FLUID POWERED MINIATURE IN-VIVO ROBOTS FOR MINIMALLY INVASIVE SURGERY (MIS)

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FLUID POWERED MINIATURE IN-VIVO ROBOTS FOR MINIMALLY INVASIVE SURGERY (MIS)

by
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A DISSERTATION

Presented to the Faculty of The Graduate College at the University of Nebraska In Partial Fulfillment of Requirements For the Degree of Doctor of Philosophy

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Minimizing the invasiveness of surgery is believed to improve patient outcomes. Bleeding, infection, and pain are major concerns in surgery afflicting patients for decades. Minimally invasive techniques have come into play to reduce these concerns and smooth the evolution of abdominal surgery to a scarless process where nearly all surgeries can be performed without a skin incision. Technology continually advances the frontier of development of novel surgical devices to implement less invasive surgical techniques.

Fusion of robotics and Minimally Invasive Surgery (MIS) has created new opportunities to develop diagnostic and therapeutic tools. Surgical robotics is advancing from externally actuated systems such as the da Vinci® Surgical System [Intuitive, 2013] to miniature in-vivo robotics where the entire robot is inserted into the patient’s body. However, with miniaturization of surgical robots there comes a trade-off between the size of the robot and its capability. Miniature electric motors have been mostly used in many in-vivo robots as the main means of actuation. Slow actuation, low load capacity, sterilization difficulty, leaking electricity and transferring produced heat to tissues, and high cost are the key limitations of use of electric motors in in-vivo applications.

The research described here presents an alternative actuation scheme to overcome these limitations by taking advantage of the inherent high power density of fluidic actuators to develop two different types of in-vivo robotic systems: a robot arm with a
multifunctional manipulator for Natural Orifice Transluminal Endoscopic Surgery (NOTES), and a fluidic disposable self-propelling self-steering robot for colonoscopy.

To create a fully hydraulically-driven surgical robot, it was first necessary to build new fluidic actuators according to design requirements. Novel miniature linear and rotary actuators were designed and built. These actuators are seal-less, disposable, light, and inexpensive. Additionally, an electro-hydraulic tool-changing manipulator was built in response to the need for frequent tool exchange in NOTES.

Bench-top testing was performed for both robotic systems and the results are presented. Future work and conclusions are discussed.
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Chapter 1: Introduction

1.1. Motivation

Miniaturization of surgical robots for insertion inside the peritoneal cavity has become a new trend in Robotic Minimally Invasive Surgery (R-MIS). Robots for Laparo-Endoscopic Single Site Surgery (LESS), also known as Single-Incision Laparoscopic Surgery (SILS), and Natural Orifice Translumenal Endoscopic Surgery (NOTES) must be fast enough to react to surgeon input, and be capable of providing high levels of force for effective tissue interactions. Size is a key design factor for in-vivo robotics. With conventional actuation methods (electric motors), there exists a tradeoff between the scale of the robot and its load capacity and actuation speed. Driving each degree of freedom (DOF) of the robot usually requires a separate onboard electric motor. Each motor has wiring and onboard electronics for power and control, and gearing with high ratios to increase the output torque. This makes the robot relatively heavy and expensive. Besides, sterilization of this robot with onboard electronics after each surgery becomes very difficult and even more costly. Leaking electricity and produced heat from
electronics to tissues and internal organs is another concern with onboard electronics. Moreover, further miniaturization of electric motor-driven robots is challenging and comes with the price of lower force and speed capacity.

1.2. Background

The digestive system helps the body to break down food and absorb nutrients. The digestive system, also known as the gastrointestinal (GI) tract, consists of the mouth, esophagus, stomach, small intestine, large intestine, rectum, and anus, as shown in Figure 1.1. The liver, gallbladder, and the pancreas are other organs necessary for digestion.

![Figure 1-1. Human digestive system [1].](image)

The digestive system is one of the most intricate systems in human body that can be diseased by genetic disorders, poor diet, emotional stress, and even malfunction of
other organs. Although lifestyle changes or medications could successfully treat many digestive system diseases, some conditions may need surgery. Removal of the gall bladder and resection of the colon are examples of these surgeries.

The field of surgery has transformed extensively as technology continues to advance. Development of novel surgical devices has led to improved patient outcomes as the advancement in surgery is moving towards less invasive surgical techniques. The vision of “non-invasive” and “scar-free” surgery is gradually becoming a reality through the development of surgical instruments which have facilitated the transition from open surgery to Minimally Invasive Surgery (MIS).

1.3. Open Surgery

Open surgery is considered an invasive procedure since a large incision is used to access the peritoneal cavity (as seen in Figure 1.2). Despite the invasiveness of this method, many surgical procedures are still performed using open surgery. Operating a surgical procedure via a large incision, the surgeon has direct vision of the surgical site; he/she can touch tissues and structures directly and distinguishes healthy tissues from diseased tissues. Bleeding, high risk of infection, post-operative pain, long recovery time, and extensive scarring are the main disadvantages of this type of surgery. To circumvent these problems, traditional open surgery is transitioning to Minimal Invasive Surgery (MIS). However, switching to minimally invasive techniques entails steep learning curves for surgeons and introduces new complexities.
1.4. Laparoscopic Surgery

Laparoscopic surgery is a less invasive form of surgery that can be performed for diagnostic and/or operative purposes. Laparoscopic abdominal procedures are carried out through several small incisions using various long and thin instruments (as seen in Figure 1.3) rather than through one large incision as in traditional surgical procedures.
Figure 1.4 compares the level of invasiveness for a cholecystectomy procedure performed laparoscopically and traditionally (open surgery). MIS offers several advantages over open surgery including: improved cosmetic scarring, reduced trauma, faster recovery time, and lower cost. In minimally invasive surgical procedures direct vision of the surgical site is no longer possible; thus, it is necessary to introduce some means of visualization. Charge-coupled device (CCD) cameras and fiber optics integrated to the distal end of the laparoscope allow collections of images that are transferred to a monitor in front of the surgeon. This method of visualization limits the surgeon’s perception of tissues and organs and could lead to longer surgery and surgical error [5].

Figure 1-4. Cholecystectomy procedure; laparoscopic surgery (left) vs. open surgery (right) [4].
1.5. Single-Incision Laparoscopic Surgery (SILS)

Single-Incision Laparoscopic Surgery (SILS), also known as Single Port Access (SPA) surgery or Laparo-Endoscopic Single-Site Surgery (LESS), is an advanced MIS procedure in which only a single entry point is used to access the abdominal cavity (see Figure 1.5) rather than several incisions as in standard laparoscopic surgery. A 15-20 mm single incision is made just below the umbilicus where three to four trocars are crowded in one disposable multi-instrument port (seen in Figure 1.6) to allow insertion of different laparoscopic tools and a scope for visualization purposes [6]. The abdominal cavity is then insufflated with CO₂ to provide enough space for maneuvering surgical instruments.

Fewer incisions in SILS means a single scar, less post-operative pain, and shorter hospital stays. However, performing a delicate surgical procedure via a single port introduces some limitations such as reduced dexterity, limited triangulation, the tool fulcrum effect, and obstructed vision. Nevertheless, transitioning from open surgery to MIS, SILS has become an established technique for many surgical procedures such as cholecystectomy, appendectomy, and nephrectomy.
1.6. **Natural Orifice Surgery**

Natural Orifice Translumenal Endoscopic Surgery (NOTES) is an emerging paradigm to eliminate external incisions by gaining access to the peritoneal cavity through a natural orifice, for diagnosis and treatment. During a NOTES procedure, typically an endoscope or a specialized tool is passed through one of the natural orifices such as the mouth, vagina, or anus, as illustrated in Figure 1.7. An internal incision in the
stomach, bladder, vagina, or colon (depending on the target area) is made to allow the surgical tool to reach the region of interest.

The first NOTES procedure was demonstrated in an animal model in 2004 [9]. Since that time, many other studies have demonstrated the feasibility of transgastric and transcolonic approaches. However, human NOTES procedures are most commonly performed using a transvaginal approach [10].

![Diagram of NOTES procedures](image)

Figure 1-7. Approaches for NOTES procedures [8].

NOTES brings about certain advantages if effectively implemented, potentially including no wounds to the abdominal wall, reduced post-operative pain, shorter hospital stay, and less cost. Currently the majority of NOTES clinical trials are performed using
flexible endoscopy platforms. With traditional endoscopes, there are significant constraints including: lack of suitable tool stability, inability to produce sufficient torque and force to perform surgical tasks, inadequate maneuverability, lack of proper triangulation, inability to exchange instruments, and obstructed vision [11]. Accordingly, widespread adoption of NOTES techniques for minimally invasive surgery has been limited to simpler procedures such as gall bladder removal. Most of the published NOTES procedures demonstrate incomplete NOTES (hybrid) approaches with use of at least one transabdominal instrument. To perform pure NOTES it is necessary to develop specialized and novel devices to circumvent the aforementioned limitations.

1.7. Colonoscopy

According to the American Cancer Society [12], colorectal cancer, also known as colon cancer, is the third most commonly diagnosed cancer and the third leading cause of cancer-related deaths in the United States. It is estimated that in 2014 around 137,000 people will be diagnosed with colon cancer and approximately 50,000 people will die from colon cancer in the United States [12].

The colon consists of four sections: ascending colon, transverse colon, descending colon, and sigmoid colon (Figure 1.8). Cancer develops much more often in the colon or rectum, also known as the large intestine, than the small intestine [12]. Colon cancer mostly begins as a polyp (a non-cancerous growth) and slowly forms in the inner lining of the large intestine over a period of 10 to 25 years [12].
The majority of the colon cancer deaths could be prevented by prescreening and detecting the precancerous growths, called polyps, at early stages. Removal of precancerous adenomatous polyps has the potential to prevent the colon cancer from occurring, although all polyps might not become cancerous.

Sigmoidoscopy and colonoscopy are the two procedures performed for inspection and removal of the polyps or cancerous tissue areas. In sigmoidoscopy, a relatively-short flexible endoscope (sigmoidoscope) is used to examine only the rectum and the sigmoid colon where most of the colon diseases occur. In colonoscopy a long flexible forward-viewing endoscope (colonoscope) is inserted through the anus and is pushed to the cecum.
to examine the entire large intestine for diagnostic and/or therapeutic purposes. To
distend the colon folds and facilitate insertion and withdrawal of the colonoscope, the
bowel is insufflated with CO$_2$ or air.

The shape of the human colon is quite complicated. This means the colonoscope
needs to be flexible enough to follow the colon. On the other hand, the colonoscope is
pushed forward from outside of the body and needs to be stiff enough to avoid buckling
while traversing the colon. Therefore, a trade-off between flexibility and stiffness is
inevitable. In practice, this means high likelihood of colon wall deflection at corners and
loop formation in the scope as the gastroenterologist is pushing the scope with relatively
high forces ($>54$ N [14]). Loop formation (as seen in Figure 1.9) is known as the major
cause of pain, bleeding, and tissue perforation in colonoscopy [15].

Figure 1-9. Bowel looping [16].
1.8. Robotics for minimally invasive surgery

1.8.1. Externally Actuated Surgical Robots

To address some of the limitations of minimally invasive surgery such as reduced dexterity and obstructed vision, surgical robotics has come into play. The first generation of surgical robotic platforms such as the da Vinci® Surgical System[17] (perhaps the most full-featured commercially available surgical robotic platform), CURES [18], CoBRASurge [19], and Raven [19] have been designed and developed to be positioned above the patient, maneuvering laparoscopes inserted through small incisions (Figure 1.10).

Hundreds of da Vinci® Surgical Systems are used worldwide and thousands of minimally invasive procedures are performed each year using this robot [17]. However, high cost is one of the main drawbacks of this robotic system.

Outside of academic research, the private sector is also developing surgical robotic platforms for clinical use for other types of surgeries such as heart surgery, brain surgery, eye surgery, and spine surgery. Examples of these platforms are Rio (MAKO Surgical), a robot for partial knee replacement [21], and Magellan Robotic System (Hansen Medical), a robot to perform intravascular procedures [22].
Figure 1-10. Externally actuated surgical robots; a) da Vinci® Surgical System [17], b) CURES: a compact surgical robot with 5-DOF spherical mechanism [18], c) CoBRASurge: Compact Bevel-geared Robot for Advanced Surgery [19], d) The RAVEN: a cable-driven telesurgery system [20].

