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DESIGN AND ANALYSIS OF MULTIFUNCTIONAL ROBOT FOR NOTES

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DESIGN AND ANALYSIS OF MULTIFUNCTIONAL ROBOT FOR NOTES

by

Akiko Nakamura

A THESIS

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DESIGN AND ANALYSIS OF MULTIFUNCTIONAL ROBOT FOR NOTES

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The elimination of all external incisions is an important step in reducing the invasiveness of surgical procedures. Natural Orifice Translumenal Endoscopic Surgery (NOTES) is an incision-less surgery and provides explicit benefits such as reducing patient trauma and shortening recovery time. However, technological difficulties impede the widespread utilization of the NOTES method. A novel robotic tool has been developed, which makes NOTES procedures feasible by using multiple interchangeable tool tips.

The robotic tool has the capability of entering the body cavity through an orifice or a single incision using a flexible articulated positioning mechanism and once inserted is not constrained by incisions, allowing for visualization and manipulations throughout the cavity.

Multiple interchangeable tool tips of the robotic device initially consist of three end effectors: a grasper, scissors, and an atraumatic Babcock clamp. The tool changer is capable of selecting and switching between the three tools depending on the surgical task using a miniature mechanism driven by micro-motors. The robotic tool is remotely controlled through a joystick and computer interface.

In this thesis, the following aspects of this robotic tool will be detailed. The first-generation robot is designed as a conceptual model for implementing a novel mechanism
of switching, advancing, and controlling the tool tips using two micro-motors. It is believed that this mechanism achieves a reduction in cumbersome instrument exchanges and can reduce overall procedure time and the risk of inadvertent tissue trauma during exchanges with a natural orifice approach. Also, placing actuators directly at the surgical site enables the robot to generate sufficient force to operate effectively. Mounting the multifunctional robot on the distal end of an articulating tube provides freedom from restriction on the robot kinematics and helps solve some of the difficulties otherwise faced during surgery using NOTES or related approaches.

The second-generation multifunctional robot is then introduced in which the overall size is reduced and two arms provide 2 additional degrees of freedom, resulting in feasibility of insertion through the esophagus and increased dexterity.

Improvements are necessary in future iterations of the multifunctional robot; however, the work presented is a proof of concept for NOTES robots capable of abdominal surgical interventions.
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Chapter 1. Introduction

Surgical procedures using minimally invasive approaches are well established. Minimally invasive surgery (MIS), replacing a large open incision with three to five small incisions offers significant advantages. However, it is difficult to have multiple instruments passing simultaneously through a natural orifice or an incision while maintaining needed manipulation and visualization capabilities. New technologies are necessary that can overcome these challenges. Natural Orifice Translumenal Endoscopic Surgery (NOTES) is a new approach to abdominal surgery that eliminates all external incisions to reduce the invasiveness of surgical procedures by accessing the surgical target through a natural orifice.

The transition from MIS to NOTES provides many of the same benefits as the transition from open procedures to MIS, namely reducing patient trauma and shortening recovery time. This transition, however, is limited by the constraints and by the size of the natural orifice. The instruments are required to be flexible to traverse the natural lumen, making a new approach to NOTES necessary.

This thesis presents a robotic tool that attempts to emulate laparoscopic surgery for NOTES procedures. The robotic tool has the capability of entering the body cavity through the orifice or a single incision using a flexible articulated positioning mechanism and once inserted is not constrained by incisions, allowing for visualization and manipulations throughout the cavity. Multiple interchangeable tips of the robotic device include three tools; a grasper, scissors, and an atraumatic Babcock clamp. The surgeon is
capable of selecting and switching between these three tools depending on the surgical tasks using a miniature mechanism driven by micro-motors.

The robotic tool is remotely controlled through a joystick and computer interface visualizing the surgical site on the screen to operate, as shown in Figure 1.

Figure 1: Natural orifice surgery with the robotic tool overview
Chapter 2. Background

Section 2.1. MIS

2.1.1. Laparoscopic Surgery

One of the biggest changes in surgery in the 1990's was the shift to MIS from traditional open surgeries. Arthroscopic knee surgery, colonoscopic polypectomy, and laparoscopic gall bladder removal are widely adopted examples of this change [1]. Studies have shown that laparoscopic procedures offer benefits such as reducing pain, and speeding recovery comparing to traditional open surgeries [2]. The ultimate goal remains emphasis on making procedures less traumatic.

2.1.2. Natural Orifice Surgery

Natural Orifice Translumenal Endoscopic Surgery (NOTES) is an incision-less surgery and provides explicit benefits such as reducing patient trauma and shortening recovery time by accessing a surgical site through a natural orifice. NOTES can be performed as a pure procedure using a single opening or as a combined procedure using multiple orifices. The feasibility of NOTES was initially demonstrated in animal models by Kalloo et al. [3]. Several more studies have been performed since the first publication. Successful survival studies include transgastric liver biopsy, tubal ligation, lymphadenectomy, gastrojejunostomy, cholecystectomy and partial hysterectomy performed in animal models [3-11]. The first human transgastric appendectomy was performed by Rao et al.; however, publications are not yet available [12].
Section 2.2. Instruments for MIS

To perform laparoscopic surgery, one typically uses an endoscope and long and slender instruments that are inserted through small incisions in the abdominal wall. These tools are limited by the size and geometry constraints of the natural orifice, making it difficult for the surgeons to estimate spatial positions because the point of incision reduces the instrument’s degrees of freedom [13]. In order to solve this problem, new technologies need to be applied to the instruments.

