COMPACT MODULAR SYSTEM DESIGN FOR TELEOPERATED
LAPAROENDOSCOPIC SINGLE SITE SURGERY

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Chapter 1

Introduction

Laparoscopic surgery or minimally invasive surgery (MIS) is a technique in which surgery is performed through small incisions, usually in the abdomen. A laparoscope, which is a long slender tubular endoscope used to view the internal body cavities, is connected to a camera that displays the view on a TV monitor. The laparoscope and thin surgical instruments are inserted through the small incisions. Laparoscopic surgery can be done manually or robot-assisted.

Some advantages of laparoscopic surgery are reduced pain and patient trauma, shorter recovery time, and smaller scars. Some disadvantages of laparoscopic surgery are limited visibility and range of motion, the small incisions reduce dexterity, and the indirect interaction with tissue.

Robot-assisted minimally invasive surgery has most of the same advantages as manual MIS but is an improvement on some of the shortcomings. In robot-assisted MIS, the robotic manipulator is teleoperated by surgeons from a master control console with joystick type controls. It results in improved accuracy, can eliminate manual tremor, can introduce scaling factors between the hand motions of the surgeon and the robotic instruments, and can provide additional articulated joints at the tips of the instruments.

Single-port access (SPA) surgery [1] or laparo-endoscopic single-site surgery (LESS) is a technique developed to perform laparoscopic surgery using a single incision. Multiple instruments as well as the laparoscope are inserted through the incision, which is typically in the navel. This has the advantage of minimal and hidden scarring compared to standard laparoscopic surgery. Similar instruments as standard laparoscopic surgery can be used and the lack of triangulation from having a single incision can be overcome by using angled or articulated instruments. Single-site surgery could benefit from the improved ergonomics, accuracy, and dexterity of

robotic systems. However, it is difficult to use existing robotic surgery systems for single-port surgery due to interference between the robotic arms used to control the surgical instruments. Having more compact positioning mechanisms would allow at least three instruments to be inserted through a single port.

The goal of this research was to develop a compact, simple, modular, teleoperated robotic system prototype for laparo-endoscopic single-site surgery by combining and modifying components of a commercial endoscope robot and a previous University of Hawaii teleoperated system. The commercial endoscope robot being used is the ViKY XL system from EndoControl SA.

Chapter 2

Literature Review

Existing commercial surgical robotics systems include the daVinciTM System [2] from Intuitive Surgical, Inc. It is a teleoperated surgical robot system which is operated from a control console. This makes it more accurate and easier for surgeons to manipulate instruments but the cost, complexity, maintenance, setup time, and size are potential issues. The daVinci can be used with a single-site surgery adapter [3], which uses curved cannulae and semirigid instrument shafts. However, it is bulky, has a limited angular range of motion, and is not ideal for single-site surgery. The single site surgery setup is shown in Fig. 2.1

There are also commercial endoscope robots such as the ViKY from Endocontrol SA, which is an endoscope positioner that holds the endoscope. It is low cost, simple, and quick to setup. The ViKY has been shown to be well suited for manual LESS [4, 5].

Researchers in Pisa, Italy have designed a teleoperated robotic system for single-port surgery called SPRINT [6]. Their design has two six degree-of-freedom arms that can be inserted and removed individually, allowing more flexibility. The arms enter the incision in a straight line and then move into position while inside the body due to all six joints being below the insertion point. Performance tests of the system showed an average latency of 16 ms between commands and the response. The SPRINT system has smaller arms, with the last four joints being actuated by motors placed inside the arms, compared to the design that will be described in this thesis.

Researchers at the University of Washington have designed a kinematically optimized, spherical surgical robot called the RAVEN [7]. The RAVEN is a seven degree-of-freedom (including tool gripper), cable-actuated, teleoperated surgical manipulator designed with safety considerations. The researchers conducted several experiments of teleoperation of the RAVEN at various distances between the master

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Figure 2.1: The daVinci single site setup

control and slave systems, including within the same lab, between labs, and in field conditions. One experiment was conducted in a remote field in Simi Valley, California with the master and slave separated by 100 meters and using an aerial datalink with an average 16 ms latency. Another experiment was done with the master in a lab at Imperial College in London, England and the slave in a lab at the University of Washington in Seattle, Washington with the latency about 140 ms. The researchers' experiments showed that it was feasible to teleoperate the RAVEN in remote locations and at long distances, even with different time delays.