1.8.2. Internally Actuated Surgical Robots

To overcome the difficulties of working through a single incision during a LESS procedure, several miniature *in-vivo* robotic platforms have been designed to be inserted inside the peritoneal cavity. Rentschler et al. [23-24] developed miniature *in-vivo* robots assisting surgeons by providing visual feedback. A family of wheel-driven modular wireless robots capable of exploring the abdominal cavity and performing some assisting
surgical tasks were also developed and tested in porcine models [25]. The main drawbacks of these robots were traumatic traction on the organs and tissues and inability to provide enough force to perform assistive tasks. In attempts to perform more complicated surgical tasks, several versions of a two-arm miniature in-vivo robotic platform with varying degrees of freedom have been designed, built, and tested in porcine models [26-29] with promising results for Single-Incision Laparoscopic Surgery (SILS). The way these robots are operated mimics more closely the method in which laparoscopic procedures are carried out. Several miniature in-vivo robots that are attached magnetically to the abdominal internal wall and are controlled by an external magnet have been developed for natural-orifice and single-incision procedures [30-32]. Lehman et al. [33] built a tethered bimanual NOTES robot that is inserted through the mouth, enters the peritoneal cavity though the esophagus and an internal incision in the stomach, and attaches magnetically to the abdominal wall. Unstable anchoring of the robot, tethered electronics, and a compromise between the size of the robot and its speed and dexterity were limitations of this robot.

Recent development has focused on design of snake-like robots for NOTES. Snake robotics experts from The Robotics Institute at Carnegie Mellon University have developed medical versions of snake robots for minimally invasive surgery. A novel highly articulated robotic surgical system, shown in Figure 1-11(e), has been tested successfully in porcine models and human cadavers in an epicardial ablation procedure [34]. The Flex System, shown in Figure 1-11(e), is basically a flexible endoscope to access hard-to-reach areas inside body such as the oropharynx [35]. The first generation
of a multifunctional snake robot for NOTES was built at the University of Nebraska-Lincoln in 2011 [36]. A multiple-instrument manipulator is delivered to the site of surgery using a snake robot. In related work, Harada et al. built robotic modules that are meant to be ingested and assembled into a reconfigurable articulated mechanism inside the stomach to perform screening and interventions in the GI tract [37].
Figure 1-11. Miniature in-vivo surgical robotic systems; a) Assistive modular robots [23-24], b) Bimanual robot for LESS [30-32], c) NOTES robots [33-36], d) Reconfigurable modular robot [37], e) Novel highly articulated robotic surgical system (left) and the Flex System (right) [34-35].
The hypothesis of the research presented here was that the inherent high power density of fluids in the form of pneumatics or hydraulics can be leveraged to build surgical robotic systems that can meet the size, speed, and force requirements without compromising one for the others. This means of actuation is compatible with the harsh \textit{in-vivo} environment, removing the aforementioned concerns with using onboard electric motors.

The vision of this research is to make a fully hydraulically-driven bimanual multifunctional robot for NOTES and a semi-autonomous flexible robot for colonoscopy.

Initially, we explored the possibility of pneumatic actuation by building a simple joint driven by a pneumatic cylinder and implementing position control using inexpensive hardware. The joint design and the control scheme are presented in chapter 2. After building the joint and implementing the position control, it was concluded that pneumatic actuation is not a viable approach for \textit{in-vivo} robotic applications due to the difficulty in obtaining a smooth and precise position control. Accordingly, it was decided to switch to hydraulic actuation to achieve an accurate, smooth, and inexpensive position control.

To actuate robotic joints hydraulically, two types of actuators are needed, a linear actuator (a hydraulic cylinder) and a rotary actuator (a hydraulic motor). Commercially available miniature hydraulic cylinders and motors were not found suitable, mainly due to relatively large size and poor sealing under high pressure. Accordingly, novel seal-less fluidic linear and rotary actuators were built. These actuators are easy to fabricate,
inexpensive, and can be customized to the sizes required for \textit{in-vivo} applications. Design, prototyping, and testing of these actuators are described in chapter 3.

Frequent tool exchange in NOTES is inevitable during a surgical procedure. Previous versions of a multiple-instrument manipulator for NOTES are still bulky and slow in tool exchange mainly due to use of miniature electric motors with limited power. In this research, an electro-hydraulic tool-changing manipulator has been designed and built. This manipulator is small enough to be easily inserted into the body via the mouth and is much faster than manual tool exchange or previous electric motor-driven versions. Chapter 4 explains the design process, prototyping method, and benchtop testing of the electro-hydraulic multiple-instrument manipulator.

Chapter 5 presents the integration of the fluidic linear and rotary actuators and the hydraulic multiple end effectors to create a robot arm with 3 degrees of freedom. Two of these arms can be connected to build a bimanual robot for NOTES.

In a separate vein, to address the complications with conventional colonoscopy and move beyond the limitations of previous robotic systems for colonoscopy, a fluidic flexible semi-autonomous robot has been developed. This novel colonoscopy robot is presented in chapter 6.

Chapter 7 concludes this research and explains the future work.
Chapter 2: Pneumatic Actuation

An alternative actuation scheme for in-vivo surgical robotics is to exploit the high power density of fluids (pneumatics or hydraulics). Here we first investigated the possibility of pneumatic actuation by making a simple pneumatic joint and implementing PID position control using inexpensive hardware. Smooth movement, precise angular displacement control on the order of 5 degrees, and relatively low cost of hardware required for implementation of the control scheme were the target goals set in this stage of research.

2.1. Previous Work

While most of the developed surgical robots are primarily actuated by electric motors, the HeartLander robot, an inchworm-like robot delivering therapy to the surface of a beating heart, is a rare example of a non-motor-driven surgical robot driven by suction force [38-39]. Pneumatic actuators are considered difficult to control, and therefore are often avoided. A few studies have been devoted to the development of precise and inexpensive position and speed control for pneumatic actuators. Different
control methods such as PID control with added friction compensation and position feed-forward [40], sliding mode control [41], and hybrid fuzzy PID logic [42] have demonstrated satisfactory outcomes. For most of these control methods, the controller was implemented on a pneumatic cylinder with relatively large bore diameter and a long stroke, using high frequency solenoid valves with low response time on the order of 5 milliseconds. Additionally, control of a humanoid robot made up of pneumatic actuators has been demonstrated [40]. Several pneumatic proportional valves and a PID control technique with force feedback were used to achieve the robot’s end-effector control and tracking performance.

2.2. Pneumatic Joint

The long-term goal of this project is to make a fluid powered *in-vivo* robot capable of performing various surgical tasks smoothly and accurately. Before fabricating the entire robot, however, it was deemed wise to fabricate a single joint and investigate potential control techniques. This simpler system is a one-DOF robot joint shown in Figure 2.1. It was built by rapid-prototyping two middle arm tubes and joining them using a pin. A pneumatic system was designed and implemented to drive the cylinder, governing the angular position of the joint. A cam profile is built in at the joint to convert linear motion of the cylinders to rotary motion of the joint. To simplify the position control of the joint, a linear relationship between translational motion of the cylinder and angular position of the joint is convenient during synthesis of the cam profile.
The pneumatic system consists of a pneumatic double-acting cylinder (12.7 mm stroke and 7.9 mm bore diameter), two poppet style three-way, two-position solenoid valves with a minimum response time of 50 milliseconds and maximum frequency of 10 Hz, a standard flow control valve, a pressure regulator, and a compressor, all of which are shown in Figure 2.2.

Figure 2-1. One-DOF representative joint [43].
The control unit consists of two rotary position sensors (potentiometers), one as a master potentiometer determining the set-point, and the other one as a slave potentiometer (attached to the joint, as shown in Figure 2.1) providing position feedback, an Arduino Mega microcontroller, two power supplies, a Darlington transistor array, and a laptop to prepare and load programming developed in C language. The 5-V output signal from the Arduino cannot drive the solenoid valves directly since 24V is required to energize them; thus a Darlington transistor array and a 24V power supply were used to amplify the output signal from the microcontroller. The output of the potentiometers is analog; an integrated A/D converter on the Arduino board converts analog signals to a 10-bit digital signal. A photograph of the entire system setup is shown in Figure 2.3.
The regular application of solenoid valves is to control the direction of movement of a cylinder, usually by only energizing or de-energizing the valve, more like a digital (0 or 1) signal. In this instance a fine flow control of the air provided to each chamber of the cylinder is required to obtain an accurate position control of the cylinder, more like an analog signal. To achieve this, a PWM (Pulse Width Modulation) technique, controlling the switching period of the solenoid valves, was used. The duty cycle of the PWM determines the on-period of the solenoid valve as the input control signal to the valves. A proportional-integral-derivative (PID) controller regulates the duty cycle of the PWM. The PID controller receives signals from the master and slave potentiometers, calculates the error (the difference between the set-point and the joint angle ($\Delta \theta = \theta_{\text{master}} - \theta_{\text{slave}}$)) and outputs a number in the range of -100 to +100 as the output signal. The sign of the output signal is the same as the sign of the error.
To control the cylinder and consequently the joint, a mathematical model of the pneumatic system was developed as follows [42]:

The free-body diagram of a double-acting cylinder was created as illustrated in Figure 2.4. According to Newton’s law the force the piston rod applies to the mass, \( M \), is determined by Equation 3.1:

\[
\sum F = Mx'' \quad (3.1)
\]

\[
pA - Cx' = Mx'' \quad (3.2)
\]

For position control of the piston in this system \( p \) (pressure) is the input and \( x \) (displacement of the piston) is the output. Thus the transfer function is calculated as:

\[
G_p(s) = \frac{X_s}{P_s} = \frac{A}{Ms^2 + Cs'} \quad (3.3)
\]
where $p$ is the pressure of the air entering the left chamber of the cylinder, $A$ is the cross-section area of the piston ($49.5 \times 10^{-6}$ m$^2$), $M$ is the mass of the piston and the attached link (0.025 kg), $C$ is the damping constant of the air (~1.5 N s/m by experiment [42]), and $x$ is the displacement of the piston.

To tune the PID parameters, we simulated the system in Matlab (see Appendix A.1 for Matlab code). Step response of the transfer function was plotted for different PID parameters (Figure 2-5). The PID values of $k=3000$, $k_p=150$, $k_i=220$, and $k_d=5$ seemed satisfactory, resulting in an overshoot of 7%, a settling time of 2 seconds, and a rise time of 0.14 second. The PID parameter values extracted from Matlab simulation are only the initial values for tuning the PID parameters and may change to achieve an optimum performance in practice.

The relation between the PID signal output and the duty cycle of the PWM as well as the sequence of the valve operation play a key role in position control of the pneumatic system. Different types of valve pulsing schemes as described in detail in [38] were implemented.
Initially, a conventional scheme of charging pressurized air into one chamber and discharging the unpressurized air from the other chamber, as illustrated in Figure 2-6, was applied. The actuator moved too fast such that a stable, non-oscillatory position control was not feasible. The attempt to reduce the air flow to reduce the actuation velocity failed due to substantial pressure drop across the flow control valve. This resulted in improper operation of the cylinder, as there was not enough air pressure to overcome the internal friction in the pneumatic seals. Also the solenoid valves and potentiometers are not fast enough to react in real-time with this configuration.
A second scheme, as illustrated in Figure 2-7, works such that when the PID output is zero both solenoid valves are energized. When $\Delta \theta$ is greater than zero and/or the PID controller outputs a positive number, solenoid valve A is kept energized. So the lower chamber of the cylinder is kept pressurized due to the duty cycle of 100% for the whole range of positive PID outputs. At the same time some air is released from the bottom chamber of the cylinder according to the PWM duty cycle of valve B. Thus the cylinder is extended to reach the set-point, adjusting $\Delta \theta$ toward zero. A similar procedure is applied for negative $\Delta \theta$, contracting the cylinder to approach the set-point. Applying this scheme, the velocity of cylinder actuation was reduced and the flow of the air actuating the cylinder was controlled properly to approach the set-point during extension without oscillation, but some overshoot occurred during contraction, especially at the middle of the actuator stroke. Assuming a specific air flow for both directions of cylinder motion, higher displacement of the piston would be obtained during contraction.
compared to extension, as the actuation area of the upper cylinder chamber is 83% of the lower chamber actuation area, which is due to the presence of the piston rod. Likewise, lower force during contraction is predicted compared to extension for similar air pressure. This difference may explain the difference between the practicality of this scheme for extension and contraction.

Figure 2-7. Second valve operation scheme [43].