Section 2.3. Robotic Surgery

2.3.1. Surgical Robotics

The introduction of robotics to MIS has shown significant capabilities. A voice-controlled surgical robot, Automated Endoscopic System for Optimal Positioning (AESOP), was the first robot to be approved for surgical use by the US Food and Drug Administration (FDA). AESOP provides a stable camera platform and avoids surgeons’ fatigue [14,15,16]. The daVinci® (Intuitive Surgical®) system is a more advanced tele-robotic device that enables a surgeon situated at a remote master console to control robotic arms that hold the laparoscopic instruments through several incisions on the patient’s abdominal wall. The surgical dexterity is enhanced through capabilities including wristed action, motion scaling, tremor reduction and stereoscopic vision feedback [14,17,18]. These robots have been proven extremely useful in MIS; however, they are not applicable to NOTES due to external implementations. Moreover, inventions over the years have been focusing on transmitting force from outside the body to the functional tips. Barnado et al. [19] have reported that the “R” scope developed by
Olympus cannot generate adequate force at the surgical site to operate effectively. As a result, there has been a shift from cable-force transmission systems to placing the actuator directly at surgical site. Lehman et al. [20] created a dexterous miniature in vivo robot which contains micro-motors to generate force more directly at the surgical tool tips.

### 2.3.2. Dexterous tools

During many types of surgical operations involving minimally invasive techniques, which can range from laparoscopy in the abdomen to biopsy, surgeons use tiny instruments such as scissors, graspers and forceps. These instruments are continually exchanged throughout the surgical procedure. Multiple surgical tasks can be performed by using multifunctional instruments, and thus the overall procedure time is reduced. A reduction in instrument exchanges also reduces the risk of inadvertent tissue trauma during exchanges. Frecker et al. proposed a multifunctional instrument consisting of a compliant mechanism end-effector which is a monolithic mechanism without hinge joints that utilizes large elastic deformation to gain motion and displacement as shown in Figure 2 [21].
The use of robotic systems has improved surgeon dexterity, reduced surgeon fatigue, and made remote surgical procedures possible [22,23]. It is important to provide force feedback to the surgeon in robot-assisted minimally invasive procedures. Tholey et al. developed an automated laparoscopic grasper to provide force feedback to the surgeon [24]. A small incision in the abdominal wall restricts the endoscope movements to 4 degrees of freedom (DOF); in order to solve this problem, 6-DOF steerable endoscopes were developed [13]. An outer-shell-type 2-DOF bending manipulator using a spring-link mechanism is presented shown in Figure 3 [25]. The mechanism was developed for a surgical robot, which makes it possible to implement various surgical devices inside of the manipulator. The spring-link mechanism is composed of a flat spring and a rigid link with a passive joint connection.
Figure 3: Prototype of outer-shell-type 2-DOF bending manipulator

(Jumpei Arata, Yoshitaka Saito and Hideo Fujimoto. Outer Shell Type 2 DOF Bending Manipulator using Spring-link Mechanism for Medical Applications. 2010 IEEE International Conference on Robotics and Automation May 3-8, 2010, Anchorage, Alaska, USA.)
Chapter 3. Design Requirements

Section 3.1. Design Premise

A multifunctional robotic device is designed to add dexterity to a miniature in vivo robot for performing minimally invasive surgery and natural orifice translumenal endoscopic surgery. The basis of the robot tool design is to select and switch between three tools in vivo depending on the surgical tasks. This device consists of a multifunctional robot and an articulating tube. Multiple interchangeable tips of the robotic device are designed to include three tools: a grasper, scissors, and an atraumatic Babcock clamp; these are a common set of tools which surgeons use frequently. The steerable and lockable tube functions as a platform for the robot during surgery and also guides the robot into the abdominal cavity via a natural orifice, such as the esophagus.
Section 3.2. Design Requirements

Definition of the forces and workspace required for performing laparoscopic surgical procedures is necessary for the successful design of a manipulator robot for minimally invasive surgery and natural orifice translumenal endoscopic surgery. Available data for laparoscopic procedures are given either for the forces applied by the surgeon at the tool handle or the actual forces applied to the tissues. Work by the Program for Robotics, Intelligent Sensing, and Mechatronics (PRISM) Laboratory at Drexel University uses equipment consisting of a scalpel-blade cutting subsystem, a computer control subsystem, a digital data acquisition subsystem, and a data post-processing subsystem to measure liver cutting forces [26]. Also, Rentschler et al. modified a normal biopsy device to contain a load cell to measure clamping forces indirectly [27]. Moreover, Mahvash et al. presented an analytical approach based on the concepts of contact mechanism and fracture mechanism to calculate forces applied to scissors [28]. The data from these studies provides useful information for determining the design requirements for a dexterous tool for manipulation. Based on this work, it was determined that a force at the tip of the tool needs to be approximately 3 N in order to cut typical soft tissue. Moreover, the multifunctional robotic device needs to be operated in vivo, accommodating the size of a human peritoneal cavity. A model of a human peritoneal cavity is shown in Figure 4, which has a 100 mm height with a domed shape on top of a square base. Each length of the square base is 320 mm.
Figure 4: Model of a human peritoneal cavity

A non-survival porcine procedure will be performed for testing of the multifunctional robotic device under university IACUC guidelines. A measured porcine cavity is shown in Figure 5, which has a 100-mm high domed shape on top of a rectangular base. Lengths of the rectangular base are 370 mm and 270 mm.

Figure 5: Model of a measured porcine cavity
Research by the University of Washington measured forces and motions applied by surgeons during various laparoscopic procedures using a device called the BlueDRAGON. The BlueDRAGON is a surgical system for obtaining the kinematics and dynamics of two endoscopic tools along with a visual view of a surgical scene for the use of defining objective criteria. Also, these data can be applied to finding design requirements for kinematic optimization of spherical surgical robotic manipulators [29,30]. Based on the data, a surgical workspace and forces required for the multifunctional robot are determined, and this is shown in Table 1.