A technique similar to laparoscopy is called natural orifice transluminal endoscopic surgery (NOTES). In NOTES, a flexible endoscope is passed through a natural orifice of the body (mouth, anus, urethra, or vagina) and a puncture through one of the viscera (internal organs, such as stomach, rectum, urinary bladder, vagina) is made into the abdominal cavity [8]. Laparoscopic surgery avoids the complexity and limitations on the accuracy, stiffness, and dexterity of NOTES and access to the abdominal cavity is more direct than NOTES.

Researchers at Columbia University in New York have created the IREP [9, 10] and researchers in London have created a universal joint based flexible robot [11] for minimally invasive surgery. Both robots are flexible snake like robots that could be used for LESS or NOTES even though the IREP was designed for LESS and the other robot designed for NOTES. However, these types of systems have limited force capabilities due to their small actuation motors and their flexible shape. The IREP, for example, was designed for a 2N working load [10].

Researchers in Nebraska have developed a miniature robot for single-port surgery and demonstrated its feasibility [12]. This system consists of a robotic platform, with two arms, which is inserted completely into the abdominal cavity through a single incision. The two arms each have four degrees-of-freedom meant to emulate standard laparoscopic instruments. These researchers had also previously developed a miniature robot for NOTES [13].

Chapter 3

Design

3.1 Objective

The goal of this research was to develop a compact, simple, modular, teleoperated robotic manipulator system for laparo-endoscopic single site surgery. The design is a modification of a previous University of Hawaii teleoperated MIS system combined with the ViKY XL system from EndoControl SA. It provides advantages in safety, portability, cost, and ease of use in setup and operation compared to currently available systems. In addition, a further goal of the system is to enable intraoperative transitions between open and minimally invasive, manual and teleoperated, and multiple incision and single-site operation. The system should also be designed to be modular with interchangeable components as well as be able to operate other commercial robotic instruments.

The previous system is shown in Fig. 3.1 and is described in [14]. It was developed to improve the effectiveness of robot-assisted surgery by creating a much smaller, simpler, modular, teleoperated robotic manipulator system for standard laparoscopic surgery.

The ViKY XL, shown in Fig 3.2 was to be used as the base of the prototype system. It consists of a base ring with a motor to allow rotation about the vertical axis, an inclination joint attached to the side of the base ring with a motor to change the angle of the rack, and a rack-and-pinion mechanism with a motor that changes the insertion depth of the endoscope. The endoscope is clamped to a support arm that is part of the rack-and-pinion mechanism.

Each instrument was to be controlled using a planar linkage having two motor actuated links and attaching each linkage to the ViKY using the existing rack and/or

Figure 3.1: Previous teleoperated robotic surgery system

Figure 3.2: ViKY XL endoscope positioner

a support frame that would be attached to the ViKY. The instruments were to be attached using a quick clamping system similar to what was used in the previous robotic surgery system.

3.2 Prototype Design Decisions

A prototype was designed using a CAD model created in SolidWorks. The design was made with links approximately 100 millimeters in length to achieve a reasonable range of motion for the instrument end effectors. Each instrument shaft was assumed to be 300 millimeters in length.

At this point in the design process, it was presumed that the links and any additional support frames were to be made primarily of aluminum square tubing having 0.5 inch width and 1/16 inch wall thickness. This choice was made so that the prototype would be lightweight but still have strength. If needed, the final design could be made using stainless steel for more strength and durability. The design was made such that motor placements would have minimal chances of colliding or interfering with motion of the system.

At the link joints, the initial idea was to cut out part of the side walls of the aluminum tubing and offset one link above the neighboring link by the 1/16 inch wall thickness so that one link slides over the other when the joint is rotated. The amount of the side walls that would be cut out would be determined by the range of motion of the joint that is needed.