A third scheme, as illustrated in Figure 2-8, was devised to overcome this issue. This scheme increases the duty cycle of valve A during contraction, so the on-time period of valve A is less compared to scheme two, and thus less air is released. An adaptive tuning method was also used to adjust PID parameters such that the controller is more aggressive during contraction than extension, which helps to establish oscillation-free position control. Consequently a stable and acceptable position control was achieved for both extension and retraction of the cylinder.
The controller software was coded in C language and the PID control was executed with an Arduino Mega. The output of the PID was used in the program to calculate the PWM duty cycle associated with solenoid valves A and B according to the third scheme. The duty cycles are then sent to two PWM pins on the Arduino board. The output of the PWM pins was amplified by the Darlington array and sent to the solenoid valves. The flow chart of the PID control algorithm is depicted in Figure 2-9. The response time and maximum frequency of the valves are 50 ms and 10 Hz, respectively; therefore, the period of the PWM for those specific PWM-pins was lowered to 33 ms, the possible maximum period (minimum frequency) that could be obtained programmatically, to minimize the failure possibility of the valves to respond to the PWM. The solenoid valves and potentiometers are not fast enough to react to the PWM. As a result, the control system was unable to self-adjust to reach the exact set-point as expected from Figure 2-7. As shown in the flow chart (Figure 2-9), any joint position in

![Figure 2-8. Third valve operation scheme [43].](image-url)
the range of ± 5 degrees was considered acceptable. The best and worst steady-state accuracies of 2 degrees (0.4 mm for cylinder) and 5 degrees (1 mm for the cylinder) without overshoot were seen for extension and retraction of the cylinder, respectively.

Control of in-vivo robots is performed by a surgeon, whose manipulation constitutes an additional visual feedback loop outside the electromechanical control system described; this allows for small errors in position control without any negative affect on a procedure.

Figure 2-9. Flowchart of the control algorithm [43].
2.3. Conclusion

As shown in the flow chart (Figure 2-9), once the joint approaches the determined vicinity of the set-point, both solenoid valves are energized, setting the pressure on both sides of the piston approximately equal. This fact, coupled with the fact that air is a compressible fluid, makes locking the joint in any given position difficult; locking positions during a procedure is a critical issue that cannot be neglected. Moreover, during small displacements, the solenoid valve provides a pulsed actuation response, which is not the most desirable type of motion. In short, pneumatic actuation does not seem to be a viable approach to obtain an inexpensive, precise and smooth motion. Besides, there is always a possibility of leaking pressurized air with continuous flow that may preclude use of pneumatics for *in-vivo* applications due to safety. When leaked into a closed space such as the peritoneal cavity, compressed air could expand and cause trauma. To circumvent these limitations while exploiting the unique advantages that fluid power offers, we decided to switch to hydraulics (using water as the fluid instead of air). The next section describes the development of hydraulic components to make a fully hydraulically-actuated robot.
Chapter 3: Fluidic Actuators

3.1. Fluidic Linear Actuator

Switching to hydraulics from pneumatics, a proper linear actuator is the first component necessary to drive a hydraulic robot. Hydraulic cylinders are the main linear actuators used in many hydraulic robotics. A double-acting cylinder is required to cause flexion and extension of a joint. The cylinder should have a high pressure rating to provide high force on the order of 5 to 20 N to perform surgical tasks. The stroke of the cylinder needs to be on the range of 2 to 6 mm for most of joint and tool actuation. The OD of the cylinder should be less than 11 mm so that the overall diameter of a bimanual robot is less than a typical esophagus diameter, which is approximately 22 mm [32]. Most off-the-shelf double-acting cylinders with high pressure ratings are quite bulky, mostly due to seals between the piston and cylinder and fittings used to connect the tubing to the cylinder. Those that are small in diameter and short in length are single-acting with poor sealing under high pressure, and thus unable to output adequate force to meet surgical requirements. These commercially available cylinders come with a stroke that is usually either larger or smaller than is desirable for driving a joint. Thus there is a need for
Fabrication of customized hydraulic cylinders. Fabrication of miniature but powerful hydraulic cylinders within the desired size range has been a challenge due to difficulties in sealing at high pressures, obtaining necessary surface finishes, and associated cost of fabrication. This motivated us to build a miniature seal-less double-acting pneumatic/hydraulic cylinder.

This linear actuator is small, seal-less, rod-less, leak-free, easy to fabricate, inexpensive, and disposable, thus ideal for single-use \textit{in-vivo} applications. It consists of an outer tube, an inner tube, a piston, a pin, and two off-the-shelf latex balloons, as depicted in Figure 3-1. The novelty of this concept is in the use of elastomeric balloons in both upper and lower chambers of the inner tube to drive the piston. When the balloon is pressurized, it inflates and pushes the piston up/down. A metal pin and groove system is used to transfer force from the piston to the outer tube. The inner tube is stationary and the outer tube can extend or contract depending upon the direction of the piston motion. The balloon itself is sealed onto a PVC tube with an outer diameter (OD) of 3.9 mm using either heat-shrink tube or tight tolerance between the hole on the inner tube and the PVC tube with the balloon. All parts were made using a 3D printer and/or laser cutting machine. The bore, OD, length, and stroke of the cylinder are 5.9, 11, 22.8, and 6 mm respectively. In an effort to further miniaturize the actuator, the second-generation design with bore, OD, length, and stroke of 4, 5.5, 26, and 2 mm respectively was built, as shown in Figure 3-2. Small stainless steel tubes were machined to make outer and inner tubes. Miniature PVC tubing with an OD of 2 mm attaches to both ends.
Bench-top testing was performed to characterize the performance of the linear actuator (Figure 3-3). Pressure was varied for a constant load and the total displacement (stroke) of the first generation actuator was measured; the results are plotted in Figure 3-4. The primary results indicated that the actuator is capable of providing approximately 7 N of force with 4 mm stroke at 0.38 MPa (55 psi). The burst pressure of the balloon was measured to be 0.62 MPa (90 psi) for a 6 mm stroke. The cylinder underwent an average of 300 cycles under an average pressure of 0.38 MPa (55 psi) before the balloon yielded. The output force efficiency of this cylinder was calculated to be approximately
68% which is somewhat comparable with 80% efficiency found in high-quality, commercially available pneumatic cylinders.

Figure 3-3. Benchtop test setup.

Figure 3-4. Displacement vs. pressure [44].
3.2. Fluidic Rotary Actuator

There is no miniature hydraulic motor (in the range of 15x15 mm, small enough for in-vivo robots) commercially available, nor in the prior art to our knowledge. Revolute joints in previous LESS robot designs do not require continuous rotation. High output torque is always a key factor in selection of small motors for in-vivo surgical robotics. Accordingly, it was decided to make a single blade vane motor with a 180 degree range of motion. This provides higher surface area to apply pressure and therefore output higher torque. An output torque on the order of 12 mNm, which is the maximum torque a similar 15x15 mm motor with a gearhead with a reduction ratio of 112 can output (considering 59% efficiency) [45], was set as the target torque. Several ideas for sealing the blade against the stator wall and the top and bottom surfaces were explored and some potential sealing solutions were tried, such as the one shown in Figure 3-5. However, a good seal was not obtained due to poor surface finish of laser-cut or 3D-printed parts. Eventually a seal-less approach similar to that explained for the linear actuator in the previous section was adopted. A limited-motion vane motor with rotational range of motion of 180 degrees was designed and built. The working principle is illustrated in Figure 3-6. When the balloon is pressurized, it inflates and pushes the blade, causing it to rotate.
Figure 3-5. Small vane motor prototype.

Figure 3-6. Working principle of the vane motor.

Three prototypes were fabricated, shrinking down the overall size of the motor from 25x25mm to 18x18 mm to 15x15 mm in subsequent steps. The final prototype is approximately the same size as a 15x15 mm motor which has been used in many
Previous *in-vivo* robots for LESS [27, 32, & 38]. Most of the components were laser-cut in acrylic with two miniature PVC tubes (OD=2 mm) attaching to the motor. Regular off-the-shelf latex balloons or a medical grade balloon from TechDevice Corporation (Figure 3-7) were used for prototyping of the motors. Figure 3-8 shows an 18x18 mm motor made out of acrylic in its two extreme states. An exploded view of the motor is shown in Figure 3-9.

![Image of balloons](image1.png)

**Figure 3-7.** Balloons used in prototyping of the vane motors; a) commercially available latex balloons, b) medical grade balloons.

![Image of motor](image2.png)

**Figure 3-8.** Limited-motion vane motor in two states.
To characterize the performance of the fluidic vane motor and compare it with a commercially available 15x15 mm electric DC motor, bench-top testing was performed. A new motor with medical grade balloon and a flange to attach to a fixture was built using a 3D printer and laser cutting machine (Figure 3-10). A flow meter, a flow control valve, a pressure regulator, and a pressure gauge were used to measure and adjust flow and pressure.
Figure 3-10. Experimental testing setup.

Figure 3-11, Figure 3-12, and Figure 3-13 show the experimental and the calculated characteristics of the vane motor. The flow rate was kept constant (4.25 L/min) for all experiments; however, higher flow rate could result in higher speed and different speed-torque characterization. A minimum pressure of 69 kPa (10 psi) was required for the balloon to start expanding and making the rotor spin. The large difference between the experimental torque and the calculated torque could be due to errors in prototyping (misalignment, tolerances, etc.), incomplete contacts between the balloon and the blade, and more importantly, the friction between the balloon and the stator wall and the top and bottom surfaces. A custom-made balloon with desired properties (higher elongation rate, higher burst pressure rate, and smaller wall thickness) could potentially improve the performance of the motor.
Figure 3-11. Torque versus pressure for a constant flow rate of 4.25 L/min.

Figure 3-12. Comparison between the calculated and the experimental characterization.
Comparison between this fluidic vane motor and a Faulhaber 17x17 mm DC motor is summarized in Table 3.1. A maximum torque of 18.5 mNm was achieved at 351.6 kPa (51 psi), providing almost 8 times as much torque as a Faulhaber 17x17 mm DC motor delivers for continuous rotation [45]. The vane motor weighs 6 grams, 3 times as light as the Faulhaber 17x17 mm DC motor. The speed of the Faulhaber 17x17 mm DC motor is much higher than the vane motor tested with a flow rate of 4.25 L/min. However, higher velocity could be achieved with higher flow rate. Nevertheless, the vane motor spins 180 degrees on the order of one second which seems to be fast enough to meet surgical task requirement.

Table 3.1. Comparison between a DC motor and the fluidic motor.

<table>
<thead>
<tr>
<th></th>
<th>Maximum Torque (mNm)</th>
<th>Weight (gr)</th>
<th>No Load Speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluidic Vane motor</td>
<td>18.5</td>
<td>6</td>
<td>180</td>
</tr>
<tr>
<td>Faulhaber 17x17 mm DC motor</td>
<td>2.2</td>
<td>18</td>
<td>14000</td>
</tr>
</tbody>
</table>
3.3. Balloon-Actuated Grasper

The bulkiest part of the previous LESS robots [27-28] is the forearm where two electric DC motors with high reduction ratio gearheads and a rotary to linear motion converting mechanism are used for opening/closing and twisting of a surgical tool. In an effort to use fewer number of actuators, and therefore decreasing the size of the robot forearm, several versions of a normally-closed grasper with a built-in actuator (a balloon) were designed, prototyped, and tested, as illustrated in Figure 3-14.

Figure 3-14. Iterations of the laparoscopic grasper [44].
After prototyping several iterations, a smaller and more robust version was fabricated out of a laminar composite of metal and acrylic (last picture in Figure 3-14). The grasper consists of a pre-loaded torsional spring that provides grasping force, an elastomeric balloon, two jaws, and a hinge pin. Pressurized air or water can be used to expand the balloon inside the grasper and open the jaws. The torsional spring was formed out of 304 stainless steel spring wire with a diameter of 0.8 mm using a mini lathe.

Figure 3-15 shows the bench-top testing of the balloon-actuated grasper. The testing results indicated a maximum grasping force of 3 N with tip displacement of 5.5 mm, and a maximum tip displacement of 7 mm with grasping force of 2.3 N using two springs with different stiffnesses. The achieved pinch force seems to be sufficient for tissue manipulation. It has been reported that a pinch force on the order of 2.5-5 N is required for tissue manipulation in abdominal surgery [49]. A pressure of approximately 600 kPa (87 psi) was used to open the grasper. The opening/closure time is less than one second.

Figure 3-15. Grasper testing setup.

This new method of tool actuation offers several advantages over electric-motor actuation. Manual operation of the grasper via a master user interface (as explained in the
next section) could be done in procedures where force feedback is desired. This would allow the surgeon to use his/her own fingers to actuate the instruments remotely, removing the need for an onboard haptic system that otherwise would require a larger amount of space inside the robot forearm. The grasper has a peak grasping force that can be set by either using torsional springs with different stiffnesses or controlling the pressure of the fluid inside the balloon *ex-vivo*. This would contribute greatly to the safety of the patient with respect to the loss of tactile feedback during surgery, where excessive forces may be applied to tissues by the laparoscopic grasper during palpation that could lead to tissue perforations and trauma. While surgeons complain about the low actuation speed of the grasper [6] in current LESS robots, the speed of the balloon-actuated grasper would exceed surgeon’s expectations, enabling them to respond to tactile feedback and/or surgical traumas at human reaction speeds. With external actuation of the grasper, it becomes feasible to shrink the bulkiest part of the previous LESS robots (the forearm) almost 60% in diameter or in length.