Table 1: Required workspace and force

<table>
<thead>
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<th>Value</th>
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<td>Workspace ΔY</td>
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<td>Workspace ΔZ</td>
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<tr>
<td>Force $F_y$</td>
<td>[N]</td>
<td>5</td>
</tr>
<tr>
<td>Force $F_z$</td>
<td>[N]</td>
<td>5</td>
</tr>
</tbody>
</table>
Chapter 4. Multifunctional Robot

Section 4.1. Design

Functional requirements are described below.

1. A reduction in instrument exchanges
   Surgeons use tiny instruments such as scissors, graspers and forceps during many types of surgical operations involving minimally invasive techniques. These instruments are continually exchanged throughout the surgical procedure. A reduction in instrument exchanges reduces the overall procedure time and the risk of inadvertent tissue trauma during exchanges.

2. Improve force transmission as compared to other designs
   Improving the force transmission at the surgical site is a significant issue for operating effectively. This may be achieved by changing from a cable-force transmission system to having actuators directly at the surgical site.

3. Eliminate restriction on the degrees of freedom of the tools
   Laparoscopic surgical tools are constrained by the entry of the small incision; therefore the degrees of freedom of the tools are lost and it is difficult for surgeons to operate them. Reduction or elimination of restrictions on the degrees of freedom of the tools improves the ease of performing the surgery.

   Based on these functional requirements, designs have been made.
The distal end of the multifunctional robot contains a surgical tool-changing cartridge which is capable of switching between three surgical tool tips, namely a grasper, scissors, and an atraumatic Babcock clamp. These three tool tips have linkages attached to them so they can be operated with only translational motion. All of them are integrated into one compact, manipulation cartridge as shown in Figure 6. There are two micro-motors located at the proximal end of the cartridge. One of them is responsible for advancing a lead screw while another rotates a tool container. These micro-motors work together to switch, advance, and control the surgical tools. The total length with the tool extended is 130 [mm] and the largest diameter is 30 [mm].

![Multifunctional robot and close-up of the cartridge](image)

**Figure 6: Multifunctional robot and close-up of the cartridge**
Figure 7: Prototype multifunctional robot

The motor container and the cartridge were rapid prototyped using stereolithography (SLA) rapid prototyping processes [31] and are made of SC1000 [32]. SC1000 is a plastic which has properties such as a low deformation due to shrinkage, water resistance, strength and durability.

4.1.1. Novel Mechanism

Creative geometries and cooperative movements between the micro-motors have to be utilized in order to insure the multifunctional robot works effectively within a constrained space using only two micro-motors. This includes the engagement flap, L-shaped connector, lead screw groove and lead screw flap as shown in Figure 8. When a particular surgical tool is chosen, the surgical tool is rotated close to the top of the lead screw. The lead screw is then advanced until the lead screw groove is parallel with the base of the L-shaped connector. The tool is further rotated to engage both the tool and lead screw together. Once this motion has been accomplished, the surgical tool can be advanced outside the cartridge through the translational motion of the lead screw. To operate the surgical tool, the engagement flap located at the side of the tool is rotated into
the groove at the distal end of the cartridge. The engagement flap prevents the tool from sliding back into the cartridge when the lead screw pulls on it. Instead, the tool tips can open through actuation of the associated linkage. Figure 9 shows a series of movements of performing this mechanism.

Figure 8: Engagement flap, L-shaped connector, lead screw groove and flap

Figure 9: A series of movements for actuating tool tips
4.1.2. Rotational Motion

Rotational motion is driven by a micro-motor through pulleys. The motor used is a Faulhaber 0816006S coreless DC motor, which is an 8-mm diameter motor with a 256:1 gear-head. A pulley made of brass is added at the distal motor; also the base of the tool container has a groove around it acting as a pulley as shown in Figure 10. An O-ring is used for the pulley belt, which has a 16-mm inner diameter and 1-mm width.

Figure 10: Rotational mechanism with the tool container, pulley and motor

The tool container has a unique shape to allow the tools to stay in place during the whole process of the rotational and translational motions. It divides into three sections with walls for each tool, and each wall has a straight groove to allow the engagement flap to track in a straight line. The base of the tool container has three holes for letting the lead
screw come in and allowing it to engage the tool as shown in Figure 11. The diameter of the tool container is 18.6 mm and the length is 36.5 mm.

![Figure 11: Details of the tool container](image)

**4.1.3. Translational Motion**

Translational motion is generated by a DC motor with a 256:1 gear-head, gears and the lead screw. The length the lead screw needs to travel is 39.5 mm, and there are not commercial linear actuators which satisfy the requirements of both small size and large travel distance. Thus, an alternative linear actuator is made using the motor, two gears, two bearings, a threaded shaft, the lead screw and the lead screw flap as shown in Figure 12. The lead screw has a 4-40 thread inside and engages the threaded shaft; however they do not rotate together, which is explained below. The threaded shaft is connected to a gear, mating with a gear attached to the motor. The cover of the lead screw holds two bearings for preventing friction from interfering with the correct device function. When
the threaded shaft rotates, the lead screw is advanced instead of rotating with the threaded shaft due to the lead screw flap and a groove on the wall of the cover of the lead screw. This lead screw flap allows the lead screw to follow the groove and gives a linear motion as shown in Figure 13.

Figure 12: Mechanism of the alternative linear actuator

Figure 13: The cover of the lead screw and the lead screw
### 4.1.4. Tool Tips

Three surgical tool tips are designed, namely a grasper, scissors, and an atraumatic Babcock clamp as shown in Figure 14. These three tool tips have linkages attached to them so they can be operated with only linear motion. The engagement flap allows the tool to move with the linear motion along the groove on the wall inside of the tool container and tool cover and prevents the tool from sliding back into the cartridge when the lead screw pulls on it. Instead, the tool tips will open.

