master-Slave Robot” 2009