### 3.4. Modeling of a Balloon-Based Actuation

Figure 3-16 shows a free body diagram of a simple balloon-based actuation. \( F_l \) is the load applied on the actuator, \( F_f \) is the friction force exerted on the expanding balloon from the container of the balloon, \( F_p \) is the force applied to the actuator from the fluid (air, water), and \( F_b \) is the elastic force caused by the elongation of the balloon. These forces can be found from the following equations.
Figure 3-16. Free body diagram of a balloon-based actuation.

\[ F_l = F_p - F_f - F_b \quad (3.1) \]

\[ F_p = pA \quad (3.2) \]

\[ F_f = \mu F_c \quad (3.3) \]

where \( p \) is the fluid pressure charged into the balloon, \( A \) is the cross-section area of the surface the balloon pushes against, \( \mu \) is the friction coefficient, \( F_c \) is the circumferential force applied to the balloon container that can be easily calculated by multiplying the pressure by the circumferential area of the balloon in contact with the container. \( \mu \) is a function of the surface finish of the internal wall of the balloon container and the balloon material. \( \mu \) could be determined for different actuators by experiment.

To determine \( F_b \), a model detailed in [67] can be used. This model derives a relationship between the applied force to an elastomer and its extension as seen in Figure 3-17.
Young’s modulus of silicone is measured using experimental results of testing a specimen of silicone. A similar approach could be used to measure the Young’s modulus of the balloon used in the actuators described in previous sections. Young’s modulus can be used then to calculate $F_b$ as follows:

$$F_b = \frac{EA_0\Delta L}{L} \quad (3.4)$$

where $E$ is the Young’s modulus, $A_0$ is the original cross-sectional area, $\Delta L$ is the balloon extension, and $L$ is the original length of the balloon.

Additionally, a similar method to that described in [68] can be used to take into account the Mullins effect and cyclic stress softening of filled elastomers. The Mullins effect states that in filled rubbers the stress-strain graph depends on the maximum loading the rubber has experienced previously.

In a simplified model, Equations 3.1 to 3.4 are used to calculate the output force of the balloon-based linear actuator described in section 3.1. The Young’s modulus is
assumed to be 0.0453 MPa according to [67] for a similar material to TC-5005 silicone. 

$A_0$, $L$, and $\Delta L$ of the balloon were assumed to be 4.7 mm$^2$, 3 mm, and 4 mm respectively based on typical characteristics of the actuators under consideration. Substituting these values in Equation 3.4, $F_b$ is calculated to be 0.284 N. Assuming a pressure of 0.38 MPa which is the pressure used for testing of the linear actuator, $F_c$ and $F_p$ are calculated to be 21.12 N and 10.38 N respectively. $\mu$ is assumed to be 0.05 which is a friction coefficient based on a well lubricated joint. $F_f$ is calculated to be 1.06 N using Equation 3.3.

Substituting the values calculated for $F_f$, $F_p$, and $F_b$ into Equation 3.1, $F_l$ is calculated to be 9.04 N.

The output force achieved from the benchtop testing, 7 N, is close to the 9 N predicted by this model. A more accurate model could be achieved knowing the mechanical properties of the balloon. The elastic force, $F_b$, which counteracts the output force of the actuator, seems to be negligible compared to the force, 10.38 N, applied to the piston by the fluid pressure. However, the friction force is relatively large and should be minimized to improve the efficiency of the actuator.
Chapter 4: Multi-Instrument Manipulator

4.1. Problem Definition

The ability to exchange instruments during NOTES and Laparo-Endoscopic Single-Site Surgery (LESS) is essential for surgical robotics in procedures such as cholecystectomy. NOTES has not been well adopted yet in the operating room due to several barriers. The relatively high number of instruments and the need to exchange them in many laparoscopic procedures is one of the most important hurdles that should be addressed to perform “pure” NOTES. The total number of different instruments required in a laparoscopic procedure (e.g., laparoscopic gastric bypass, hiatus hernia repair, removal of gastric band) can be as high as nine with 50 total instrument changes [46]. Additionally, transporting instruments from the external environment to within the body, removing the tool outside of the body, and changing functional tips manually is time consuming and may lead to complications such as bleeding, bowel perforation, and splenic injury due to increased chance of contact between tool edges and internal organs/tissues, endangering the safety of the patient.
Previous designs of multiple-instrument manipulators [32, 46, 47] use electric motors for tool exchange and actuation. With electric motors, there is always a tradeoff between size and performance in terms of speed and load capacity. Accordingly, previous designs are still bulky (outer diameter = 28mm, length = 104 mm [32]) making the insertion process difficult, tool exchange and actuation slow, and cost high. This motivated development of a hydraulically-actuated multifunctional manipulator which is half the size in both diameter and length and much faster compared to electric motor-driven designs.

4.2. Design and Prototyping

Figure 4-1 shows the multifunctional manipulator with two different tool tips deployed, a laparoscopic grasper and surgical scissors. The length and outer diameter (OD) of the manipulator are 55 mm and 14 mm respectively. The OD is well below that of a typical human esophagus, which is approximately 22 mm [32]. The robotic tool consists of a cartridge, four different types of combined piston-instruments stored in the cartridge, and a master actuation system. Commercially available single-acting hydraulic cylinders (Sub-Miniature Minimatic® Cylinder, SM-3-4) with a bore of 4 mm were cut and sized to the desired length of 47 mm. Four of these modified cylinders were attached to a plastic manifold as seen in Figure 4-2. Four miniature tubes with an OD of 2 mm were connected to the manifold to transfer water (as the hydraulic fluid) from the master system to the cartridge. Pistons were extracted from the hydraulic cylinders; the piston rods were cut to the desired length of 7 mm and were coupled to four different types of 2-
mm laparoscopic instruments (as seen in Figure 4-3). All other parts were fabricated out of ABS material using a 3D printer. To prevent the surgical tools from unwanted rotation when deployed, a special part (stopper part) with a snap, as seen in Figure 4.3, was added to the piston-instrument assembly. A match tab was cut into the cartridge. The diameter of the stopper is a little larger than the ID of the corresponding holes in the cartridge to stop further advancement of the tool and allow it to open as the pressure rises.

Figure 4-1. Multifunctional manipulator with a grasper (left) and scissors (right) deployed.
Figure 4-2. Instrument cartridge [48].

Figure 4-3. Piston-instrument assembly.
The instruments are normally closed due to use of a pre-loaded spring. They are opened when pressurized water is applied in the lower chamber of the piston-instrument/cylinder assemblies and close when the pressure is released.

Both instruments slide in and out of the slave cylinders with an inner diameter (ID) of 4 mm. Thus, the OD of the spring must be smaller than 4 mm. The ID of the spring should be larger than the OD of the instrument shaft (1.5 mm). The length of the spring is determined according to the spring stiffness, deflection required to provide the desired force, and length of the slave cylinders. A model, depicted in Figure 4-4, was created to analyze the forces acting on the scissors and determine the spring stiffness.

A relatively higher level of force is required for closing of the scissors due to high friction between the scissor blades. The minimum force required to close the scissors manually ($F_c$) was measured to be 2.5 N. To keep the scissors closed under normal conditions (default) the spring should be pre-loaded. The force exerted from spring to the piston ($F_{pre}$) can be found using Equation 4.1.

$$F_{pre} = kx_0 \quad (4.1)$$

where $k$ is the spring constant and $x_0$ is the pre-loaded spring deflection. To open the scissors, the stopper and snap locks in the tab, the water pressure is applied to the piston, and the spring is compressed by $x_1$. 

The total force exerted on the piston from the spring can be calculated using Equation 4.2.

$$F_{sp} = k(x_0 + x_1) = kx_0 + kx_1 \quad (4.2)$$

Substituting $kx_0$ from Equation 4.1 in Equation 4.2, $F_{sp}$ can be determined as follows:

$$F_{sp} = F_{pre} + kx_1 = F_c + kx_1 \quad (4.3)$$

According to the free body diagram shown in Figure 4-4 and Equation 4.3, the force required to open the scissors ($F_{op}$) can be found from the following equation.

$$F_{op} = pA = F_c + kx_1 \quad (4.4)$$
where \( p \) is the pressure applied to the piston and \( A \) is the cross-section area of the piston. \( F_c \) is constant (2.5 N) as is \( A \) (10.349 mm\(^2\)). To achieve a full opening of the scissors (an angular displacement of 64 degrees), the scissors shaft should displace about 2.5 mm \((x_1=2.5 \text{ mm})\). According to Equation 4.4, the higher the spring constant \((k)\) the higher the pressure needs to be to fully open the scissors. The pressure rating for the “weakest link” in the system (plastic tubing) is 0.689 MPa (100 psi). Substituting \( p=0.689 \text{ MPa} \) in Equation 4.4, \( k \) was calculated to be 1.852 N/mm. Commercially available springs with equal or lower stiffness and proper ID and OD and length as described previously were searched. A compression spring (W.B. Jones Spring Co., C04-016-016) with an ID, OD, length, and spring constant of 2.2 mm (0.088 in), 3.1 mm (0.120 in), 12.7 mm (0.50 in), and 1.471 N/mm (8.40 lbs./in) respectively was selected. Using this spring constant in Equation 4.1 and 4.4, \( x_0 \) and \( p \) were calculated to be approximately 1.7 mm and 0.597 MPa (86.6 psi) respectively.

The higher the pressure applied in the lower chamber of the slave cylinder, the higher the stiffness of the spring which could be used, and the higher pinch and cutting force could be delivered by the instruments. However, the limiting factor here is the pressure rating of the hydraulic system components, with its minimum being 0.689 MPa (100 psi) for the plastic tubing as the “weakest link” of the system. Using Matlab, a model (described by Equations 4.5 to 4.16) was created. The purpose of this model is to calculate the pinch force of the grasper and the water pressure as a function of the angular opening of the grasper.
A picture of the grasper was imported to SolidWorks and the grasper link lengths were measured (Figure 4-5). The measurements were then scaled properly to obtain actual dimensions.

\[ \alpha = \sin^{-1}\left(\frac{l_c}{l_b} \times \sin \theta\right) \quad (4.5) \]

\[ \alpha_0 = \sin^{-1}\left(\frac{l_c}{l_b} \times \sin \theta_0\right) \quad (4.6) \]

\[ X = l_b + l_c - (l_b \times \cos \alpha) - (l_c \times \cos \theta) \quad (4.7) \]

\[ X_0 = l_b + l_c - (l_b \times \cos \alpha_0) - (l_c \times \cos \theta_0) \quad (4.8) \]

\[ F_{rod} = k \times (X - X_0 + x_0) \quad (4.9) \]

\[ F_{pin} = \frac{F_{rod}}{2 \times \cos \theta} \quad (4.10) \]
\[ \sum M_0 = 0 \quad (4.11) \]

\[ F_{\text{tip}} \cdot l_a - F_{\text{pin}} \cdot l_b \cdot \sin(\theta + \alpha) = 0 \quad (4.12) \]

\[ F_{\text{tip}} = \frac{F_{\text{pin}} \cdot l_b \cdot \sin(\theta + \alpha)}{l_a} \quad (4.13) \]

\[ F_{\text{tip}} = \frac{1}{2} \cdot \frac{l_b}{l_a} \cdot F_{\text{rod}} \cdot \cos \theta \cdot \sin(\theta + \alpha) \quad (4.14) \]

\[ p = \frac{F_{\text{rod}}}{A} \quad (4.15) \]

\[ \gamma = \alpha - 12.93 \quad (4.16) \]

where \( X \) is the grasper rod displacement (equal to zero when \( \theta \) is zero), \( X_0 \) is the rod displacement when the grasper is closed, \( x_0 \) is the rod displacement caused by the pre-loaded spring, \( k \) is the spring constant, \( F_{\text{rod}} \) is the force applied to the piston by water pressure and transferred to the grasper shaft, \( F_{\text{tip}} \) is the pinch force delivered by the grasper jaws, \( p \) is the water pressure in the system, and \( \gamma \) is half the angle between the grasper jaws.

It is desired to achieve as high a pinch force \( (F_{\text{tip}}) \) on the order of 3 N (required for tissue manipulation [49]) as possible with a water pressure less than 0.689 MPa (100 psi) for a maximum opening of 46 degrees (similar to the opening of the scissors).