![Tool Tip Designs](image)

**Figure 14:** Tool tip designs: (a) grasper, (b) scissors, (c) Babcock clamp
These tool tips consist of slider-crank linkages, an inner rod, an outer rod, a base, linkage pins and a hinge pin as shown in Figure 15. The slider-crank linkages, linkage pins and hinge pin are made of stainless steel. The inner rod, outer rod and base are made of SC1000 [30]. The tool tip is closed when the inner rod is pushed. This prevents the tool tip from opening during switching the tool tips since this multifunctional tool changer is used upside down during surgeries. In other words, a positive capture of the tool tip is maintained so that the tool tip’s self weight does not cause it to move in the groove. Comparing these tools to normal surgical tools using a cable-force mechanism, these tools can generate forces outward to spread the tissue for dissection, in addition to clamping forces for cutting or grasping the tissue.

Figure 15: Details of the tool tip
4.1.5. Tool Cover

The tool cover has three straight grooves and two rounded grooves inside as shown in Figure 16. These three straight grooves allow the tool tips to track along a straight path, and the two rounded grooves make the tool tip be fixed so the rod can be pulled relative to it.

Figure 16: Tool cover: (a) overview (b) section view (c) details of the mechanism

Section 4.2. Force Analysis

4.2.1. Tool Tip Force

Rentschler et al. [27] presented experimental analysis of forces required to biopsy tissue using a normal biopsy device modified to contain a load cell to measure clamping forces indirectly. Figure 17 shows a schematic of the tool used for the experiment. Figure 18 shows the results of the experiment and shows that the required cable force ($F_{cable}$) to cut porcine liver is 14 N. Based on the schematic, the calculated force at the tip of the tools (Figure 18) is approximately 2 N when the tool is nearly closed in order to perform this cutting operation.
The equation for calculating the force at the tip is

\[ F_{\text{tip}} = \left( \frac{d}{a+b} \right) F_{\text{cable}} \]  

(1)

where \( a = 2.9 \text{ mm} \), \( b = 1.7 \text{ mm} \), and \( d = 0.65 \text{ mm} \)

Integrating the calculations into our tool schematic as shown in Figure 19, the tools need approximately 12 N of pushrod force.
Figure 18: Measured cable force during the *in vivo* biopsy of porcine liver


Figure 19: Schematics of the tool for NOTES
Figure 20: Force analysis on the tool for NOTES

The force at the tip of the tools for NOTES (Figure 19, 20) when the tool is nearly closed is given by Equations 2-5 using moment analysis:

\[ F_{pin} = \frac{F_{cable}}{2 \cos \theta} \]  
\[ M - l_a F_{pin} = 0 \]  
\[ l_b F_{pin} - M = 0 \]  
\[ F_{tip} = \left( \frac{l_a}{2l_b \cos \theta} \right) F_{cable} \]

where \( l_a = 3.8 \text{ mm} \), \( l_b = 16.25 \text{ mm} \), \( \theta = 45.87 \text{ deg} \).

According to a force analysis, which will be mentioned later in Section 5.2.2, the force generated by the power screw using the chosen motor is 92.8 N, acting as the “cable
force” or “pushrod force” of the tools. This force provides 15.6 N at the tip of the tools for NOTES. This value seems more than enough; however, this analysis is defined under the assumption that there is no force transmission loss at the connection between the linkages and considering that the speed of opening/closing the tools is a significant consideration for the surgeons to operate the tools properly and safely, it should be also noted that the speed to operate the tools is approximately 0.653 mm/s or 6.0 s overall. Equation 6 shows the calculation using the parameters from Table 2.

\[ V_{\text{linear}} = \left( \frac{V_{\text{motor}}}{60} \right) \left( \frac{25.4}{N} \right) \left( \frac{1}{G_{\text{ratio}}} \right) \]  

(6)

where \( V_{\text{motor}} \) is no-load speed, \( N \) is the number of threads per inch, and \( G_{\text{ratio}} \) is a gear-head reduction ratio.

<table>
<thead>
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</tr>
<tr>
<td>( N )</td>
<td>[-]</td>
<td>40</td>
</tr>
<tr>
<td>( G_{\text{ratio}} )</td>
<td>[-]</td>
<td>256</td>
</tr>
</tbody>
</table>

4.2.2. Power Screw

The motor used to drive the lead screw is a Faulhaber 0816006S coreless DC motor with an optical encoder. The selected reduction ratio of the gearhead is 256:1. The stall torque is 0.4 mNm, and the no-load speed is 15800 rpm. A 4-40 threaded shaft and a lead
screw are used for generating a linear force to advance and open/close the tool. The force generated by the screw system is calculated using Equation 7 [33] and parameters from Table 3.

\[ P = \frac{2T_s (\cos \lambda - \mu \sin \lambda)}{d_p (\mu \cos \lambda + \sin \lambda)} \]  

(7)

where \( P \) is the force generated by the motor, \( T_s \) is the motor torque, \( d_p \) is the pitch diameter of the threaded shaft, \( \mu \) is the coefficient of friction, and \( \lambda \) is the lead angle.

<table>
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<tr>
<td>( d_p )</td>
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<tr>
<td>( \mu )</td>
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<tr>
<td>( \lambda )</td>
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Table 3: Parameters for force analysis
Chapter 5. Articulating Tube

The multifunctional robot is operated with an articulating tube. The steerable and lockable tube functions as a platform for the robot during surgery and also guides the robot into the abdominal cavity via a natural orifice, for example the esophagus as shown in Figure 1.

