Design and Analysis of a 5-DoFs Robot-Assisted Surgery Tool

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Abstract

Minimally Invasive Surgery (MIS) is advantageous compared to open surgery as it decreases postoperative pain, bleeding, infection risk, and the length of patient's hospital stays. However, it is difficult to perform and necessitates the use of robotic instruments to aid surgeons in performing complex tasks such as cutting and suturing. This research aims to design a robot-assisted surgical tool that can be attached as an end-effector to an existing surgical manipulator and allow the operator approach organs in multiple configurations, reach and operate in the region behind another organ, and be able to perform complex movements like stitching in the suturing task. To achieve this, we formulate the design requirements and conclude that five degrees-of-freedom (DoFs) are required to perform the above-mentioned tasks with dexterity. We synthesize potential kinematic arrangements to achieve 5-DoFs at the tip of the surgical instrument. We develop the static force analysis of the final design and perform manipulability, singularity, and workspace analyses to identify the suitability of the proposed design to the surgical needs. To be able to seamlessly integrate it with the surgical manipulator, the surgical tool is driven by a combination of gear-based and tendon-driven transmission. To evaluate the effectiveness of the proposed design, we design a CAD model of the 5-DoF surgical tool. In future experiments, we will fabricate a 3-D printed prototype and integrate it with a test-bench to perform 5-DoFs movements.

Chapter 1: Introduction

1.1 Relevance of MIRS

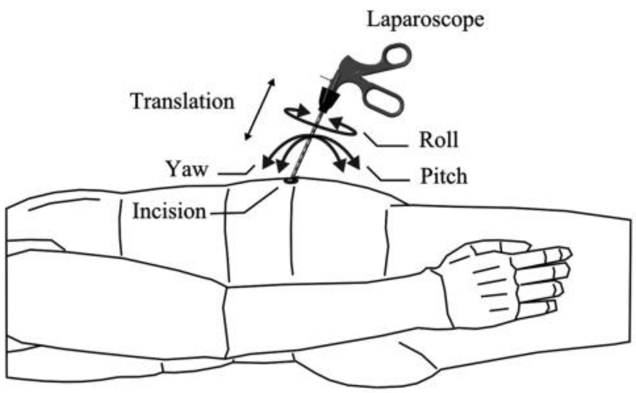


Figure 1.1: Minimally Invasive Surgery (Source: Nisar & Hasan, 2018).

Minimally Invasive Surgery (MIS) is when laparoscopes, surgical instruments that are long, slim, and rigid, are inserted into a patient's body through three or four small incisions. These incisions are created by cutting the outer layers of the skin tissue. Endoscopes, a tool with a camera at the end inserted beneath the patient's skin tissue, allows the surgeon to view the surroundings of the end effector on a 2D high-definition computer monitor. MIS can be seen in *Figure 1.1*. Minimally Invasive Robotic Surgery (MIRS) is when the surgeon utilizes teleoperated robotic tools to complete MIS instead of manual instruments (Liu, 2010).

Using Minimally Invasive Robotic Surgery (MIRS) is advantageous for several reasons. It is less invasive than other surgical methods because the size of the incision is significantly smaller than incisions created in traditional surgery. For example, traditional surgery methods that require a 20 cm incision would only require four 0.5 to 1.0 cm incisions with MIRS (Liu, 2010). The smaller incisions allow for less blood lost during surgery, trauma, post-operative pain, and wound infection risks. Consequently, MIRS shortens patients' hospital stays and the cost of operation.

Utilizing robotics in surgeries allows for surgeons to perform operations remotely. This creates the possibility for a patient to be operated in a different continent than the experts in the respective field are located in. The surgeon's performance will also be improved by utilizing MIRS. This surgical technique allows surgeons to avoid feeling the effects of fatigue. The placement of the surgeon's hands will be more comfortable than conventional methods. Operators can also sit while operating remotely, rather than standing for extended periods of time.

MIRS is also advantageous because the robots can be programmed to filter out tremors or movements in the surgeon's hands that could otherwise cause delays or additional vibrations. This improved precision and dexterity could help further limit post-operative pain; surgeries performed by hand can be precise to 100 micrometers, while precision in surgical robotics can be lower than 10 micrometers. With MIRS, surgeons often have a greater accuracy and control in their instrument placement compared to traditional surgical methods.

While MIRS allows for a wider scope of operations to take place and makes existing operations more efficient, there are many ways it can be improved. Surgeons lose sensory information they would have received while completing an open surgery, including depth perception, sense of touch, and force feedback based on the material properties of organs. Because the only sense of distance is the two-dimensional view on the computer monitor, it is challenging for surgeons to understand the exact distances and directions surgical tools should move. Operators also struggle to understand how much force they are applying to and the stiffness of the organ. These obstacles surgeons encounter while performing surgery create the need for additional training for MIRS. This training is challenging and requires a lot of time; presently, there are not enough surgeons with this training.