From the previous system, it was known that brushless DC gearmotors of diameters from 16 to 24 mm could provide sufficient torques for manipulating robotic surgical instruments for typical operations of grasping, cutting, and suturing. They also can be obtained in autoclavable and immersible versions. The gearmotors were to be attached directly at the linkage joints, without the use of any cable, belt, or remote center linkage mechanisms. This enables the system to be simple and compact.

Chapter 4

Design Details

4.1 Prototype Characteristics

In this section, the prototype design will be described. Figure 4.1 shows the annotated CAD model. As mentioned before, the base of the system is the ViKY XL, which will be clamped to the operating table and be shared by the endoscope and instrument manipulators. The three shafts will be inserted through a single trocar. The instrument shafts cross at the insertion point and bend back toward each other inside the body for triangulation and to stay within the view of the endoscope, which is a similar configuration as manual LESS. The ViKY is operated using motion control software and motor controllers developed for the previous teleoperated robotic surgery system.

The existing ViKY endoscope rack will be used to support one instrument and its manipulator. A second rack would be attached to the opposite side of the ViKY and a support structure would be added to connect the two racks together. This added rack will be used to support a second instrument and its manipulator. Having a common support structure with an inclination motor allows the endoscope and instruments to move as a unit. This behavior is desired so that the instruments will stay within the view of the endoscope.

The endoscope and each instrument manipulator have their own rack-and-pinion motor for independent motion. The endoscope is clamped directly to its rack-and-pinion mechanism, which was an existing part of the ViKY. Each instrument is connected to its own rack-and-pinion by two motor actuated links and a universal joint. The instruments are attached at the universal joint using a quick clamping system.

Figure 4.1: Annotated CAD model

Figure 4.2: Instruments from previous system

The instruments from the previous system, shown in Fig. 4.2, are used with some modifications, primarily a fixed 45 degree bend in the shaft while keeping the three-dimensional, fully articulated end effector wrists the previous instruments had.

Some specifications of the system are its 180 millimeter diameter base ring, an approximately 330 millimeter high rack-and-pinion support structure in the vertical inclination configuration, and approximately 6 kilogram weight including instruments. Other characteristics of the system include that it is easy to setup and operate, portable, low cost, and safer than industrial scale robots. It does not occupy additional floor space or obstruct access to the patient. The system is sterilizable by autoclave and immersible in fluids.

4.2 Range of Motion

The range of motion of the system was determined by moving the 3D CAD model in SolidWorks. This enabled the motion and positions to be seen visually as well as see where there may be collisions between instruments, links, or other parts of the support structure. In addition, the measurement tool in SolidWorks was used to measure angles and distances between parts of the system in various configurations.

This process was done with some joint variables fixed to better see how different values affect the range of motion. Setting the inclination vertical and the rack and pinion distance at the lowest allowed for finding out the deepest the instrument can be inserted. The instrument was then moved around to see how it moves and where it could reach. Keeping the inclination vertical but increasing the rack and pinion distance allowed for more experimentation with the motion. After setting the inclination at lower angles and doing more experimentation with moving the instrument, it was found that as the inclination is lowered toward the horizontal, it becomes more difficult to move the end of the instrument to desired locations. This

Figure 4.3: Workspace of the system in the vertical configuration

behavior seems to occur due to the geometry of system, including the rack and pinion and the linkage, and having the trocar as a pivot point.

Mathematica was also used to look at a subset of the workspace of the system. Figure 4.3 shows the workspace volume for the second (left side) instrument when the inclination is vertical. The figure shows an unreachable volume which occurs due to the two links having different lengths. Self-collision of the manipulator linkage will further reduce the reachable volume at this base rotation angle and inclination angle. However, this should not cause any problems because those unreachable locations can be reached by rotating the base and most likely the other instrument will be located in that area.

The results of the range of motion analysis determined that the instruments can be angled up to about 32.5 degrees from the endoscope shaft at their minimum insertion and up to about 44 degrees at their maximum insertion. The endoscope can be rotated 360 degrees and inclined from vertical down to within 15 degrees of horizontal

and has a 200 millimeter insertion range. The instruments have a similar insertion range. It can be noted that the instrument that shares a rack with the endoscope is restricted to a greater insertion depth than the endoscope. However, this should not be a significant issue in the operation of the system as the instruments should only be operated while within view of the endoscope.