Section 5.1. Steerable and Lockable Mechanism

The tube is made up of 25 cylindrical linkage pieces that are connected with wire cables. Each linkage piece has a diameter of 14 mm and a length of 32.5 mm. The maximum angle each linkage piece can rotate relative to one another is 30 degrees as shown in Figure 21.

![Articulating tube](image)

**Figure 21: Articulating tube**

The tube is controlled by two pairs of opposing directional wire cables along the surface of the cylindrical linkages with a central cable providing the locking function. Although three wires are sufficient to provide movements in these directions, this
redundancy is needed to ensure symmetrical movement and stability and simplify control. The directional wire cables are controlled by two motors, one controlling the up/down movement, and another controlling the left/right movement. The central wire cable is controlled with its own motor. This cable runs through the center of each linkage piece and is attached to a motor at the proximal end. When the motor applies tension to the central cable, the linkage pieces are pulled towards one another and the friction on the surface of each linkage piece stops the pieces from moving and thus “locks” the tube in place.

**Section 5.2. Theoretical Workspace**

The theoretical workspace area for the articulating tube has been developed using Matlab®. Volumes for pig and human peritoneal cavities are used to determine the needed workspace area for the robot. Figure 22 shows the workspace area for 3 linkage pieces under the assumption that these would protrude past the gastric incision into the abdomen. The code used for calculating the workspace area is described in Appendix A. As seen in Figure 22, the workspace of the articulating tube is essentially a section of a spherical shell centered about the tube. The workspace has 4.35 mm thickness at the center of the spherical shell and gradually getting thinner towards the edge of the workspace. Figure 23 shows the comparison of the workspace with the human cavity. This workspace becomes much larger and eventually reaches throughout the whole cavity when more linkage pieces are inserted past the gastric incision.
Figure 22: Workspace area for 3 linkage pieces

Figure 23: Comparison of the workspace with the human cavity
**Section 5.3. Kinematic Model**

Using the general kinematic model, the equations that describe the location of the end effector (a scissors tool in Figure 24) in a frame \(\{1\}\) are defined.

![Kinematic model diagram](image)

**Figure 24: Kinematic model**

Three linkage pieces of the articulating tube are connected with the multifunctional robot at the distal end. The articulating tube is assumed to have no twist, which allows it to generate 2 DOF for each linkage piece. Frame \(\{4\}\) is rotated relative to frame \(\{1\}\) about \(Z_1\) by \(\alpha_4\) degrees. Frame \(\{3\}\) is rotated relative to frame \(\{2\}\) about \(Z_2\) by \(\theta_1\) degrees. Frame \(\{1\}\), frame \(\{2\}\), and frame \(\{3\}\) can be combined using a homogeneous transform [34]. This transform is described as \(A_{21}^T\) as shown in Equation 8.
Frame \{5\} is rotated relative to frame \{4\} about \(Z_4\) by \(\alpha_2\) degrees. Frame \{6\} is rotated relative to frame \{3\} about \(Z_3\) by \(\theta_2\) degrees. Frame \{3\}, frame \{4\}, and frame \{5\} can be combined and described as \(\hat{B}T\), as shown in Equation 9.

\[
\hat{B}T = \begin{bmatrix}
\cos(90) & 0 & \sin(90) & L\sin(\alpha_1) \\
0 & 1 & 0 & L\cos(\alpha_1)\cos(\theta_1) \\
-\sin(90) & 0 & \cos(90) & L\cos(\alpha_1)\sin(\theta_1) \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  

(8)

Now frame \{6\} is rotated relative to frame \{5\} about \(Y_5\) by 90 degrees. The rotational transform is described as \(\hat{C}R\), and shown in Equation 10. The position of the end effector is described as \(6P = \hat{P}\). Also, the position of the end effector in frame \{1\} is derived by Equations 11-13.

\[
\hat{C}R = \begin{bmatrix}
\cos(90) & 0 & \sin(90) \\
0 & 1 & 0 \\
-\sin(90) & 0 & \cos(90)
\end{bmatrix}
\]  

(9)

\[
\hat{P} = \begin{bmatrix}
d \\
L_t \\
0
\end{bmatrix}
\]  

(10)

\[
6P = \hat{C}R\hat{P}
\]  

(11)

\[
6P = \hat{C}R\hat{P}
\]  

(12)

\[
A_P = \hat{B}T\hat{C}T\hat{C}P = \begin{bmatrix}
L(\sin(\alpha_1) + \cos(\alpha_2)) \\
L_t + L\cos(\alpha_1)\cos(\theta_1) + L\cos(\alpha_2)\cos(\theta_2) \\
-d + L\cos(\alpha_1)\sin(\theta_1) + L\cos(\alpha_2)\sin(\theta_2) \\
1
\end{bmatrix}
\]  

(13)
Chapter 6. Multifunctional Robot Ver. 2

The next evolution in the design of the multifunctional robot requires an overall size reduction, shortening the duration of tool changing, improvement of translating force efficiently on tool tips, achievement of camera vision, and adding 2 degrees of freedom. Although the initial design was useful as a prototype, the lack of a vision system limited the usefulness of the robot to simple manipulations. In order for the robot to feasibly perform an insertion through a natural orifice, the reduction of the diameter of the robot is significant.