There are other issues with MIRS robots, requiring further evaluation before its widespread use. The manufacturing processes for MIRS systems and completing the operations is expensive. Furthermore, since the incision is the pivot point of the surgical tool, the movement of the tool is limited by the angle of the incision. These limitations cause a loss of dexterity in the surgeon's movements. Challenges with the technical aspects of the robots include robot arm collisions and gas leakage. Thus, there are many shortcomings in MIRS that need to be improved, but when perfected, MIRS will be extremely advantageous to surgeons and patients.

1.2 Report Outline

The current prototype, shown in *Figure 1.2*, has three degrees of freedom. Actuated by three Coreless brush DC motors, the tool's design allows for the motors to spin pulleys connected to tendons. The tendons control the movement of the surgical robot. Utilizing tendons in addition to gears, allows for the placement of actuators several inches away from the end effector. This quality in tendon-driven robotic tools allows for the end effector to be sanitized without the cleaning chemicals damaging electronics. *Chapter 2* discusses the prototype further and considers how to add degrees of freedom to the surgical tool. Tendon- driven robotics and existing surgical systems, including da Vinci, Raven, SOFIE, MicroSurge, and Al-Zahrawi, are also examined in this chapter.

Chapter 3 presents the procedure and considerations applied in designing and testing a five degrees of freedom surgical tool. The relevance of each process and design objective will also be described in this chapter. *Chapter 4* discusses how the 5-DoF model addresses the objectives in designing a MIRS system, the system's components, and the results from the tests completed. The CAD model of the tool consists of two rotational joints allowing for translation perpendicular to the transverse axis, wrist rotation, and utilization of the DoF within the original model (*Figure 1.2*).

Chapter 5 discusses the impact of innovating MIRS processes on people and the environment. The chapter analyzes the ethics of the design and testing of the tool. *Chapter 6* summarizes the findings of the research in a conclusion and provides recommendations for future work.

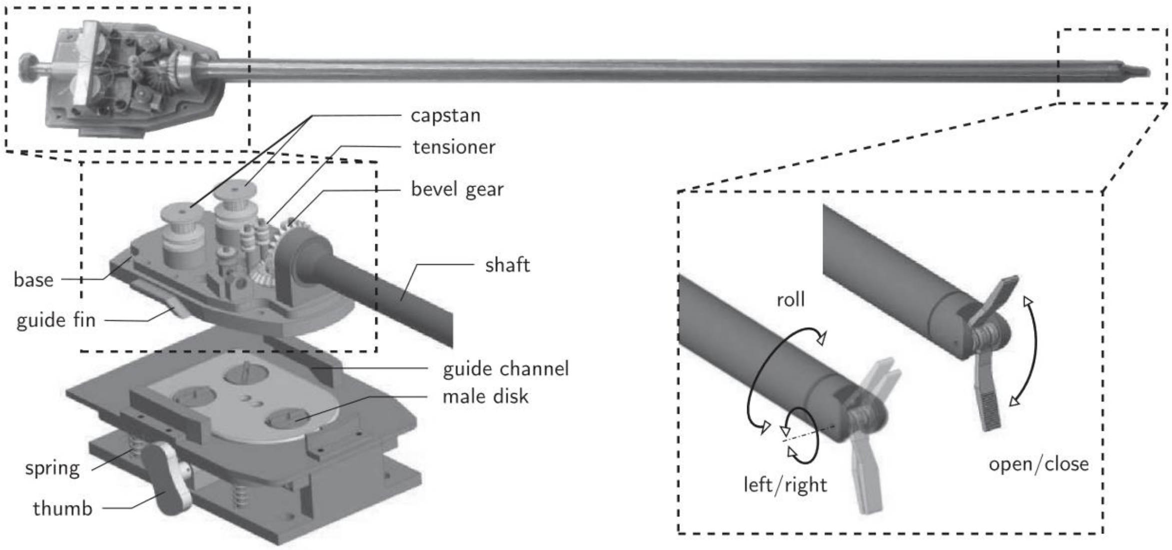


Figure 1.2: A 3 Degrees of Freedom Model of a MIRS Tool (Source: Nisar et al., 2020).

Chapter 2: Background

2.1 Tendon-Driven Robotics

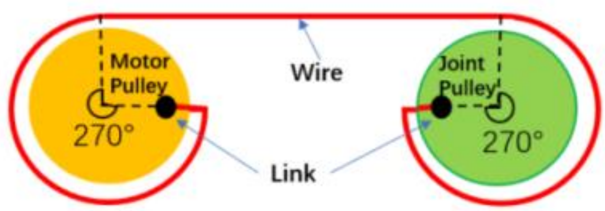


Figure 2.1: The connection between the wire, actuator, and joint (Source: Li et al., 2018).