4.3 Motor Selection

To determine the size of the motors needed for the instrument linkages, it was determined that the end of the instruments should be able to move at 50 mm/sec and be able to apply a force of 5 N. At first, it appeared to be simple enough using intuition to determine the linkage configurations that would require the largest motor speeds and torques. However, it was not as simple as expected due to the closed-loop manipulator having changing lever arm ratios and also needing to account for the approximately 5 N weight of each instrument. Configurations where the location of the end effector has a large effect on the required torques are often significantly different from configurations where the weight of the instrument dominates.

The next idea was to try using the symbolic variable, optimization, and solving features of Mathematica to determine the linkage configurations from the Jacobian of the system. Those calculations turned out to require a lot of computing power and time due to having the matrix inverse of the Jacobian in the equation being solved. It was thought that instead of solving the equation, it might be better to create a table of values of the joint input velocities needed for an end effector velocity of 50 mm/sec in all directions for all linkage configurations and then search the table for the maximum values. This method was thought to be better since Mathematica would be working with numbers and substituting them into equations instead of solving equations, so it would not be as computationally intensive. However, again it appeared to require a lot of time to calculate this data. Before giving up on this method, the code was slightly modified for parallel processing and run on a quad-core computer. After running for over 24 hours and still having no results, something else had to be done.

It was suggested by someone to try using C++ to do the calculations. This person helped with rewriting the code in C++. After compiling the C++ code and running it, it took only about 3 seconds to generate the table of values. I was shown how to modify the C++ code for other similar calculations. I then modified the C++ code to create a table of values of the joint input torques needed for an end effector

force of 5 N in all directions for all linkage configurations. The main difference in the calculations is that the transpose of the Jacobian is used instead of its inverse.

A possible reason for the difference in time that Mathematica and C++ required, is that Mathematica required large amounts of RAM. To compensate, Mathematica may have been reading and writing to the hard drive, resulting in greatly slowing down the computer.

After searching the data for the largest values, the results show that all the required joint velocities are between 1-2 rev/s or 60-120 rpm, which is well within the motor specifications. The data was also analyzed for other large values. These required joint velocities are for most of the workspace that would typically be used. Areas that would require more joint velocity are near some of the edges of the workspace and when the end effector is within 5 cm below the trocar. The areas within 5 cm the trocar are unlikely to be used for typical surgeries. The closer the end effector is to the trocar the higher the required joint velocity. This is due to the high ratio of the length of the instrument shaft above the trocar to the length below the trocar.

The required force for the rack-and-pinion joint is 12.638 N, which is equivalent to a torque of 63.191 mNm, if a 5 mm pinion gear is used. The required torque for the first link is 2465.449 mNm and for the second link is 1656.448 mNm. Those last two values are really large due to the long lever arms from the length of the links and the weight of the instrument wrist and end effector actuation mechanisms that are located above the instrument clamps. This occurs when the inclination is close to horizontal and the links are out to the side, which is an extreme case that may not be needed but shows that those motors are the most likely to have problems.

The plan was to use 20 mm motors and the specifications of the gearheads for those motors end up being the limiting factor rather than the motor specifications. The gearhead specifications list a continuous torque of 500 mNm, an intermittent torque of 700 mNm, and a recommended maximum input speed for continuous operation of 5000 rpm for all reduction ratios. However, the motors can be run at a higher voltage for short periods of time. The gearheads with a 66:1 reduction ratio were chosen to get a good balance between motor velocity and torque. For a joint velocity of 120 rpm and a 66:1 reduction ratio, the motor velocity needed is just below 8000 rpm which is reasonable. With a 66:1 reduction ratio, the rack-and-pinion joint needs a motor torque of less than 1 mNm, which is well within the specifications. If the link motor torques are not high enough, there is the option of adding an extra reduction gear to the links.

Chapter 5

Fabrication

A prototype model of the two link manipulator and its rack-and-pinion was created using a 3D printer to see how it fits with the ViKY and to look for any issues with interference and collisions. Parts can be created directly from CAD files, which greatly simplifies fabrication as complex shapes can be easily made. The parts are made of ABS polymer deposited in layers and can be used soon after the printing process completes. Additionally, minimal work is needed after printing since features such as holes can be incorporated into the CAD model.