Major difficulties in the design of the first prototype were to manage the configuration of the motors into the limited volume and to achieve a robust mechanism for engaging and transmitting force to tools; this resulted in a design lacking facility of insertion and overall effectiveness. In order to overcome this, a conceptual model for the next generation prototype has been developed which would effectively transmit the force without greatly increasing the size of the robot. The conceptual design, shown in Figure 25, consists of a multifunctional robot with a camera which is stowed during insertion and folded out during manipulation, an arm A which has one degree of freedom to rotate the multifunctional robot ±90 degrees, an arm B which generates 360 degrees rotational motion to the arm A, and the articulating tube.
The camera is connected to the body of the multifunctional robot with a superelastic ribbon made of Nitinol which acts as a spring. During insertion, the multifunctional robot goes through the inside of an over-tube which is placed in the esophagus. When the robot is inserted into the over-tube, the Nitinol ribbon is deformed into a straight shape, as shown in Figure 26. Once the robot is released from the over-tube, the camera mount goes back to its initial position.
Section 6.1. Design

6.1.1 Overall Size Reduction

Replacing the Faulhaber 0816006S coreless DC motor with a Faulhaber 1512012SR DC-gearmotor achieves a reduction of the overall size of the multifunctional robot, although the mechanism of switching, advancing, and controlling the surgical tools is the same as the previous version. Comparing this new version to the previous one, the diameter is reduced from 30 mm to 22mm and the total length is shortened by 27mm, as shown in Figure 27.

Figure 27: Overview of the multifunctional robot ver.2
6.1.2 2 Degrees of Freedom

Adding 2 degrees of freedom between the multifunctional robot and the articulating tube is significant in order to satisfy 3-dimensional workspace requirements of the robot without relying on the articulating tube, resulting in obtaining increased dexterity. The arm A in Figure 20 provides $\pm 90$ degrees of rotational motion normal to the axis of the body. A cross-section view of the arm A joint assembly is shown in Figure 28. This assembly houses a 1512012SR DC gearmotor which uses two spur gears to drive an output shaft. The output shaft is constrained by bearings, which are seated in the motor housing.

![Figure 28: Arm A joint assembly cross section](image)

The arm B in Figure 20 provides 360 degrees of rotational motion parallel to the axis of the body. A cross-section view of the arm B joint assembly is shown in Figure 29. This assembly houses a 1512012SR DC gearmotor which uses two spur gears to drive an
output shaft. The output shaft is constrained by a bearing, which is seated in the motor housing.

Figure 29: Arm B joint assembly cross section

6.1.3 Position of Camera

The camera used for the multifunctional robot is a BCM26P ultra-mini CCD color camera which has a minimum 3-inch focus distance. The camera has to be a minimum of 3 inches away from the tool tip to achieve good visibility. In order to achieve this requirement, a ribbon mode of Nitinol is used. Nitinol is a metal alloy of nickel and titanium and has unique properties: shape memory and superelasticity. Nitinol SW508 is used to apply these properties to positioning of the camera. Figure 30 shows the position of the camera during insertion (parallel to the body), and when it reaches inside the abdomen (3 inches away from the tool tip). Details and specifications for Nitinol SW508 are shown in Appendix B.
Section 6.2. Kinematic Model and Analysis

Using the general kinematic model, the equations that describe the location of the end effector (shown as a grasper in Figure 31) in a frame \{0\} are defined.
The multifunctional robot is connected to arm A which is connected to arm B. The arm A can be rotated 360 degrees about the \( Z_2 \) axis and also can provide \( \pm 90 \) degrees of rotational motion about \( Z_3 \) to the multifunctional robot. Frame \( \{1\} \) is rotated relative to frame \( \{0\} \) about \( Z_0 \) by \( \Theta_1 \) and translated by \( L_1 \) along \( Z_0 \). Frame \( \{2\} \) is rotated relative to frame \( \{1\} \) about \( Z_1 \) by \(-90\) degrees and translated by \( L_2 \) along \( Z_1 \). Frame \( \{3\} \) is rotated relative to frame \( \{2\} \) about \( Z_2 \) by \( \Theta_2 \) degrees. Frame \( \{4\} \) is translated by \(-L_t\) along \( Y_3 \) and by \( d \) along \( Z_3 \) relative to frame \( \{3\} \). The location of the end effector in frame \( \{0\} \) is defined using homogeneous transforms [34] and is described in Equation 18.

\[
\begin{align*}
{0}^1T &= \begin{bmatrix}
\cos\Theta_1 & -\sin\Theta_1 & 0 & 0 \\
\sin\Theta_1 & \cos\Theta_1 & 0 & 0 \\
0 & 0 & 1 & L_1 \\
0 & 0 & 0 & 1
\end{bmatrix} \\
{1}^2T &= \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & L_2 \\
0 & 0 & 0 & 1
\end{bmatrix} \\
{2}^3T &= \begin{bmatrix}
\cos\Theta_2 & -\sin\Theta_2 & 0 & 0 \\
\sin\Theta_2 & \cos\Theta_2 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \\
{3}P &= \begin{bmatrix}
0 \\
-L_t \\
d
\end{bmatrix}
\end{align*}
\]

\[
{0}^P = {0}^1T {1}^2T {2}^3T {3}P = \begin{bmatrix}
L_t\cos\Theta_1\sin\Theta_2 - d\sin\Theta_1 \\
L_t\sin\Theta_1\sin\Theta_2 + d\cos\Theta_1 \\
L_1 + L_2 + L_t\cos\Theta_2 \\
1
\end{bmatrix}
\]
Differentiating the location of the end effector under the assumption that simple manipulations do not generate significant moments yields the Jacobian of the manipulator given in Equation 19.

\[
J = \begin{bmatrix}
-d\cos\theta_1 - L\cos\theta_1\sin\theta_2 & L\cos\theta_1\cos\theta_2 \\
-d\sin\theta_1 + L\cos\theta_1\cos\theta_2 & L\sin\theta_1\cos\theta_2 \\
0 & -L\sin\theta_2
\end{bmatrix}
\] (19)

Using the location of the end effector, which is given in Equation 18, a workspace of the manipulator is generated, as shown in Figure 32. In the figure, the robot is shown in the middle of the workspace. The workspace of the manipulator is a section of a sphere centered about the end of the arm A.