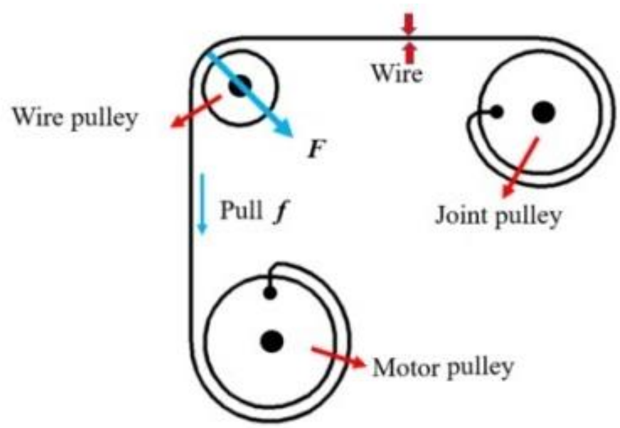


Figure 2.2: Tendon connected to multiple pulleys (Source: Li et al., 2018).

The elements of the current three-degree of freedom (DoF) prototype and the proposed five-DoF CAD model will be driven by tendons. Tendon-driven robotics uses steel wires, the tendons, to drive multiple joints and the end effector in a robotic arm by applying a pulling force. The force in the wire is generated by the motor pulling the wire such that the tendon's length is shortened. The connection between the wire, pulleys, and the actuator can be seen in *Figure 2.1*.

The tendon is often attached to several pulleys in order to successfully control different components in the robotic arm; an example can be seen in *Figure 2.2*. Utilizing this technique can facilitate a reduction in the number of tendons and actuators in a robotic arm, allowing for further mass reduction. Eliminating tendons and actuators will lower the manufacturing cost of the robotic arm and the time spent programming the robotic arm. Several tendons are often required to complete the required operations of robotic arms.

There are many reasons to utilize tendon-driven robotics. Because a steel wire replaces gears and other components within traditional robotic arms, tendon-driven systems are lightweight. Programming DC motors to spin pulleys and, consequently, move tendons is more efficient than programming movement in traditional robotic arms. Due to their durability and mass distribution, tendon- driven robotic arms are often safer and easier to move than traditional robotic arms. Placement of tendons and pulleys can vary significantly, allowing for tendon-driven robotics to have a wide variety of applications.

Despite the advantages of tendon-driven robotics, there are challenges to be conscientious of when designing a robotic arm. After extensive use, the tendon becomes weak near joints. The wire has the same probability of breaking even if the design is changed to use a thicker wire. This difficulty is further complicated by tendons often requiring large forces to move joints. Tendons also are susceptible to wear, stretching, variable tension, and variable friction. The latter two make it challenging for the designer to determine when the components may deform after extensive use.

However, tendon breakage can be avoided by considering rotation torques in each pulley, radial tension from the pulley, and the forces on the pulleys and tendons. The diameter of the pulleys should also be acknowledged when calculating these forces. Calculating these forces while reviewing the yield strength of the tendons will help avoid material deformation. These calculations can also be used to determine when the tension within cables and friction will not be able to be determined, notifying the user to replace the tool. Furthermore, many tendon-driven robotic assemblies have restraints for the cables around the center of the pulleys. The restraint will prevent material deformation of components in the assembly.

Since there are several methods to overcoming the challenges related to tendon – driven robotics and several benefits of utilizing these mechanisms, these systems are practical. Utilizing tendon-driven robotics is especially feasible in surgical robotics. A difficulty in designing surgical systems is any portion of the robot that contacts human flesh must be sanitized. Actuators cannot be sanitized because cleaning chemicals will damage their electrical components. Tendon-driven robots with long wires allow for the actuator to be located away from the patient's body; the wires connect the actuator to the joints that are often several inches from the electrical components of the robotic arm.