This prototype was first attempted to be made as a single print job, with parts separated with small spaces between them to allow movement of the joints. However, when the printing process completed, the parts had fused together and would not allow movement of the joint, as shown in Fig. 5.1.

The next attempt at printing the parts was done using separate parts for each link with pins at the joints, as shown in Fig. 5.2. This time, the parts were able to rotate at the joints. However, there were issues with too much of the side walls of the square tubing cut out weakening the ABS parts near the joint. This finding would suggest possible changes in the design to reduce the problem, such as cutting out only half the height of the side walls for each link.

When figuring out how the motors would be attached to the links, it was noticed that the screws to attach the motors would not be accessible with the current design of the links. Furthermore, the motor diameter of 20 mm is larger than the 0.5 inch (12.7 mm) width of the square tubing.

Another member of the project team was able to use the linkage geometry of the design to redesign the linkage to enable the attachment of the motors with screws, while keeping the original distances between the joints. A CAD model of the redesigned linkage is shown in Fig. 5.3. The redesigned linkage parts were 3D printed

Figure 5.1: First attempt at 3D printing

Figure 5.2: Second attempt at 3D printing

Figure 5.3: Redesigned linkage assembly

due to it being faster and easier to create the complex geometry than machining metal. The 3D printed linkage seemed to perform well enough and was able to support the weight of the instrument.

Most of the added structure of the prototype and parts of the instruments were also created by 3D printing. The assembled surgical robot system prototype design is shown in Fig. 5.4.

Figure 5.4: Assembled surgical robot system prototype design

Chapter 6

Kinematics

6.1 Coordinate Frames

In order to obtain kinematic equations that describe the motion of the manipulator, coordinate frames must be defined and fixed to various parts of the system. This enables the computation of the position and orientation of the instrument end effector in relation to the base of the system as a function of the joint variables. The following kinematic analysis is for the left side instrument manipulator. The kinematics for the right side instrument manipulator are the same except for being a mirror image configuration.

This process starts by defining a base frame, frame $\{0\}$, that is fixed to the base of the system and does not move. The base frame origin was chosen to be located at the intersection of the axes of rotation for the base rotation and inclination joints. The base frame was defined with a right-handed coordinate frame such that the x-axis is pointed toward the base rotation motor and the z-axis is pointed up.

For the rest of the coordinate frames, the z-axes for rotational joints are also the axes of rotation, and the z-axes for prismatic joints are in the displacement direction. Frame $\{1\}$ for the base rotation joint has the same origin as the base frame and is in the same direction as the base frame when the joint angle, θ_1 , is zero. Frame $\{2\}$ for the rack inclination rotational joint is located below the rack with the z-axis pointing outward of the base ring. When the joint angle θ_2 is zero, the rack is in the vertical position and the y-axis of frame $\{2\}$ is pointing down. Frame $\{3\}$ is for the rack-and-pinion prismatic joint and is located on the linkage support with the z-axis pointing away from joint 2. The joint offset (variable) d_3 is zero when the linkage and its support are at the lowest position. Frames $\{4\}$ and $\{5\}$ are for the rotational joints

Figure 6.1: Coordinate Frames

of the linkage and are attached to the first and second linkage links, respectively. The z-axes point in the same direction as the z-axis of frame $\{3\}$, and the x-axes point to the other ends of their respective links. The joint angle θ_4 or θ_5 is zero when its x-axis points in the same direction as the x-axis of the previous frame.

The resulting coordinate frames are shown in Fig. 6.1. The relationship between the frames are described using the Denavit–Hartenberg parameters [15] as shown in Table 6.1.