Different spring constants (selected from a commercially available spring catalogue) and varying \( x_0 \) were input to the model and the output pinch force and the required water pressured were examined. Finally, a spring (W.B. Jones Spring Co., C05-021-010) with an ID, OD, length, and constant of 2.7 mm (0.106 in), 3.8 mm (0.148 in), 7.9 mm (0.313 in), and 4.605 N/mm (26.3 lbs/in) respectively were selected. Figure 4-6 and Figure 4-7 show the pinch force and the required water pressure to provide corresponding pinch
force versus grasper opening. With an \( x_0 \) value of 1 mm, the pinch force is 1.7 N and the pressure is below 100 psi for an opening of 46 degrees.

Figure 4-6. Pinch force vs. angular opening.

Figure 4-7. Water pressure vs. angular opening.
A novel master-slave system was devised to control opening and closing of the instruments (Figure 4-8). The master system consists of a master motorized cylinder, pressure transmitter (ProSense, SPT25-10-0150A), three solenoid valves (3-way, two-position valve, STC Valve 3S012-1/8-A), and a microcontroller board (Arduino Uno with motor shield).

![Master-slave system](image1.png)

Figure 4-8. Master-slave system.

The master motorized cylinder consists of a double-acting hydraulic cylinder (Bimba Manufacturing, BR-011-D) with a bore of 8 mm and stroke of 25.4 mm coupled to a linear stepper motor (Anaheim Automation, 11AV102AX06), as seen in Figure 4-9.

![Hydraulic cylinder with stepper motor](image2.png)

Figure 4-9. Hydraulic cylinder coupled with a stepper motor [48].
Unlike traditional hydraulic systems where a hydraulic pump with high flow rate is used, here a master cylinder is coupled to a linear stepper motor to build an inexpensive and simple but accurate flow-controllable pump. This closed system removes the concern of leaking high pressure fluid with continuous flow into the abdominal cavity. The bore of the master cylinder was chosen to be larger than the slave cylinders (cylinders in the cartridge). Although this may seem contrary to the main advantage (mechanical advantage) a hydraulic system offers, a master cylinder with larger bore provides higher suction power per stroke of the cylinder which is required to overcome the pressure losses occurring in tubing and valves, and the friction between piston and cylinder during closure and retraction of instruments.

Figure 4-10 illustrates the working principle of the electro-hydraulic robotic manipulator, which is essentially a master-slave system. The slave system (multifunctional manipulator) is intended to attach to a robotic arm and be placed \textit{in-vivo}. The entire master system would be placed \textit{ex-vivo} so that high levels of pressure/force can be provided using larger motors since the space constraints which exist \textit{in-vivo} are not applicable \textit{ex-vivo}; this is in contrast to previous designs. This would also address the low mechanical advantage mentioned previously.
Figure 4-10. Schematic of the master-slave system [48].

Table 4.1. Solenoid valves sequencing scheme [48].

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Valve 1</th>
<th>Valve 2</th>
<th>Valve 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument 1</td>
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<td>Instrument 2</td>
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<tr>
<td>Instrument 3</td>
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<tr>
<td>Instrument 4</td>
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</tbody>
</table>

Tool exchange involves four stages: advancement, opening, closing, and retraction of the instrument. The overall system works as follows: first the user (the surgeon) decides which instrument to use (for instance instrument 1 as illustrated in Figure 4-10). Then signals are output via the microcontroller to energize the related solenoid valves (in this case valves 1 and 3) to deploy the selected instrument. The
microcontroller also converts displaced fluid volume to motor rotation needed to deploy each instrument and outputs a corresponding signal to the motor. When the surgeon decides to manipulate tissue, the instrument is first opened and then closed. Opening of the instrument is done in the same fashion as the advancement of the instrument except that in this stage high pressure is required to compress the spring while the flow is low. To close the instrument the motor rotates in the opposite direction; water is sucked back towards the master cylinder until the pressure sensor reads a pressure on the order of 0.006 to 0.034 MPa (the back pressure can be adjusted to control the amount of applied force); the energy in the spring is now released, closing the instrument. In the last stage (retraction), the system works as during the advancement stage except that the motor rotates in the opposite direction. The sequence of energizing the solenoid valves for deployment of each instrument is shown in Table 4.1.

4.3. Testing Results

All parts of the electro-hydraulic manipulator system were assembled. The manipulator was tested with two instruments and without the pressure transmitter to verify the functionality of the system. The entire manipulator and the master cylinder were submerged in water to fill the hydraulic fluid (water) into the system. A syringe was used to further inject water into the system. Bleeding the air out of the hydraulic system was performed without difficulty due to the opening at the top of the slave cylinders in the cartridge; however, preventing air infiltration during closure and retraction stages (suction) required plumbing sealant (Loctite 1366077).
All four stages of tool exchange worked as expected. Smooth and swift tool exchange was achieved. Tool exchange time is a function of the velocity of the stepper motor in the master motorized cylinder. The higher the velocity of the stepper motor, the higher the fluid flow rate, and therefore the shorter the tool exchange time. The velocity of the stepper motor was set at two values, 50 rpm and 120 rpm, and the manipulator was tested separately for each velocity. With the velocity of 50 rpm, the tool advancement/retraction time and the tool actuation time were measured to be approximately 4 and 1.5 seconds respectively. With the velocity of 120 rpm the tool advancement/retraction speed and tool actuation were measured to be approximately 1.35 and 1 second(s) respectively. These results indicate a significant improvement over manual interchange and/or previous designs [32 & 46]. The coupled motor-cylinder pump created around 0.345 MPa of pressure with 5 V input and approximately 700 mA of current. The pinch force of the grasper was measured to be 1 N for an angular opening of 28 degrees using the same setup as explained in section 3.3. This experimental result is close to the 1.25 N found from the model described in section 4.3. The scissors successfully opened up 46 degrees and closed with a pressure on the order of 100 psi. Although the pressure is higher than the 87 psi predicted by the model, it is still acceptable considering the safety factor used in building hydraulic components.

4.4. Interpretation

The presented electro-hydraulic manipulator offers several advantages over previous electric motor-driven manipulators. With loss of tactile feedback in most
MIS robotic surgeries, the surgeon may apply excessive forces to tissues that could lead to tissue perforations and trauma. The electro-hydraulic manipulator, on the other hand, has a peak force that can be set by either using springs with particular stiffness or controlling the fluid pressure. In this design, all electronics are placed ex-vivo, eliminating the concerns of leaking electricity into the tissue, transferring heat produced by motors to the tissue, and the difficulty of sterilization after surgery. The cost of fabrication is much less for the electro-hydraulic manipulator than the electric motor-driven versions, making this an ideal manipulator for one-time (disposable) use in in-vivo robotic applications. Lastly, by simply replacing the manipulator’s metallic parts with nonferrous materials, it could be used for MRI-compatible robotics.

Adding the pressure transmitter and additional instruments to the system and performing animal testing is part of upcoming future work. Shrinkage of the manipulator OD to 12 mm and length to 50 mm is also possible by using cylinders with 3 mm bore in the cartridge and shortening the length of the coupling and the piston on the piston-instruments.
Chapter 5: Fluid Powered Robot Arm

5.1. Introduction

The vision of this work is to develop a fully hydraulically-driven miniature bimanual robot for Natural Orifice Translumenal Endoscopic Surgery (NOTES). However, it was deemed wise to first build one arm using the linear actuator, the vane motor, and the tool-changing manipulator described in previous chapters. The robot arm, seen in Figure 5-1, has 3 degrees of freedom in addition to 1 degree of freedom of opening and closing of the instruments. The first prototype was built to demonstrate the proof of concept and investigate the functionality of the fluidic actuators.

One of the main advantages of the developed actuators is the ease of fabrication and the flexibility of integrating them in different designs. These actuators were re-designed and fabricated according to intended application, size limitation, and connection method. The actuators can be driven either hydraulically or pneumatically. They were tested with both fluids (water and air) separately with successful results before their integration into the system. When tested with water, bleeding the air out of these balloon-based actuators was difficult since one end of the balloon is closed. A syringe with a long,
thin needle was used to inject water in the balloon and push the air out. For initial testing of the robot arm, it was decided to use pneumatics due to ease of setup, availability of pneumatic components, and not having to deal with filling the entire system with water and bleeding the air out of the system. Future work includes developing a master control system similar to that of used for the electro-hydraulic manipulator to allow use of water instead of air and obtain a precise and inexpensive position control for the linear actuator and the vane motor.

Figure 5-1. Robotic arm.
5.2. Design Description

Figure 5-2 shows the detailed design of the vane motor used to rotate the base of the robot arm, providing the roll DOF. This motor is a customized version of the limited-motion rotary actuator presented in section 3.2. Two miniature high-precision stainless steel ball bearings (McMaster-Carr, 57155K341 and 7804K111) were mounted in the flange and the cap to facilitate rotation of the motor shaft and support radial and axial load. A connecting link (connector in Figure 5-2) was added to the motor allowing easy attachment of other parts to the motor and providing room for routing plastic tubing transferring fluid, as seen in Figure 5-6. To keep the motor shaft from spinning inside the blade and the connector, a flat as depicted in Figure 5-3 was cut in the blade and the connector. A matching flat was cut on the shaft. The cap was glued to the stator using cyanoacrylate glue.

Figure 5-2. Vane motor 3D model and exploded view.
To give the manipulator a yaw (a rotational DOF), a linear actuator with a linear to rotary converter was used. The linear actuator is another customized version of the linear actuator described in section 3.2 with a stroke of 6 mm (Figure 5-4). A plastic rack-pinion gear set with a module of 0.5 mm was used to convert the cylinder linear motion to the joint rotary motion. The rack gear (Gizmoszone, GRG0.5-125) was glued to the top of the outer tube of the cylinder. The pinion gear (Gizmoszone, GM0.5-08-19) was glued to the link connecting the manipulator to the joint. Two small ball bearings (McMaster-Carr, 57155K339) were used to provide a rolling support for the rack gear and to facilitate translating movement of the rack gear (Figure 5-5).
Figure 5-4. Linear actuator 3D model and exploded view.

Figure 5-5. Linear to rotary motion converting mechanism.

Most parts of the robot arm were fabricated out of ABS material using a 3D printer. Regular off-the-shelf balloons were used in the linear and rotary actuators. The
Actuators, multi-instrument manipulator, and all other sub-components were assembled together to make a fluid powered robot arm (Figure 5-6).

5.3. Testing Results

To test the functionality of the robot arm, bench-top testing was performed. A simple control setup (Figure 5-7) consisting of a compressor, a pressure regulator, a flow meter, a flow control valve, and two directional control solenoid valves was used to run...
the linear actuator and the vane motor. The multifunctional manipulator was tested separately as presented in section 4.3.

Each actuator was run separately. The vane motor was able to rotate the entire robot arm 180 degrees in both directions (clockwise and counter-clockwise) in 0.61 seconds with a flow rate of 5.2 L/min and a pressure of approximately 0.345 MPa (50 psi). The linear actuator- rack and pinion gear set was able to rotate the elbow joint nearly 100 degrees clockwise (upward) and counterclockwise (downward) in 19 and 3 seconds respectively with the same flow rate and pressure as used for the vane motor. While gravity helped the manipulator to move downward faster, there were other factors that could cause the speed difference between clockwise and counter-clockwise displacement of the elbow joint. These factors include: a poor mate between the rack gear and the pinion gear, radial expansion of the balloon in the upper chamber of the linear actuator compared to axial expansion in the lower chamber, and friction in moving parts. A better surface finish on the back of the rack gear where it has a continual contact with two small ball bearings providing rolling support could decrease the friction and lead to a better mate between the rack gear and the pinion gear. A customized L-shaped balloon could be used in the upper chamber of the linear actuator so that the balloon will expand axially. The entire robot arm with 4 instruments weighs approximately 50 grams.
Figure 5-7. Pneumatic test setup.
Chapter 6: Disposable Fluidic Self-Propelling

Robot for Colonoscopy

6.1. Introduction

According to the American Cancer Society, one out of 20 Americans will be diagnosed with colorectal cancer in their lifetime [12]. Men have higher risk (30% to 40%) of being diagnosed with colon cancer than women [12]. The cancer incidence rate increases with age. About 90% of colon cancer deaths occur above the age of 50 [12]. Precancerous polyps slowly grow to invasive cancer cells (over the course of 10 to 25 years). This provides a unique opportunity for undergoing screening for early detection and removal of precancerous growths. It has been shown that early screening has reduced colorectal cancer incidence and the associated mortality rate. Millions of Americans with a history of colon cancer are alive. There are several options for screening of colon cancer including: colonoscopy, sigmoidoscopy, computed tomographic colonography (CTC). Colonoscopy is the most effective method for detecting growths with the longest rescreening interval [12]. Conventional colonoscopy is performed manually by a
gastroenterologist inserting a long flexible colonoscope at the anus and pushing it forward to the cecum. Screening of the colon and possible removal of polyps is performed upon extraction of the scope. Maneuvering the scope to explore the entire length of the collapsed colon with sharp bends and loose surrounding tissues is difficult and requires a steep learning curve for gastroenterologists. Accordingly, there is a high risk of loop formation in the scope during this procedure that could cause pain, bleeding, bowel tears, and other complications. Moreover, the scopes used in colonoscopy are not disposable and need to be sterilized after each procedure. Maintenance and sterilization of colonscopes is time-consuming and adds extra cost to the procedure. Yet, there remains a chance of transmitting diseases/infection from one patient to another. To overcome the difficulties and complications associated with conventional colonoscopy, recent advancements are moving towards use of robotic and imaging technology to automate this procedure to reduce the trauma and discomfort to patients and facilitate high-volume screening.