2.2 Design of the Existing Prototype

Sajid Nisar, Professor of Mechanical and Electrical Systems Engineering at Kyoto University of Advanced Science, and his colleagues at both National University of Sciences and Technology (Pakistan) and Kyoto University presented the current three degree of freedom model in their 2020 article (Nisar et al., 2020). The model consists of a drive manipulator (*Figure 2.3*) and a driven manipulator (*Figure 2.4*). The drive manipulator is the surgeon's user interface and senses the movements in his or her hand. Each action done within the drive manipulator corresponds to a movement within the driven robotic arm. The driven robotic arm performs MIS inside the patient's body by entering the incision. The 2020 prototype is a further

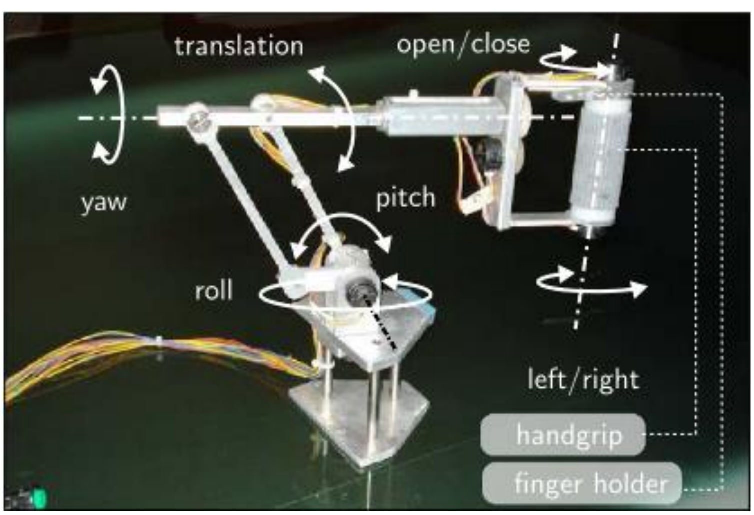


Figure 2.3: The drive manipulator in the (Nisar et al., 2020) model.

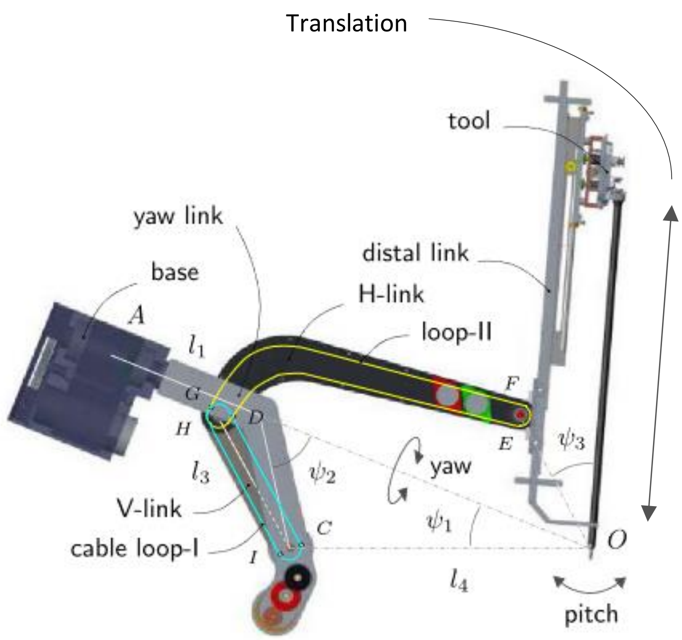


Figure 2.4 The driven manipulator (robotic arm) in the (Nisar et al., 2020) model.

innovated model of the 2014 Al-Zahrawi Sugical System, presented by engineers at Smart Machines and Robotics Technology Laboratory (SMART, Pakistan). Al-Zahwari Surgical System is discussed in *Section 2.4*.

The drive manipulator has six degrees of freedom (DoF). These DoF are created by the fingers that open and close, the handle that spins to the left and right, translation created by moving the handle away from and then closer to the surgeon's body, the rotation of the entire handle causing rotation about the yaw axis, rotation about the roll axis, and rotation in the pitch direction. Each of these motions adds one DoF to the drive manipulator.

The movements completed in the translation direction of the drive manipulator correspond to the translation of the surgical tool within the driven robotic arm. Rotation about the pitch and yaw axes in the drive manipulator correspond to rotation about these same axes in the driven system.

Several of these elements drive the actions done by the surgical tool in *Figure 1.2*. Rotating the handle about the roll axis in the drive manipulator rotates the shaft of the arm. Opening and closing the two fingers in the drive manipulator opens and closes the forceps at the end of the driven surgical tool. Rotating the handle in the drive manipulator to the left and right, creates wrist motion in the driven surgical tool; this movement allows for the forceps to move to the left and right together. Each of these movements create a DoF in the surgical tool. Each of the three DoF are actuated by a separate coreless brush DC motor. In *Chapter 4* of the paper, I will present a model that has two added degrees of freedom.