Table 6.1: Denavit–Hartenberg parameters

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	-90°	0	$l_1 = 93.25$	θ_2
3	90°	0	d_3	0
4	0	$a_3 = 17.00$	0	θ_4
5	0	$a_4 = 88.90$	0	θ_5

6.2 Forward Kinematics

The kinematic equations were derived using transformations between adjacent frames. In other words, the transformation (matrix), ${}^{i-1}_iT$, that describes frame $\{i\}$ relative to the previous frame $\{i-1\}$, is needed for each set of adjacent frames. For the Denavit–Hartenberg parameters, the general form of ${}^{i-1}_iT$ is:

$${}^{i-1}_iT = \begin{bmatrix} \cos \theta_i & -\sin \theta_i & 0 & a_{i-1} \\ \sin \theta_i \cos \alpha_{i-1} & \cos \theta_i \cos \alpha_{i-1} & -\sin \alpha_{i-1} & -\sin \alpha_{i-1} d_i \\ \sin \theta_i \sin \alpha_{i-1} & \cos \theta_i \sin \alpha_{i-1} & \cos \alpha_{i-1} & \cos \alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6.1)$$

The transformation matrices are:

$${}^0_1T = \begin{bmatrix} \cos \theta_1 & -\sin \theta_1 & 0 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6.2)$$

$${}^1_2T = \begin{bmatrix} \cos \theta_2 & -\sin \theta_2 & 0 & 0 \\ 0 & 0 & 1 & l_1 \\ -\sin \theta_2 & -\cos \theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6.3)$$

$${}^2_3T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & -d_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6.4)$$

$${}^3_4T = \begin{bmatrix} \cos \theta_4 & -\sin \theta_4 & 0 & a_3 \\ \sin \theta_4 & \cos \theta_4 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6.5)$$

$${}^4_5T = \begin{bmatrix} \cos \theta_5 & -\sin \theta_5 & 0 & a_4 \\ \sin \theta_5 & \cos \theta_5 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6.6)$$

The transformations can be multiplied together to obtain the transformation from the base frame to frame $\{5\}$.

$${}^0_5T = {}^0_1T {}^1_2T {}^2_3T {}^3_4T {}^4_5T \quad (6.7)$$

Next, the location of the instrument clamp was determined using the vector from frame $\{5\}$ to the center of the clamp, 5P . The transformation from the base frame to frame $\{5\}$ is then multiplied by the vector to obtain the position of the instrument clamp relative to the base frame.

$${}^5P = \begin{bmatrix} l_2 & 0 & 0 & 1 \end{bmatrix}^T \quad (6.8)$$

$$\begin{aligned} P &= {}^0_5T {}^5P = \begin{bmatrix} P_x & P_y & P_z \end{bmatrix}^T = \\ &= \begin{bmatrix} c_1[c_2(a_3 + c_4a_4 + l_2c_{45}) + s_2d_3] - s_1(l_1 + s_4a_4 + l_2s_{45}) \\ s_1[c_2(a_3 + c_4a_4 + l_2c_{45}) + s_2d_3] + c_1(l_1 + s_4a_4 + l_2s_{45}) \\ -s_2(a_3 + c_4a_4 + l_2c_{45}) + c_2d_3 \end{bmatrix} \end{aligned} \quad (6.9)$$

where, $c_i = \cos(\theta_i)$, $s_i = \sin(\theta_i)$, $c_{ij} = \cos(\theta_i + \theta_j)$, and $s_{ij} = \sin(\theta_i + \theta_j)$.

The last step was to use a unit vector from the instrument clamp to the trocar opening to obtain the position of the end effector relative to the base frame.

$$\{FP\} = P + l_3 \frac{(\{tr\} - P)}{\sqrt{(\{tr\} - P) \bullet (\{tr\} - P)}} \quad (6.10)$$

where,

$$\{tr\} = \begin{bmatrix} tr_1 & tr_2 & 0 \end{bmatrix}^T \quad (6.11)$$

is the location of the insertion point for the instrument on the trocar (x and y coordinates), and l_3 is the length of the instrument shaft.

$$\{FP\} = \begin{bmatrix} P_x + l_3(tr_1 - P_x)/den \\ P_y + l_3(tr_2 - P_y)/den \\ P_z + l_3(-P_z)/den \end{bmatrix} \quad (6.12)$$

where,

$$den = \sqrt{(tr_1 - P_x)^2 + (tr_2 - P_y)^2 + P_z^2} \quad (6.13)$$

6.3 Inverse Kinematics

The inverse kinematics are used to calculate the joint angles needed to achieve the desired position of the end effector. The desired position is $\{FP\}$, and θ_1 and θ_2 are given. First, the position of the instrument clamp must be determined. Similarly to what was done for the forward kinematics, a unit vector from the end effector to the trocar opening was used.