Perhaps the most challenging part of a robotic design for colonoscopy is a propulsion mechanism that could enable painless colonoscopy by reduction of looping as well as excessive forces to the colon wall. Inch-worm locomotion is one of the most common propulsion approaches used in previous designs. Examples of this approach, as seen in Figure 6-1 to Figure 6-4, are the Endotics® System [50-51], an inch-worm like robot with hollow body and steering device [52], a micro robotic system [53], and a micro creeping robot [54]. Disadvantages of the inch-worm mechanism are slow advancement and relatively large friction/contact with the inner wall of the intestine.
Other researchers have used inflatable balloons to provide less invasive locomotion for screening and therapeutic colonoscopy. The Aer-O-Scope (seen in Figure 6-5), from GI-View, is a disposable pneumatic robot using balloons and CO$_2$ gas for self-propelling [55]. This robot is a screening-only device with no instrument channel for biopsy sampling and removal of polyps. Dodou et al. [56] developed a snail robot using a series of alternatively inflated and deflated balloons. The robot slides on a layer of mucus on the colonic surface (Figure 6-6).

In other designs [57-58] legged mechanisms and/or tracks have been used for active locomotion (Figure 6-7). The anchoring mechanism of this approach is invasive with a relatively high risk of tissue trauma including perforation.

Figure 6-1. Endotics® System [50-51].
Figure 6-2. Inchworm-like colonoscopic robot with hollow body and steering device [52].

Figure 6-3. Micro robotic system for colonoscopy [53].

Figure 6-4. A micro creeping robot for colonoscopy based on the earthworm [54].
Figure 6-5. The Aer-O-Scope Colonoscope [55].

Figure 6-6. Snail robot [56].
Several colonoscope modifications (Figure 6-8) have been developed and are either commercially available in Europe or in an FDA clearance process for use in the USA. The common theme in these platforms is the use of pneumatics or hydraulics for propulsion and a disposable sleeve to facilitate sterilization.

In recent years, a great deal of research and development has been devoted to wireless capsule endoscopy [61-64]. PillCam® COLON from Given Imaging is a commercially available capsule endoscope that has received FDA clearance (Figure 6-9). The capsule naturally passes through the gastrointestinal tract (GI) without discomfort. Intubation, insufflation, or sedation is not required in capsule endoscopy compared to standard colonoscopy. However, inability to control the trajectory of the capsule to
localize an identified lesion, and incapability of collecting biopsy samples are considered the main restrictions of this minimally invasive endoscopy approach.

In efforts to actively control wireless capsules and circumvent the aforementioned limitations of passive capsule endoscopy, Arezzo et al. [65], implemented an external locomotion strategy. External magnetic fields were used to impart forces to the \textit{in-vivo} capsule. A 6-DoF robotic arm (Figure 6-10) holding a permanent magnet creates the magnetic field. The robot arm is controlled remotely by the surgeon. Although the elimination of onboard miniature actuators and mechanisms is the unique advantage of this technique, use of an extra expensive component (the robotic arm) which makes the procedure less affordable, more complex for training, and longer compared to conventional colonoscopy is the main disadvantage. Furthermore, the external magnetic field draws the capsule upward, creating continual friction and contact with the internal wall of the intestine that could increase the risk of tissue perforation.

Figure 6-9. Pillcam colon capsule endoscope [64].
In contrast to previous designs, here we present a fluidic self-propelling self-steering robot that is very flexible and thus less invasive, simple, skill-independent, inexpensive, and disposable.

6.2. Method

An early version of the fluidic robot is shown in Figure 6-11. It consists of an anal introducer, a tip, and a latex tube with ID and OD of 1.6 mm and 3.2 respectively. The tip of the robot would be inserted first into the colon and then the anal introducer with a small portion of the latex tube left between them. One end of the tube is closed and tied over the tip, while another end attaches to a PVC tube transferring air from a compressed air source. The closed end part of the latex tube is pre-stressed to make the latex tube expand from the robot’s tip towards the anal introducer when pressurized. The tube expands radially first to a maximum diameter of 16 mm and then axially until it contacts the flat surface of the anal introducer. The anal introducer is kept immobile; thus the axial
expansion of the latex creates a thrust pushing the robot head forward. As the robot advances, more tube is pulled into the colon from outside though a hole in the anal introducer having a larger diameter than the OD of the deflated latex tube. The pulled-in latex tube inflates and provides the tip of the robot a continuous, smooth, and swift propulsion. The latex tube acts like a flexible linear actuator with a long stroke. This locomotion method is demonstrated in Figure 6-12.

Figure 6-11. Early version of the robot [66].

Figure 6-12. Advancement of the robot head [66].

To test this propulsion method, a colonoscopy simulator (Figure 6-13) was built. A scaled anatomically-matched profile was cut into soft foam. A synthetic colon (SynDaver™ Labs, O-LIN-A-0005) was laid out in the simulator bed. The robot’s tip with approximately a 12-mm long latex tube was inserted in the synthetic colon. The anal
introducer was fixed at the end of the colon using a tie rod. A pressure of 0.207 MPa (30 psi) was loaded into the tube. The tip of the robot passed the first two curves of the colon and stopped in the middle of the descending colon. The same test was performed several times and with a different latex tube with larger diameter (ID of 3.2 mm and OD of 4.8 mm) to investigate the effect of larger propulsive force on further advancement of the robot head. The advancement of the robot varied with different pressure, flow rate, and tube diameter; however, the robot was incapable of traversing the descending colon, going around the third curve, and making its way to the transverse colon.

It was first thought that the lack of active steering was the main cause of robot stoppage. To investigate this hypothesis, a simple cable steering and manual guidance of the robot head was performed. The robot was still incapable of passing the transverse colon and stopped about halfway through the intended path. The testing was video recorded and examined in more detail. The following factors seemed to be responsible for the failure of this propulsion approach.
1- Too much friction and contact between the inflated latex tube and the internal wall of the synthetic colon as the robot advances. The entire length of the inflated tube has to move along the colon following the robot’s tip. This creates an undue amount of friction, especially on the corners/curves.

2- The friction between the robot’s tip and the internal wall of the synthetic colon. Buckling and tube looping occurred in many tests as a negative effect of friction.

3- Lack of a flexible joint between the tip and the tube to keep the tip straight and keep it from getting jammed sideways. A joint with one or two DOF seemed necessary to help facilitate navigating the curves.

4- The head of the robot was not able to distend colon folds, clearing the robot’s way forward.

To address each of these issues, some modifications were made in design, prototyping, and the propulsion approach. The new robot is shown in Figure 6-14. It is composed of an anal introducer, a latex tube, a concave aperture, a tip, a packing mechanism inside the tip, and a sealing mechanism.
To address the first issue, the latex tube deployment was modified. In contrast to the first propulsion method where the tube is dragged into the colon from outside, here, a 300-mm tube is packed inside the tip with about a 10-mm tube left available between the tip and the anal introducer. A PVC tube attaches to the end of the latex tube and runs through the hole in the anal introducer. There is no latex tube available outside of the body in this approach. When the tube is loaded with compressed air, the free (unpacked) portion of the tube first expands radially and then grows axially towards the tip until it contacts the concave aperture, pushing the tip forward. As the tip advances, more tube is paid out from the tip and expands, giving the tip of the robot a propulsive force moving it forward. This way, there is less friction between the internal wall of the colon and the tube as there is very little relative motion between the inflated tube and the colon, making it easier for the tip to navigate the entire length of the colon. The most challenging part of this approach was to devise a packing mechanism. The mechanism should be small enough to fit in the tip and should enable smooth deployment of the tube. It is necessary
to prevent the air from passing through the packed tube; otherwise, the tube will inflate a little bit requiring more room inside the tip and compromising the smooth deployment of the tube. A few packing mechanisms were explored. One example was an accordion-type design where the folds prevent the air from entering the packed tube and keep the packed tube un-inflated; however, implementation of this mechanism seemed difficult.

Eventually, a novel winding/unwinding mechanism with a complementary sealing mechanism to prevent air from entering the packed tube was designed and prototyped. A latex tube (Kent Elastomer Products, Inc., #402) with a larger diameter (ID and OD of 3.2 mm and 4.8 mm respectively) than the first version was used in this approach. This larger tube expands to a diameter closer to the ID of the colon leaving less room for buckling and loop formation. The larger diameter also provides higher propulsive force for a given air pressure.

The sealing mechanism (Figure 6-15) consists of two sets of miniature bearings mounted on two parallel shafts and two sets of set screws and nuts. A flanged bearing (see Figure 6-15) was mounted on each shaft at opposite sides to keep the latex tube from sliding off and running into the sides, which could cause jamming. Three bearings on each shaft press the tube to prevent passage of air. The lower shaft is fixed in place, while the upper one can slide slightly in a short slot. Two set screws and fixed nuts with fine threads are used to adjust the distance between these two shafts. The distance is tuned until an optimal pressure providing both sealing and smooth unwinding is achieved. One end of the tube is closed and the tube is pressed between two bearing sets. As the tube is pulled in the tip, the air is pushed out, creating a vacuum in the tube (see Figure 6-16).
The vacuumed tube is then rolled around the internal shaft of the packing mechanism (Figure 6-17). Two bearings were mounted on the shaft to facilitate free spinning of the shaft during winding and unwinding of the tube. A hex key is used to rewind the tube around the shaft for ease of repeating testing.

Figure 6-15. Sealing mechanism.

Figure 6-16. Vacuumed tube.
Not surprisingly, friction is an adverse factor, with conditions deteriorating as the robot goes further inside the colon. To minimize the friction between the tip and the internal wall of the colon (addressing the second issue), the outer surface of the two
halves of the tip was coated using UV curing adhesive. Alternatively, a hydrophobic spray was used with quite similar outcomes.

To address the third issue (lack of a flexible joint between the tip and the inflated tube), a concave part was added to the tip. The concave aperture provides a surface for the tube to push against to produce propulsive force. A concave was formed into this part to keep the balloon in direct contact with the tip all the time to avoid buckling. The concave surface also acts like a ball-socket joint providing two degrees of freedom. The entire length of the tip including the sealing mechanism and the concave aperture is short enough to enable the tip to navigate curves easily.

To overcome the fourth issue (collapsed colon), it was decided to insufflate the colon similar to conditions in a typical colonoscopy. Air was used to insufflate the synthetic colon during testing as explained in the next section.