The existing prototype consists of the drive manipulator, the driven manipulator, and the surgical tool (a component within the driven manipulator). This paper will focus on adding degrees of freedom to the surgical tool. The surgical tool consists of "a slender hollow shaft, a base platform to mount the hollow shaft, [and several …] idler pulleys to route actuating cables" (Nisar et al., 2020). The shaft contains the tendons that are used to drive the forceps. The length of the shaft is also beneficial because it will take several rotations for the twist between the cables controlling the forceps to impact the tool's function. The base platform is designed so that, if the surgical tool is damaged, it can easily be removed using a quick release mechanism. The guide fins facilitate easy attachment and detachment of the surgical tool to the base. The tensioner ensures smooth movements and no backlash. Each of these components within the surgical tool are shown in *Figure 1.2*.

There are two major advantages to this surgical tool, making it beneficial to continue innovating the tool. First, the links that rotate in the pitch direction within the drive manipulator allow a large range of movement without interfering with the links that move in the yaw direction. The design also allows for right-angled tool entry and an unrestricted workspace (Nisar et al., 2020).

2.3 Adding Degrees of Freedom to the Existing Prototype

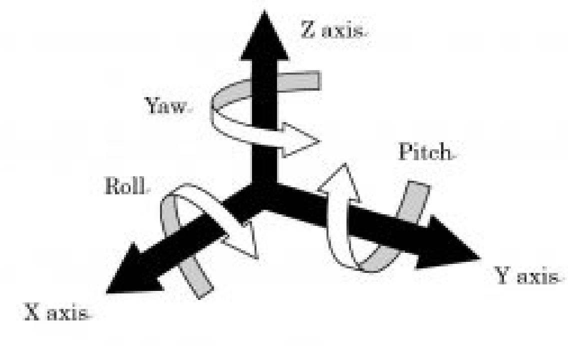


Figure 2.5: Illustration of the six degrees of freedom (Source: Mechanism of 6 Degrees of Freedom Vibration Test System, 2017).

In the prior section of this chapter, the need to add degrees of freedom to the existing surgical tool was discussed. This section provides an explanation of adding degrees of freedom. Rigid bodies in three-dimensional space, like the surgical tool, can have six degrees of freedom. Three of these degrees of freedom are created by motion or translation in the respective x, y, and z directions. The other three degrees of freedom are created by rotation about these same axes. Rotation about the x-axis is known as roll, rotation about the y-axis is known as pitch, and rotation about the z-axis is known as yaw. A visual representation of the six degrees of freedom can be seen in *Figure 2.5*.

The surgical tool can be compared to the human arm. The human arm has seven degrees of freedom: three degrees in the shoulder, one degree in the elbow, and three degrees of freedom in the wrist. These degrees of freedom can be seen in *Figure 2.6*. The fingers are not included in this model but can add several more degrees of freedom. The degrees of freedom in the current tool can be represented by one degree of freedom from the rotation at the shoulder (*Figure 2.7a*), one degree of freedom in the rotation of the forceps at the wrist (*Figure*

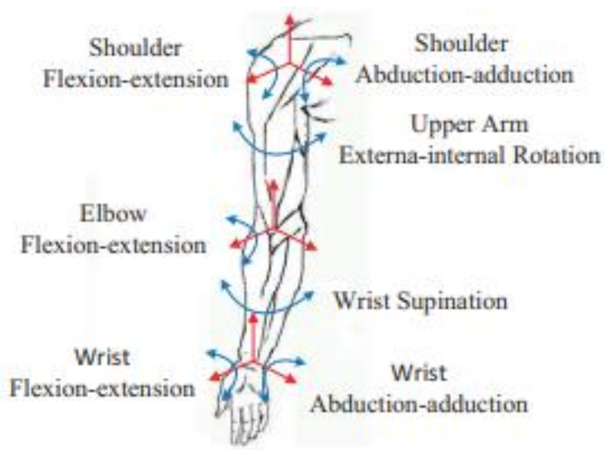


Figure 2.6: Degrees of freedom in a human arm (Source: Huo et al., 2012).

Figure 2.7: Three degrees of freedom in the current surgical tool.

2.7b), and one degree from the forceps opening and closing (*Figure 2.7c*); the forceps are analogous to the fingers in the human body.

The similarity between DoF in the tool and in the arm make controlling the drive manipulator attainable, especially because the human arm has more DoF than the tool (7 DoF instead of 6). The rotational DoF's in the human wrist and shoulder facilitate the ease of rotating the tool at different axes. The resemblance between the forceps, and the human thumb and index fingers facilitates easy control of the forceps.

Furthermore, in this tool, rigidity in the shoulder and in the elbow are essential. This tool should be able to go straight through the ribs and pelvis to operate on essential organs. Thus, degrees of freedom should not be added to the shoulder (the portion of the shaft nearest the actuators) or elbow (the middle of the shaft) areas in the surgical tool. Adding degrees of freedom in these areas will forfeit the rigidity of the design, making it difficult to reach essential organs through the ribs. Instead, the degrees of freedom should be added to the wrist, allowing the surgeon to have more freedom in the movement of the surgical tool held by the forceps.