$$P = \{FP\} + l_3 \frac{(\{tr\} - \{FP\})}{\sqrt{(\{tr\} - \{FP\}) \bullet (\{tr\} - \{FP\})}} \quad (6.14)$$

The system geometry was projected onto the base frame x-z plane as shown in Fig. 6.2. In the following inverse kinematics analysis x_i and z_i do not necessarily represent the coordinate frame axes. In the figure, line 1 is the projection of the rack and line 2 is the projection of the manipulator from the rack-and-pinion joint to the instrument clamp. The equation for line 1 is

$$z = -\tan(90^\circ + \theta_2)x \quad (6.15)$$

and the equation for line 2 is

$$z = \cot(90^\circ + \theta_2)(x - P_x) + P_z \quad (6.16)$$

Next, the intersection of line 1 and line 2 at $O_3(x_3, z_3)$ was determined. At the intersection, the z-coordinates will be equal so equations 6.15 and 6.16 were set equal to each other.

$$\begin{aligned} -\tan(90^\circ + \theta_2)x_3 &= \cot(90^\circ + \theta_2)(x_3 - P_x) + P_z \\ &= \cot(90^\circ + \theta_2)x_3 - \cot(90^\circ + \theta_2)P_x + P_z \end{aligned} \quad (6.17)$$

Figure 6.2: Projection of system on x-z plane

Rearranging equation 6.17 results in

$$\cot(90^\circ + \theta_2)P_x - P_z = [\tan(90^\circ + \theta_2) + \cot(90^\circ + \theta_2)]x_3$$

$$\begin{aligned}
 x_3 &= \frac{\cot(90^\circ + \theta_2)P_x - P_z}{\tan(90^\circ + \theta_2) + \cot(90^\circ + \theta_2)} \\
 x_3 &= \frac{\cot(90^\circ + \theta_2)P_x - P_z}{\tan(90^\circ + \theta_2) + \cot(90^\circ + \theta_2)} \cdot \frac{\sin(90^\circ + \theta_2) \cos(90^\circ + \theta_2)}{\sin(90^\circ + \theta_2) \cos(90^\circ + \theta_2)} \\
 x_3 &= \frac{\cos(90^\circ + \theta_2)[\cos(90^\circ + \theta_2)P_x - \sin(90^\circ + \theta_2)P_z]}{\sin^2(90^\circ + \theta_2) + \cos^2(90^\circ + \theta_2)} \\
 x_3 &= \cos(90^\circ + \theta_2)[\cos(90^\circ + \theta_2)P_x - \sin(90^\circ + \theta_2)P_z] \tag{6.18}
 \end{aligned}$$

To find the equation for the z-coordinate of O_3 , the value of x_3 from Equation 6.18 was substituted into Equation 6.15.

$$\begin{aligned}
z_3 &= -\tan(90^\circ + \theta_2)x_3 \\
z_3 &= -\frac{\sin(90^\circ + \theta_2)}{\cos(90^\circ + \theta_2)} \cdot \cos(90^\circ + \theta_2)[\cos(90^\circ + \theta_2)P_x - \sin(90^\circ + \theta_2)P_z] \\
z_3 &= -\sin(90^\circ + \theta_2)[\cos(90^\circ + \theta_2)P_x - \sin(90^\circ + \theta_2)P_z]
\end{aligned} \tag{6.19}$$

Now the joint offset d_3 can be determined using simple trigonometry.

$$d_3 = \frac{z_3}{\sin(90^\circ + \theta_2)} - d_{3,0} \tag{6.20}$$

$$\begin{aligned}
d_3 &= \frac{-\sin(90^\circ + \theta_2)[\cos(90^\circ + \theta_2)P_x - \sin(90^\circ + \theta_2)P_z]}{\sin(90^\circ + \theta_2)} - d_{3,0} \\
d_3 &= \sin(90^\circ + \theta_2)P_x - \cos(90^\circ + \theta_2)P_z - d_{3,0}
\end{aligned} \tag{6.21}$$

where, $d_{3,0}$ is an offset for the zero position of the prismatic joint.