![Multifunctional robot ver.2 workspace](image)

**Figure 32: Multifunctional robot ver.2 workspace**
6.2.1. Velocity of the Robot

Calculations of linear and angular velocities of links of the robot are given in Equations 20 and 21 [34].

\[ i+1\omega_{i+1} = i+1R \ i\omega_i \] (20)

\[ i+1v_{i+1} = i+1R\left( i\mathbf{v}_i + i\omega_i \times i\mathbf{p}_{i+1}\right) \] (21)

where i is the number of the frame, \( \omega \) is an angular velocity, \( \mathbf{v} \) is a linear velocity, \( R \) is a rotation matrix, and \( \mathbf{P} \) is a position vector.

Applying these equations to the multifunctional robot yields a linear velocity of the end effector in frame \{0\}, and is as shown in Equation 22.

\[
\begin{bmatrix}
  v_x \\
  v_y \\
  v_z
\end{bmatrix} =
\begin{bmatrix}
  -d\cos\theta_1 - L_t\sin\theta_1\sin\theta_2 & L_t\cos\theta_1\cos\theta_2 \\
  -d\sin\theta_1 + L_t\cos\theta_1\cos\theta_2 & L_t\sin\theta_1\cos\theta_2 \\
  0 & -L_t\sin\theta_2
\end{bmatrix}
\begin{bmatrix}
  \dot{\theta}_1 \\
  \dot{\theta}_2
\end{bmatrix} \tag{22}
\]

6.2.2. Joint Static Force

With the assumption that gravity or dynamic forces are considerably smaller than the contributions of the required tool tip forces to the joint torques, the joint torques are determined using transpose Jacobian mapping. Using the determined force requirements, previously given in Table 1, required joint torques are calculated as shown in Equation 23.

\[
\tau = J^TF =
\begin{bmatrix}
  -d\cos\theta_1 - L_t\sin\theta_1\sin\theta_2 & -d\sin\theta_1 + L_t\cos\theta_1\cos\theta_2 & 0 \\
  L_t\cos\theta_1\cos\theta_2 & L_t\sin\theta_1\cos\theta_2 & -L_t\sin\theta_2
\end{bmatrix}
\begin{bmatrix}
  F_x \\
  F_y \\
  F_z
\end{bmatrix} \tag{23}
\]
where $\tau$ is a required torque and $F$ is a force.

Figure 33 shows the joint torque for $\theta_1$, applying 10 N force at the tip of the tool in the X-direction, 5 N tip force in the Y-direction and 5 N tip force in the Z-direction. The range of $\theta_1$ is from 0 to 360 degrees and $\theta_2$ is from -90 to 90 degrees. Figure 34 shows the joint torque for $\theta_2$ under the same condition. The code used to generate torques is shown in Appendix C.

![Figure 33: Joint torque for $\theta_1$](image)
Figure 34: Joint torque for $\theta_2$
Chapter 7. Summary and Conclusions

This thesis presents the design and analysis of two generations of multifunctional robots for natural orifice surgery. The first generation robot possesses several limitations but is useful as a conceptual model and baseline for future iterations of the robot. The novel mechanism of switching, advancing, and controlling the tool tip is presented. It is believed that this mechanism achieves a reduction in instrument exchanges and can reduce an overall procedure time and risk of inadvertent tissue trauma during exchanges with a natural orifice approach. Also, placing actuators directly at the surgical site generates sufficient force to operate effectively. Mounting the multifunctional robot on the distal end of the articulating tube provides reduced restriction on the degrees of freedom of the robot and helps solve some of the difficulties faced during surgery.

Designs of the second-generation multifunctional robot are then introduced in which the overall size is reduced and two arms provide 2 degrees of freedom, resulting in obtaining feasible insertion through the esophagus with increased dexterity.

Improvements are necessary in future iterations of the multifunctional robot; however, the work presented is a proof of concept for NOTES robots capable of abdominal surgical interventions. Further work must be completed for benchtop tests and animal surgeries. Incorporating an additional arm to operate is significant in order to perform NOTES surgeries. Although these hurdles remain, the approach demonstrated may prove to be the next step to allow robotic natural orifice abdominal surgery.
References


Appendix A. Workspace area code in Matlab®
% calculation of the workspace area of the articulating linkage

% Angles of each linkage [rad]
theta_1 = -pi/6:pi/180:pi/6;
theta_2 = -pi/6:pi/180:pi/6;
theta_3 = -pi/6:pi/180:pi/6;
theta_4 = -pi/6:pi/180:pi/6;
theta_5 = -pi/6:pi/180:pi/6;
theta_6 = -pi/6:pi/180:pi/6;

% Length of the linkage [mm]
L = 32.5;

for theta_1 = -pi/6:pi/180:pi/6;
    T01 = [cos(theta_1) -sin(theta_1) 0 L*cos(theta_1); sin(theta_1) cos(theta_1) 0 L*sin(theta_1); 0 0 1 0; 0 0 0 1];
end

for theta_2 = -pi/6:pi/180:pi/6;
    T12 = [cos(theta_2) -sin(theta_2) 0 L*cos(theta_2); sin(theta_2) cos(theta_2) 0 L*sin(theta_2); 0 0 1 0; 0 0 0 1];
end

for theta_3 = -pi/6:pi/180:pi/6;
    T23 = [cos(theta_3) -sin(theta_3) 0 L*cos(theta_3); sin(theta_3) cos(theta_3) 0 L*sin(theta_3); 0 0 1 0; 0 0 0 1];
end

for theta_4 = -pi/6:pi/180:pi/6;
    T34 = [cos(theta_4) -sin(theta_4) 0 L*cos(theta_4); sin(theta_4) cos(theta_4) 0 L*sin(theta_4); 0 0 1 0; 0 0 0 1];
end

for theta_5 = -pi/6:pi/180:pi/6;
    T45 = [cos(theta_5) -sin(theta_5) 0 L*cos(theta_5); sin(theta_5) cos(theta_5) 0 L*sin(theta_5); 0 0 1 0; 0 0 0 1];
end

for theta_6 = -pi/6:pi/180:pi/6;
    T56 = [cos(theta_6) -sin(theta_6) 0 L*cos(theta_6); sin(theta_6) cos(theta_6) 0 L*sin(theta_6); 0 0 1 0; 0 0 0 1];
end