2.4 Literature Review of Existing Surgical Robots

In this section, five common surgical robots will be discussed in general: MicroSurge Surgical System, Raven Surgical System, SOFIE Surgical System, da Vinci Surgical System, and Al-Zahrawi Surgical System. Technical specifications of each robot are presented in *Figure 2.13*.

The MicroSurge Surgical System (*Figure 2.8*) is being developed at a German Aerospace Center (DLR) to perform both MIRS and open surgery. The robot was presented to the public for the first time in 2010 and consists of three MIRO robotic arms and two MICA surgical instruments. The DLR is innovating both the MIRO robotic arms and MICA surgical instruments (*DLR - Institute of Robotics and Mechatronics - MiroSurge*, n.d.).

Figure 2.8: MicroSurge Surgical System (Source: DLR - Institute of Robotics and Mechatronics - MiroSurge, n.d.).

In the BioRobotics laboratory at the University of Washington, the Raven I Surgical System was innovated to create the Raven II Surgical System (*Figure 2.9*). Raven is a robot developed in an academic setting to facilitate an open-source system for collaborative research and advances in medical robotics. Researchers at the University of Washington hope Raven II furthers advancement in medical robotics, allowing for improvement in telesurgery and autonomous robotic surgery.

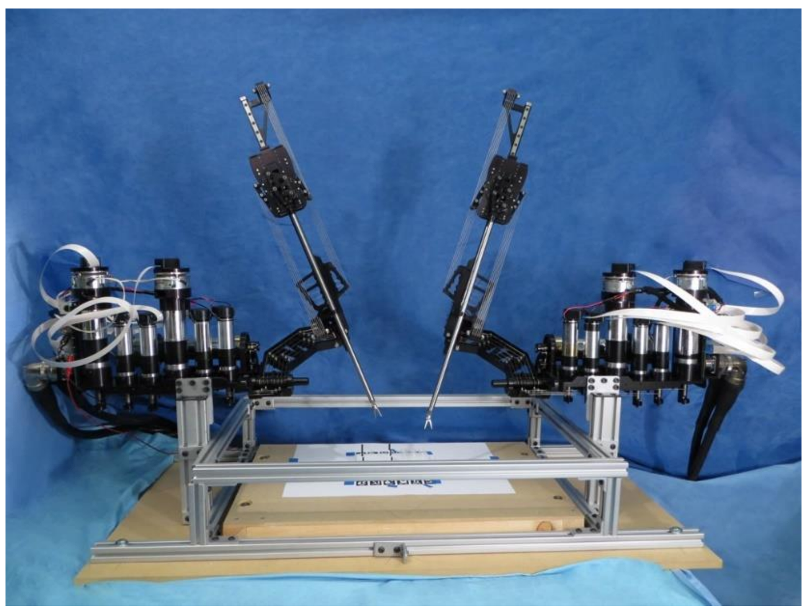


Figure 2.9: Raven II Surgical System (Source: Raven II - ROBOTS, n.d.).

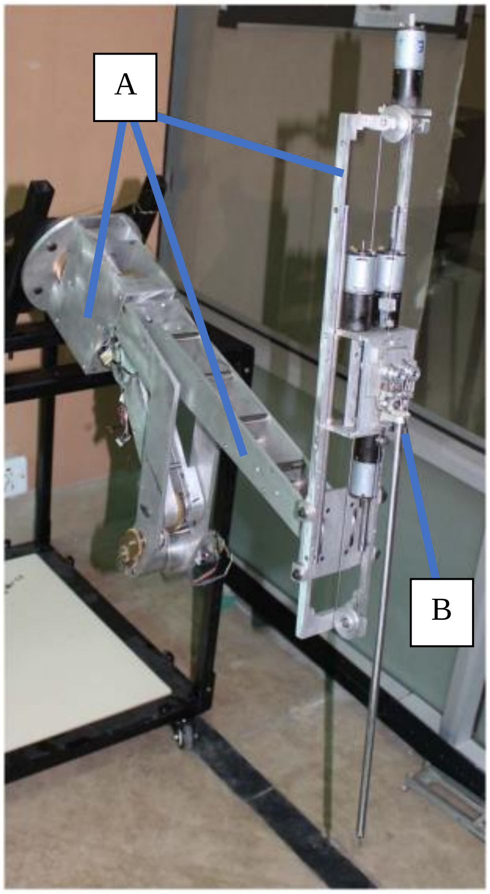
Figure 2.10: SOFIE Surgical System (Source: SOFIE, n.d.).