The location of O_3 is determined with an offset from O_4 .

$$x_4 = x_3 + a_3 \sin(90^\circ + \theta_2) \tag{6.22}$$

$$z_4 = z_3 + a_3 \cos(90^\circ + \theta_2) \tag{6.23}$$

The joint angles θ_4 and θ_5 can be found by first solving for the angles of the triangle shown in Fig. 6.3. Angles B and C can be determined using the law of cosines as shown below.

$$l_2^2 = a_4^2 + (P - O_4) \bullet (P - O_4) - 2a_4\sqrt{(P - O_4) \bullet (P - O_4)} \cos(B) \tag{6.24}$$

$$B = \cos^{-1} \left[\frac{a_4^2 + (P - O_4) \bullet (P - O_4) - l_2^2}{2a_4\sqrt{(P - O_4) \bullet (P - O_4)}} \right] \tag{6.25}$$

$$(P - O_4) \bullet (P - O_4) = l_2^2 + a_4^2 - 2l_2a_4 \cos(C) \tag{6.26}$$

$$C = \cos^{-1} \left[\frac{l_2^2 + a_4^2 - (P - O_4) \bullet (P - O_4)}{2l_2a_4} \right] \tag{6.27}$$

Figure 6.3: Linkage on its plane

Angle D is determined using a dot product as shown below.

$$(O_4 - O_3) \bullet (P - O_4) = \|O_4 - O_3\| \|P - O_4\| \cos(D) \quad (6.28)$$

$$D = \cos^{-1} \left[\frac{(O_4 - O_3) \bullet (P - O_4)}{\|O_4 - O_3\| \|P - O_4\|} \right] \quad (6.29)$$

$$D = \cos^{-1} \left[\frac{(O_4 - O_3) \bullet (P - O_4)}{a_3 \|P - O_4\|} \right] \quad (6.30)$$

Now the joint angles are determined as shown below.

$$\theta_4 = B - D \quad (6.31)$$

$$\theta_5 = C + 180^\circ \quad (6.32)$$

Chapter 7

Results

The prototype design was initially validated by other members of the project team doing a test using a single instrument setup as shown in Fig. 7.1. The system was controlled using inverse kinematics and velocity joint commands. Evaluation of the system design was done using simple tests to find its useful range of motion, locations of unreachable volumes, any problems with manipulator collisions, and configurations that may be problematic in actual operation of the system.

End effector trajectories were determined to be accurate and repeatable by testing the system using a Northern Digital Polaris Vicra for optical motion tracking. The optical tracker works by following tracking targets that were attached to the top of the instrument as shown in Fig. 7.1. In order to enable the observation of all effects from control error and manipulator, frame, and mounting hysteresis, position measurements were done from a stationary base frame. The end effector motion is shown in Fig. 7.2 during three consecutive traces of a 30 mm square using a hand operated Phantom teleoperation master with the scaling factor for the master-slave teleoperation set at 1:1. The square traced by the instrument end effector is rotated somewhat about the z-axis and slightly out of the x-y plane due to the teleoperation frame being aligned with the endoscope axis and not the motion tracker.

The results show some hysteresis in the motion, partly due to the use of 3D printed parts for the manipulator and instruments. The 3D printed parts also introduce additional friction into the system compared to machined metal. However, these frictional effects have been minimized by adjusting part tolerances, orienting of parts in the 3D printer in different ways to reduce rough layer edges, and sanding of parts to smooth joints.

Figure 7.1: Surgical robot system with one instrument and motion tracker installed

Figure 7.2: Instrument tip motion measured by optical tracker during square trajectory tracing

Chapter 8

Future Work

The next step is to proceed with clinical trials by using the system to perform skills training tasks established by the Society of American Gastrointestinal and Endoscopic Surgeons as the Fundamentals of Laparoscopic Surgery (SAGES FLS), which are a standard set of tasks used as a benchmark in surgical training. The tasks will be performed by untrained volunteers and by trained medical students and surgeons.

As previously mentioned, the system should be able to operate other commercial robotic instruments. Further work needs to be done to ensure that this is possible without negatively affecting performance of the system.

Also, 3D printing can be investigated as a possible means of production of the system. This may allow the production of cheap, disposable parts for the system.

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