6.3. Testing

The robot was first put in a straight transparent tube (Figure 6-18) with an ID of 35 mm to evaluate the functionality of the modified locomotion method. The robot successfully traveled the entire length of the tube which was about 920 mm. This indicated that the packing and sealing mechanisms functioned properly and all packed tube was unwound.
Similarly, a second experiment was conducted to test the performance of the robot on the corners. A U-shaped profile and a 180-degree bend were cut into soft foam to shape the colon simulator. The robot was inserted inside the synthetic colon. The anal introducer was attached to the end of the colon (the anus). The colon was then insufflated using air from the other end of the colon (the cecum). A pressure on the order of 0.138 MPa (20 psi) with a low flow rate of approximately 1.75 L/min was loaded into the latex tube. The robot successfully passed two curves and advanced to the proximity of the cecum in both testing scenarios. In both testing setups only the tip of the robot was in contact with the internal wall of the colon, and the latex tube acted like a flexible linear actuator with minimal contact with the colon.
Finally, to assess the performance of the robot in a more realistic setup, an experiment in real tissue was conducted. Figure 6-20 shows a slice of a pig colon after the robot entered the colon from one end, and successfully passed all the way through to the other end. Periodic insufflation was done as necessary to maintain consistent distention conditions while the robot was moving inside the tissue. The same level of pressure and flow rate as the second experiment was used. It seemed the friction was much less in this testing as the robot moved much more smoothly in real tissue than the synthetic tissue.
Figure 6-20. Porcine tissue testing.
Chapter 7: Conclusion

7.1. Review

The field of surgery is moving towards less invasive techniques to improve patient outcomes. The dream of scar-free surgery is becoming a reality with advancements in surgical tools and imaging technology. Fusion of robotics and surgery has created a unique opportunity to develop novel devices for implementation of minimally invasive techniques. The da Vinci surgical system is one example of a robotic system enabling surgeons to perform a delicate laparoscopic procedure through a single incision. Beyond the da Vinci surgical system, a wide variety of surgical robotic platforms have been reported in the literature. The new trend in surgical robotics is development of miniature \textit{in-vivo} robots that can enter the human body from natural orifices for diagnosis and treatment. It is believed that Natural Orifice Translumenal Endoscopic Surgery (NOTES) is an important part of the future of surgery with its great potential benefits resulting from elimination of external incisions. A number of \textit{in-vivo} robots for different surgical tasks were presented in Chapter 1. The primary choice of actuation in many of these devices has been electric motors. While some of these
miniature *in-vivo* systems have demonstrated promising results, many of them encountered the challenge of balance between scale and robotic capability. Besides, the nature of inserting electric motors inside body among biological tissues and organs introduces additional design concerns and limitations such as the risk of leaking electricity to tissues, transferring heat from motors to the organs, and difficulty in sterilizing electronics. With the current state of technology in building electric motors, it appears very difficult to solve the scale-power challenge and move past the *in-vivo* introduced concerns/limitations.

Fluid power in the form of hydraulics or pneumatics has a long history in driving many industrial devices. Many simple fluidic medical devices are either commercially available or have been reported in the literature. The hypothesis for this research was that fluid power could be exploited in development of miniature *in-vivo* surgical robots. High power density and good compatibility with *in-vivo* environment are the key advantages of fluid power over electric motors when it comes to *in-vivo* applications.

To build a fluid-powered robot, it was first necessary to develop small fluidic actuators to drive robot joints and impart force and torque to surgical tools. A miniature cylinder and a limited-motion vane motor were built. These balloon-based actuators are small, powerful, easy to fabricate, and inexpensive, ideal for disposable applications. Testing of these actuators showed promising results. The performance of these actuators could be enhanced by the use of customized balloons with improved properties. Fabrication of a customized balloon was beyond the scope of this research. Simulation of the balloon-based actuation in actuators and colonoscopy robot was difficult due to
unknown properties of the balloons and the latex tubes used in this research. However, balloons could be custom-made and mechanical characterization testing could be performed, potentially leading to a model for simulating these actuators. Air, water, or saline could be used in these actuators. While air is clean and available in many operating rooms, control difficulty, cost of control hardware, and risk of leaking into the body are limitations for use in in-vivo surgical robotics. Water and saline are better choices, although bleeding the air out of the system can be difficult.

An electro-hydraulic multifunctional manipulator capable of carrying four different instruments was built in response to the frequent tool exchanges needed in natural orifice surgery. This tool-changing manipulator is small enough to be inserted through natural orifices and much faster than previous electric-motor versions. It is possible to even further miniaturize the manipulator as explained in Chapter 5. Higher pressure will deliver higher levels of tool pinch and cutting forces; however, plastic tubing and fittings with higher pressure ratings should be used.

The fluidic actuators and the electro-hydraulic manipulator were used to build a surgical robot arm. Bench-top testing of the robot arm confirmed the usability of the newly-developed actuators in in-vivo surgical robotics. The vision of this research is to make a bimanual robot for NOTES using two of these arms connected together and delivered to the abdominal cavity by a snake robot as described in [32]. This would be the first fully hydraulically-driven bimanual robot for NOTES with up to eight surgical instruments available at the site of surgery.
Colonoscopy is another form of natural orifice surgery for diagnosis and removal of precancerous growths and/or cancerous cells. Looping is a serious issue in colonoscopy and is responsible for most of the traumas related to this procedure. Robotic experts have tackled this issue with a variety of solutions. However, each solution has had its own limitations as discussed in Chapter 5. In this research, it was believed that fluid power delivered via a flexible balloon could be used to develop a semi-autonomous robot. The first prototype was built and tested in a colon simulator. Observations and feedback were collected to revise the locomotion technique and prototyping method. The second version of the robot was then designed and prototyped. Successful results were obtained in the colon simulator and porcine tissue testing. The robot is self-propelling, self-steering, flexible, disposable, and simple. The robot is skill-independent and can quickly travel the entire length of colon.

7.2. Future work

This research introduces a new and novel concept in actuating robotic joints and locomotion. There is a lot of room for improvement and modification in building each of the developed components and design of the bimanual robot in particular.

As mentioned in the previous section, customization of the balloon used in the fluidic actuators could enhance their performance. Future work could include first identification of the required properties to achieve the desired level of force and torque, and then fabrication of the balloons according to these properties. New prototypes of the actuators with these balloons could then be made and tested.
As for the electro-hydraulic manipulator, the pressure transmitter as mentioned in Chapter 3 could be integrated into the system to obtain a more precise pressure control of the system that could lead to more accurate tool deployment and deliverable tool force. Two more laparoscopic instruments should be added to the manipulator cartridge. Real tissue testing needs to be performed to quantify the pinch and cutting force that each instrument can deliver. A small valve that is either internally driven (hydraulically) or externally driven (cable) can be developed and incorporated to the cartridge to minimize the number of PVC tubes transferring fluid from the master system to the slave system.

Upon improvement of each component as described in the previous paragraphs, the performance of the robot arm will also be improved. The robot arm was tested using pneumatics to demonstrate the proof of concept. However, a master control system similar to that developed for the electro-hydraulic manipulator needs to be designed and built in order to use water instead of compressed air to drive the entire arm. When the robot arm is successfully driven using only hydraulics, the work could advance to put two of these arms together to make a hydraulic bimanual robot for NOTES.

Regarding the colonoscopy robot, this research presented a novel and promising locomotion technique. Integration of a miniature wired or wireless HD camera is a must in order to, at least, use the robot for colon screening. A biopsy sampling tool could be carried by the robot’s tip to add therapeutic capability to the robot. Benchtop testing is essential to get feedback and improve upon unexpected failures and shortcomings. Eventually an animal model should be used to test the robot in a real situation.
References


Appendix A

Matlab and C programming/Scripts
A.1 Step response of the transfer function for PID position control of the pneumatic cylinder

clear all
clc
clf
m=0.025;
A=(4.95/100000);
c=1.5;

% Plant transfer function
num=[0 0 A];
den=[m c 0];
t=(0:0.01:20);
plant=tf(num, den);

%PID parameters
kc=3000;
kp=150;
ki=220;
kd=5;

num_Gpid=[kc*kd kc*kp kc*ki];
den_Gpid=[1 0];
Gpid=tf(num_Gpid, den_Gpid);

system = feedback(plant*Gpid,1);
clear all
close all
clc
Theta0= 0.2091; % 11.94 degree
x0=1; %mm
k=4605.06/1000; % N/mm
A=12.31; % mm^2

% All in mm
la=4.634;
lb=2.452;
lc=2.651;
alpha0=asin((lc/lb)*sin(Theta0));
X0=lc+lb-(lc*cos(Theta0))-(lb*cos(alpha0));
Theta=Theta0:.1:.81;
alpha=asin((lc/lb)*sin(Theta));
X=lc+lb-(lc*cos(Theta))-(lb*cos(alpha));
Frod=k*(X-X0+x0);
figure(1);
plot(X,Frod);

\[ F_{tip} = 0.5 \times \frac{lb}{la} \times \cos(\Theta) \times \sin(\Theta + \alpha) \]

\[ p = \frac{Frod}{A} \]

\[ p = p \times 145 \quad \text{psi} \]

\[ \alpha_{deg} = \frac{\alpha \times 180}{\pi} \]

\[ \Gamma = \alpha_{deg} - 12.93 \]

\[ \text{AngOpening} = 2 \times \Gamma \]

figure(2); plot(AngOpening,Ftip);

\text{title(}'k=4.605 \text{ N/mm and } x0=1 \text{ mm}'\text{'})

\text{xlabel(}'Grasper angular opening (deg)'\text{'})

\text{ylabel(}'F_{tip} (N)'\text{'})

figure(3);

plot(AngOpening,p)

\text{title(}'k=4.605 \text{ N/mm and } x0=1 \text{ mm}'\text{'})

\text{xlabel(}'Grasper angular opening (deg)'\text{'})

\text{ylabel(}'Water pressure (psi)'\text{'})

\%Maximum physically possible angular opening=66
A3. Force analysis for the laparoscopic scissors of the multi-instrument manipulator

clear all

close all

clc

% knowns

Freq=2.5; %N based on benchtop testing

x=2.5; %mm

Dpis=3.63; %mm

A=pi*(Dpis^2)/4;

% Variables

p=100; %psi

p=p/145.037738; %MPa

Fop=A*p;

k=(Fop-Freq)/x; %N/mm

x0=Freq/k; %mm
A2. PID position control of the pneumatic joint

#include <PID_v1.h>
#include <TimerOne.h>

int potPin0 = A0;    // select the input pin for the
        potentiometer#1 (master)
int potPin1 = A1;    // select the input pin for the
        potentiometer#2 (slave)
int solApin = 6;     // select the input pin for the
        potentiometer#1 (master)
int solBpin = 7;

int check=0;
double val0 = 0;
double val1 = 0;
double PWM_val = 0;
double error=0;
double er1=12;
double dutycycleA=0;
double dutycycleB=0;
double k=1;
double kc=1;
double kp=2;
double ki=5;
double kd=0.12;

double kpn=0, kin=0, kdn=0;

PID myPID(&val1, &PWM_val, &val0, kp, ki, kd, DIRECT);

void setup() {
    Serial.begin(9600);             // initialize serial communication with computer:

    int prescalerVal = 0x07;       //create a variable called prescalerVal and set it equal to the binary number "00000111"

    TCCR4B &= ~prescalerVal;       //AND the value in TCCR0B with binary number "11111000"

    //Now set the appropriate prescaler bits:
    prescalerVal = 0x05;           //set prescalerVal equal to binary number "00000001"

    TCCR4B |= prescalerVal;        //OR the value in TCCR0B with binary number "00000001"

    pinMode(6, OUTPUT);            // declare the solAPin as an OUTPUT

    pinMode(7, OUTPUT);            // declare the solAPin as an OUTPUT

    analogWrite(6, 0);

    analogWrite(7, 0);
myPID.SetOutputLimits(-100, 100);

myPID.SetMode(AUTOMATIC);  //turn on the PID
}

void loop() {

  //val0=400;

  er1=15;

  loweringerror:
  val0= analogRead(potPin0);
  val1=analogRead(potPin1);

  if (val0<210 || val0>435){
    analogWrite(6, 255);
    analogWrite(7, 255);
  }
  else {
    error=abs(val0-val1);
    kc=20*k;
    myPID.Compute();
    kpn=kc*kp;
    kin=kc*ki;
    kdn=kc*kd;
    myPID.SetTunings(kpn, kin, kdn);
    myPID.Compute();
dutycycleA= (0.5*(PWM_val)+50)*255/100;
dutycycleB= (-0.5*(PWM_val)+50)*255/100;
}

if (error>er1){
analogWrite(6, dutycycleA);
analogWrite(7, dutycycleB);
}

if (error<=er1){
analogWrite(6, 255);
analogWrite(7, 255);
}
A4. Stepper motor control (electro-hydraulic manipulator)

```cpp
#include <AFMotor.h>

// Connect a stepper motor with 200 steps per revolution
// (1.8 degree)
AF_StepperMotor(200, 1);

int Valv1Pin = 5;
int Valv2Pin = 6;
int Valv3Pin = 7;

t void setup() {
    Serial.begin(9600); // set up Serial library at 9600 bps
    pinMode(Valv1Pin, OUTPUT);
    pinMode(Valv2Pin, OUTPUT);
    pinMode(Valv3Pin, OUTPUT);
    motor.setSpeed(50); // 10 rpm
}

t void loop() {
    Serial.println("Single coil steps");
    digitalWrite(Valv1Pin, HIGH);
}
```
digitalWrite(Valv2Pin, HIGH);
digitalWrite(Valv3Pin, LOW);
motor.step(775, FORWARD, SINGLE);
delay(8000);
motor.step(200, FORWARD, SINGLE);
delay(7000);
motor.step(230, BACKWARD, SINGLE);
delay(7000);
motor.step(670, BACKWARD, SINGLE);
delay(7000);
Appendix B