The acronym SOFIE (*Figure 2.10*) stands for surgical robot with force feedback. The robot is being designed at the University of Technology Eindhoven (TU/e). The objective of the researchers at TU/e is to develop an innovative drive-driven system for MIRS with haptic feedback in multiple degrees of freedom (DoF), optimize the design of the driven manipulator, and ultimately, create an eight DoF haptic master console design (SOFIE, n.d.).

The da Vinci Surgical System (*Figure 2.11*) was the first commercially used MIRS robot and is manufactured by Intuitive surgical. The United States Food and Drug Administration (FDA) approved the robot for many surgical operations in 2000. Da Vinci is the only surgical system with this approval. Intuitive Surgical innovated the Black Falcon driven telesurgical manipulator, presented in Dr. Akhil J. Madhani's PhD thesis at the Massachusetts Institute of Technology (MIT), to finalize the da Vinci's design. da Vinci is the currently the best and most common surgical system. Ruihua Xue and Rong Liu, from the First Medical Center of Chinese PLA General Hospital (Beijing), state in their journal article that at the end of 2021, at least 6730 systems had been installed in 69 countries. da Vinci had been used for more than ten million surgeries worldwide and 1.5 million procedures in 2021 (Xue & Liu, 2022).

Figure 2.11: da Vinci Surgical System (Source: "DaVinci Surgical System," 2018).

However, despite its initial success and



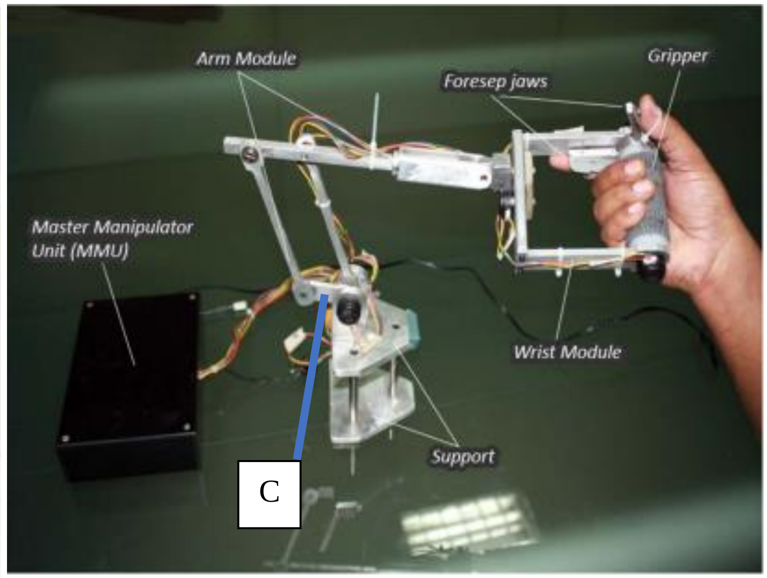


Figure 2.12: The 2014 Al-Zahrawi Surgical System. (a) shows the driven robotic arm, (b) shows the interchangeable instrument module (IM), and (c) shows the drive manipulator (Source: Hassan et al., 2016).

approval, there are issues with the system. For operations where the affected organ is several inches away from the incision, da Vinci loses its maneuverability after a few hours of use. Issues with the loss of dexterity became severe enough for the da Vinci to be recalled for several operations. Specifically, the da Vinci is no longer used for operations where the surgical tool needs to extend past the pelvis or ribs. The Al-Zahrawi Surgical System is being developed in response to the da Vinci's shortcomings.

The Al-Zahwari Surgical System (*Figure 2.12*) is utilized for MIRS. Its initial prototype was developed at National University of Sciences and Technology (Pakistan) in 2014 by members of their faculty and engineers from Smart Machines and Robotics Laboratory (SMART). The development of this model is presented in Hassan's 2016 journal article, Nisar's 2020 journal article, and will be discussed further in this paper.

Based on this literature review, it is evident there are many reasons to use the da Vinci machine for several operations; its ergonomics, large number of degrees of freedom, and its 3D imaging capability make it practical. However, there are other operations that da Vinci is not suited for. Despite its advantages, there are operations the da Vinci is not fit to complete. Although, it does not have as many DoFs as da Vinci, Al-Zahrawi may have the capabilities to complete the operations da Vinci was recalled for. Studying the haptic feedback and control elements of SOFIE and MicroSurge Surgical Systems may also be helpful. Raven II’s ability to be mounted to the patient could be a design feature utilized in the future. By studying haptic feedback and control, and adding DoF, the Al-Zahrawi could be approved for surgical operations where the affected organ is several inches from the incision.

Figure 2.13: Specifications of Existing Surgical Systems.