T01;
T12;
T23;
T34;
T45;
T56;
T03 = T01*T12*T23;
T05 = T01*T12*T23*T34*T45;
T06 = T01*T12*T23*T34*T45*T56;

[theta_11,theta_22] = meshgrid(0:0.05:pi/6, 0:0.05:pi/6);
x = 
L*cos(theta_11)+L*cos(theta_11+theta_22)+L*cos(theta_11+theta_22+theta_22);
y = 
L*sin(theta_11)+L*sin(theta_11+theta_22)+L*sin(theta_11+theta_22+theta_22);
z = zeros(11,11);
mesh(x,y,z);
hold on;

for theta = 0:pi/180:2*pi;
    r = sqrt(x.^2+y.^2);
    theta_t = theta';
    p = cos(theta');
    k = sin(theta');
    X1 = x;
    Y1 = y.*p;
    Z1 = y.*k;
    mesh(X1,Y1,Z1);
    colormap (summer);
end

hold off;
xlabel('x [mm]');
ylabel('y [mm]');
zlabel('z [mm]');
set(gcf, 'color', 'white');
hidden on;
grid on;
axis equal;
calculation of the workspace of the multifunctional robot ver.2

L1=31.4;
L2=24.4;
Lt=111;
d=4.8;

theta_22 = meshgrid(-pi/2:0.05:pi/2);
x = L1+L2+Lt*cos(theta_22);
y = Lt*sin(theta_22);

hold on;

for theta = 0:pi/180:2*pi;
    r = sqrt(x.^2+y.^2);
    theta_t = theta';
    p = cos(theta');
    k = sin(theta');
    X1 = x;
    Y1 = y.*p;
    Z1 = y.*k;
    mesh(X1,Y1,Z1);
colormap (summer);
end

hold off;
xlabel('x [mm]');
ylabel('y [mm]');
zlabel('z [mm]');
set(gca, 'color', 'white');
hidden on;
grid on;
axis equal;
Appendix B. Nitinol SE508 Data Sheet
Material Data Sheet

donated from Nitinol Devices & Components • 47533 Westinghouse Drive • Fremont, California 94539
(510) 623-6996 • Fax: (510) 623-6995 • sales@nitinol.com • www.nitinol.com

Nitinol SE508 Wire

PHYSICAL PROPERTIES
Melting Point: 2390°F 1310°C
Density: 0.234 lb/in³ 6.5 g/cm³
Electrical Resistivity: 32 μohm-in 82 μohm-cm
Modulus of Elasticity: 6-11 x 10⁶ psi 41-75 x 10³ MPa
Coefficient of Thermal Expansion: 6.1 x 10⁻⁶/°F 11 x 10⁻⁶/°C

MECHANICAL PROPERTIES
Ultimate Tensile Strength (UTS): 160-200 x 10³ psi 1100-1150 MPa
Total Elongation (min): 10% 10%

SUPERELASTIC PROPERTIES
Loading Plateau Stress @ 3% strain (min): 65 x 10³ psi 450 MPa
Permanent Set (after 6% strain) (max): 0.2% 0.2%
Transformation Temperature (Aᵣ): 41 to 64°F 5 to 18°C

COMPOSITION (Meets ASTM F2063 requirements)
Nickel (nominal): 55.8 wt.%
Titanium: Balance
Oxygen (max): 0.05 wt.%
Carbon (max): 0.02 wt.%
Appendix C. Joint Torque Code in Maple
restart;with(inttrans):with(plots):

> d:=4.8;Lt=111;

> JT:=matrix([[d*cos(theta1)-Lt*sin(theta1)*sin(theta2),-
d*sin(theta1)+Lt*cos(theta1)*cos(theta2),0],[Lt*cos(theta1)*cos(theta2),Lt*sin(theta1)*cos(theta2),-Lt*sin(theta2)]]);

> F:=matrix([[10],[5],[5]]);

> Torque:=evalm(JT&*F);

> Torque1:=-10*d*cos(theta1)-10*Lt*sin(theta1)*sin(theta2)-
5*d*sin(theta1)+5*Lt*cos(theta1)*cos(theta2);

> Torque2:=10*Lt*cos(theta1)*cos(theta2)+5*Lt*sin(theta1)*cos(theta2)

> plot3d(-10*4.8*cos(theta1*Pi/180)-10*111*sin(theta1*Pi/180)*sin(theta2*Pi/180)-
5*4.8*sin(theta1*Pi/180)+5*111*cos(theta1*Pi/180)*cos(theta2*Pi/180), theta1=0..360,
theta2=-90..90,orientation=[45,45], axes=framed,style=patch);

> plot3d(10*111*cos(theta1*Pi/180)*cos(theta2*Pi/180)+5*111*sin(theta1*Pi/180)*cos(theta2
*Pi/180)-5*111*sin(theta2*Pi/180), theta1=0..360, theta2=-90..90,axes=framed,style=patch);