Technical Details of Commercial Components
B.1. Laparoscopic grasper

MiniSite ENDO GRASP

<table>
<thead>
<tr>
<th>Order Code</th>
<th>Description</th>
<th>Ship Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>171321</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Features and Benefits
B.2. Laparoscopic Scissors

2-mm MiniSite Scissors
B.3. Single-acting miniature cylinder

SM-3-4

**SM-2**
- Single Acting
- Bore: 5/32"  
- Mount: Rear Thread
- Type: Spring Return
- Materials: Stainless steel body, piston & rod, Buna-N U-cup, Beryllium copper spring

**SM-3-4**
- Single Acting
- Bore: 3/16"  
- Mount: Rear Thread
- Type: Spring Return
- Model: SM-3-3
- Stroke: 1/2"
- Length: 1.286"
- Materials: Stainless steel tube and rod, brass piston, Buna-N U-cup

**SM-6**
- Single Acting
- Bore: 1/4"  
- Mount: Body
- Type: Spring Return
- Available Stroke Lengths: 3/8"
- Materials: Brass body, Buna-N U-cup, stainless steel piston & rod

*Superstructure recommended

Nuts included, but not shown on drawing.
B.4. Double-acting cylinder

BR-011-D

<table>
<thead>
<tr>
<th>MODEL/PRICE</th>
<th>DESCRIPTION/WEIGHT (lbs.)</th>
<th>DIMENSIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$20.20 BASE PRICE</td>
<td>Add $2.55 per inch of stroke</td>
<td></td>
</tr>
<tr>
<td>$17.25 BASE PRICE</td>
<td>Add $2.55 per inch of stroke</td>
<td></td>
</tr>
<tr>
<td>$19.95 BASE PRICE</td>
<td>Add $2.55 per inch of stroke</td>
<td></td>
</tr>
<tr>
<td>$24.90 BASE PRICE</td>
<td>Add $2.55 per inch of stroke</td>
<td></td>
</tr>
<tr>
<td>$18.20 BASE PRICE</td>
<td>Add $1.55 per inch of stroke</td>
<td></td>
</tr>
</tbody>
</table>
B.5. Compression Spring

P/N C04-016-016

Compression Spring - P/N C04-016-016 | W.B. Jones Spring

Compression Spring - P/N C04-016-016
0.120OD, 0.016 music wire, 0.650 overall length

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part Number</td>
<td>C04-016-016</td>
</tr>
<tr>
<td>Outside Diameter</td>
<td>0.120</td>
</tr>
<tr>
<td>Inside Diameter</td>
<td>0.008</td>
</tr>
<tr>
<td>Overall Length</td>
<td>0.500</td>
</tr>
<tr>
<td>Wire Diameter</td>
<td>0.016</td>
</tr>
<tr>
<td>Rate (lbs/in)</td>
<td>8.40</td>
</tr>
<tr>
<td>Load (lbs)</td>
<td>1.8</td>
</tr>
<tr>
<td>Deflection at Load</td>
<td>0.214</td>
</tr>
<tr>
<td>Total # of Coils</td>
<td>12</td>
</tr>
<tr>
<td>Active # of Coils</td>
<td>10</td>
</tr>
<tr>
<td>Solid Height</td>
<td>0.028</td>
</tr>
<tr>
<td>Pitch (in)</td>
<td>0.043</td>
</tr>
<tr>
<td>Space between the Coils (in)</td>
<td>0.029</td>
</tr>
<tr>
<td>Ends</td>
<td>CLOSED</td>
</tr>
<tr>
<td>Material</td>
<td>MUSIC WIRE</td>
</tr>
<tr>
<td>Finish</td>
<td>PLAIN</td>
</tr>
</tbody>
</table>

These prices are for immediate acceptance and may be affected by conditions beyond our control. All goods are FOB our plant in Wilder, Kentucky. Our terms are net 30 days. We do not assume any responsibility for plating since this is not done in our plant. Blocks tolerances on prints do not apply as tolerances are to Spring Manufacturers Institute specifications. The quantities for custom made springs can vary +/- 10%.

Phone: 1-859-581-7600
Fax: 1-859-581-7700

140 South Street
Wilder, KY 41074
Fax: 1-859-581-7700
toll free fax
800.621.1792
B.5. Plastic tubing

Clear polyurethane tubing

<table>
<thead>
<tr>
<th>Model</th>
<th>TU0212</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD x ID (mm)</td>
<td>2 x 1.2</td>
</tr>
<tr>
<td>Fluid</td>
<td>Air, Water</td>
</tr>
<tr>
<td>Max. operating pressure (at 20°C)</td>
<td>0.8 MPa</td>
</tr>
<tr>
<td>Burst pressure</td>
<td>10 MPa</td>
</tr>
<tr>
<td>Max. bending radius (mm)</td>
<td>4</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-20 to 60°C (Water: 0 to 40°C) (No freezing)</td>
</tr>
<tr>
<td>Material</td>
<td>Polyurethane</td>
</tr>
<tr>
<td>Color</td>
<td>Black(B), White(W), Red(R), Blue(BL), Yellow(Y), Green(G), Clear(C)</td>
</tr>
</tbody>
</table>
B.7. Linear stepper motor

11AV102AX06-AB (200-SN)
B.7. Solenoid valve

STC 3S012-020-A

**STC 3S012-020-A Series Solenoid Valves**

<table>
<thead>
<tr>
<th>Valve Model</th>
<th>3S012-1/8-A</th>
<th>3S012-1/4-A</th>
<th>3S020-1/8-A</th>
<th>3S020-1/4-A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port Size (NPT)</td>
<td>1/8</td>
<td>1/4</td>
<td>1/8</td>
<td>1/4</td>
</tr>
<tr>
<td>Valve Type</td>
<td>3 Way, Universal Normally Closed (NC) or Normally Open (NO) Diverting Valve (diverts one supply to two outlet)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Action</td>
<td>Direct Acting, Response Time &lt;20 ms.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orifice, Cv</td>
<td>1.2mm, C=0.06</td>
<td>2.0mm, C=0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating Pressure</td>
<td>NC: Vacuum to 50 PSI NO &amp; Diverting: Vacuum to 150 PSI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>NBR: Seal 14 to 176°F (-10 to 80°C); Option: Viton Seal 5 to 248°F (-15 to 120°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body Materials</td>
<td>Stainless Steel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seal Materials</td>
<td>NBR, Option: Viton</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil Duty</td>
<td>H Class, IP55, 100% ED (Continuous Duty)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage</td>
<td>Options: 12, 24 VDC, 24, 110/120, 220/240 VAC (50/60Hz)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage Tolerance</td>
<td>±10% of Specified voltage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil Power</td>
<td>3 to 6.5W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical Connections</td>
<td>DIN</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation</td>
<td>No Orientation Requirement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Service</td>
<td>Air, Liquid, Oil, Water</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3S012-020-A Series Solenoid Valve Components

- Stainless Steel Nut
- Stainless Steel Washer
- Plastic Encapsulated Coil
- Stainless Steel Armature Tube
- Stainless Steel Spring
- 630F Stainless Steel Plunger
- O-Ring
- Stainless Steel Valve Body
Installation and Operation:

To connect the valve Inlet and Outlet:

Connect the inlet and outlet in the direction of the arrow marked on the valve.

To install coil:

Put the coil onto the armature tube of the valve. Put the lock-washer and nut onto the armature tube. Hand tighten the nut, then use a wrench to tighten the nut to a quarter turn; do not overtighten the nut, it may cause the armature tube to fail prematurely.

To connect DIN coil:
1. Remove the Philip screw from the plastic housing and unplug it from the DIN coil.
2. From the screw opening, push the terminal block out from the plastic housing.
3. Note the 1, 2 and ground markings on underside of DIN enclosure.
4. For DC DIN Coil, Connect 1 to Positive, 2 to Negative.
5. For AC DIN Coil, connect 1 to HOT wire, 2 to Neutral wire, and if required connect.

6. Do not energize the coil without installing it onto the valve, it will burn the coil and create fire hazards.

Safety Note: Standard valves are supplied with continuous duty coils. The proper class of insulation for the service is indicated on the coil. The coil temperature may become hot after being energized for extended periods, but it is normal. Do not energize the coil without installing it onto the valve or connect the coil to a wrong voltage, as it may overheat and damage the coil; although the coil is made of flame retarded material, misuse of the coil in this manner could create fire hazards and generate smoke or burning odor which indicates excessive coil temperature and should disconnect the power to the coil immediately.
DIMENSIONS (MM)

MODEL: 3S012-020-1/8A

CONNECTION OF PORT:
NORMALLY OPEN/INVERTER:
A = SUPPLY
E = OUTPUT 1 (NO)
P = OUTPUT 2 (NC)

NORMALLY CLOSED:
P = SUPPLY
A = OUTPUT (NC)
E = EXHAUST

D 2 NO 100%
B.8. Pinion gear

GM0.5-08-19

<table>
<thead>
<tr>
<th>Part no.</th>
<th>Module</th>
<th>No. of teeth</th>
<th>Bore</th>
<th>Pitch dia.</th>
<th>Outside dia.</th>
<th>Face width</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM0 5-08-14</td>
<td>0.5</td>
<td>8</td>
<td>1.4</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>GM0 5-09-14</td>
<td>0.5</td>
<td>9</td>
<td>1.4</td>
<td>4.5</td>
<td>5.5</td>
<td>5</td>
</tr>
<tr>
<td>GM0 5-10-14</td>
<td>0.5</td>
<td>10</td>
<td>1.4</td>
<td>5</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>GM0 5-11-14</td>
<td>0.5</td>
<td>11</td>
<td>1.4</td>
<td>5.5</td>
<td>6.5</td>
<td>5</td>
</tr>
<tr>
<td>GM0 5-12-14</td>
<td>0.5</td>
<td>12</td>
<td>1.4</td>
<td>6</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>GM0 5-13-14</td>
<td>0.5</td>
<td>13</td>
<td>1.4</td>
<td>6.5</td>
<td>7.5</td>
<td>5</td>
</tr>
<tr>
<td>GM0 5-14-14</td>
<td>0.5</td>
<td>14</td>
<td>1.4</td>
<td>7</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>GM0 5-15-14</td>
<td>0.5</td>
<td>15</td>
<td>1.4</td>
<td>7.5</td>
<td>8.5</td>
<td>5</td>
</tr>
<tr>
<td>GM0 5-16-14</td>
<td>0.5</td>
<td>16</td>
<td>1.4</td>
<td>8</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>GM0 5-17-14</td>
<td>0.5</td>
<td>17</td>
<td>1.4</td>
<td>8.5</td>
<td>9.5</td>
<td>5</td>
</tr>
<tr>
<td>GM0 5-18-14</td>
<td>0.5</td>
<td>18</td>
<td>1.4</td>
<td>9</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>GM0 5-08-10</td>
<td>0.5</td>
<td>8</td>
<td>1.9</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>GM0 5-09-15</td>
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Remarks: * The above bore size is for press-fit motor axis (ø1.5mm / ø2mm).

Unit: mm
B.9. Rack gear

GRG0.5-125
# B.10. Latex tube

402

<table>
<thead>
<tr>
<th>CAT. NO.</th>
<th>SIZE</th>
<th>BULK/FT</th>
<th>BOX</th>
<th>REEL</th>
<th>#/MFT.</th>
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<td>0.063 X .032 X .125 1/16&quot; X 1/32&quot;</td>
<td>$0.18</td>
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<tr>
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<td>0.063 X .063 X .188 1/16&quot; X 1/16&quot;</td>
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<td>0.094 X .032 X .156 3/32&quot; X 1/32&quot;</td>
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<td>415 4,000 ft min</td>
<td>0.156 X .313 X .250 5/32&quot; X 3/32&quot;</td>
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<td>426**</td>
<td>0.156 X .313 X .750 5/32&quot; X 5/32&quot;</td>
<td>$1.74</td>
<td>* $88.50</td>
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</tbody>
</table>

**AMERICAN OR BLACK PRICES

| LONG 4,000 ft min | .156 X .032 X .219 5/32" X 1/32" | $0.19  | $19.90 | $10.20 | 8      |
| 503**    | 0.156 X .047 X .250 3/32" X 3/64" | $0.21  | $21.70 | $12.20 | 12     |
| 504 4,000 ft min | 0.156 X .063 X .281 3/32" X 1/16" | $0.27  | $27.40 | $14.30 | 18     |
| 505 4,000 ft min | 0.156 X .074 X .313 5/32" X 5/32" | $0.29  | $29.20 | $15.60 | 24     |

* INDICATES 30' BOX
** AVAILABLE IN BLACK AS STANDARD