MicroSurge Surgical System:

- Utilizes a drive-driven system with a contact-free interface in the drive manipulator for both MIRS and open surgery
- The drive system has 7 DoF with options for left and right-handed control
- Surgeons have better perception of the surgical field with bimanual haptic force and partial tactile feedback
- Tracked hand-held forceps provide the ability to control instruments
- Uses force reflection, controlled RCM, and a strong control system
- Operates with two surgical arms with haptic feedback
- One arm has two endoscopic High-Definition cameras, creating a stereoscopic 3D image of the surgical site
- Drive manipulators can lose RCM (very dangerous), but force-torque sensors are implemented to stop power from entering the system when this occurs (safety measure)
- Mounts to the side of the bed, limiting portability

Raven Surgical System:

- Mounted directly to the patient on either side of him/her
- Removable surgical instruments allow for easy tool replacement during surgery
- Has 7 DoF (Movement in each direction (3 DoF), rotation about each axis (3 DoF), grasp (1 DoF))
- Drive- Driven system with drive manipulator, driven manipulator, and an integrating unit
- Utilizes a maximum of four arms
- Operates in four degrees of freedom
- Actuated by a spherical mechanism for RCM that is complicated
- Employs Phantom Omni devices as drive manipulators, multipurpose devices that are not specialized for medical robotics
- Drive manipulators do not remain in comfortable positions easily, making it challenging for surgeons to use them
- Uses cable-actuated mechanisms with no haptic feedback
- Tools cannot be changed during surgery

SOFIE Surgical System:

- Compact system with haptic feedback and software control
- Utilizes driven manipulators specifically designed for robotic surgery
- Employs a comfortable user interface for surgeons
- Driven manipulator consists of two robotic arms
- Based on the tool orientation, there is a limited workspace. Making the system fit for only a narrow scope of operations
- The instrument module is in proximity to the actuator such that it cannot be sanitized
- Uses a bulky toolhead, inhibiting the surgeons' ability to change tools during surgery.

da Vinci Surgical System:

- Utilizes a trolley for easy docking
- Designed with metallic cables with high fatigue life
- Comfortable hand and body placement for surgeons
- Enhanced stereoscopic vision systems installed
- Uses a simpler design than its competitors
- Has 7 DoF (3 directional, 3 rotational, and 1 in the grip)
- Driven manipulator filters out shaking in surgeon's hands
- Drive – Driven System with two drive manipulators
- Consists of surgeon console, patient side cart, EndoWrist surgical instruments, and a 3D Vision system
- Incorporates either three or four arms
- Robotic arms apply a double parallelogram mechanism for remote center of motion (RCM)
- Detachable surgical instruments facilitate required tool replacement after a specified number of operations
- Operating cost is high, and size is large, making it unpractical for small and medium-sized hospitals to use the surgical system

Al- Zahrawi Surgical System:

- Components designed for robotic surgery include Drive- driven system with drive manipular mounted over surgeon console, a trolley attached to the driven manipulator, an interchangeable instrument module (IM), and a control unit
- IM can be sterilized, as it contains no electronics or motors
- IM has a simpler design than its competitors with unique forceps design and mobility, facilitating greater dexterity of the tool tip
- Adopted a unique modular surgical tool that can be changed during surgery
- Smaller and lighter than its competitor systems, including da Vinci, making the robot better for transportation, docking, and adjusting in operating theatre environment
- Presently, only operates in 6 DoF (3 in the tool and 3 in the manipulator), while its competitors operate in 7 DoF

Chapter 3: Methodology

The purpose of this research is to add two degrees of freedom (DoF) to the existing surgical tool (*Figure 1.2*), giving the tool five DoF. Additionally, the updated design needs to maintain the same precision and accuracy as the existing tools, even when significant forces are applied to the tool. The innovation will allow the tool to operate within a wide scope of surgical operations, especially those that are challenging to complete by hand and do not have an approved MIRS procedure. Within this chapter, I will outline my process to design and test the updated prototype. While presenting my procedure, I will provide and discuss the major objectives I expect to attain in my design:

1. **Conceptualize a practical design, facilitating further design improvements, and a logically designed system with a convenient user interface and a wide scope of functionality (*Section 3.1*).**
2. **Maintain a safe environment for the surgeon, the patient, and their surroundings by ensuring the appropriate materials are used based on the function and loads applied to each component of the robotic arm (*Section 3.2*).**

3.1 Objective 1: Developing a Practical Design for Innovation and for the Surgeon

A sensible design for the tool will have optimal strength for its size and weight. However, size and weight of the surgical system should be minimized because systems that are large in size and weight are challenging to use, requiring more time, effort, and people to move the manipulator or tool. Based on the cost of materials and issues with transportation, larger systems are also more expensive.

Optimal strength is needed in each component of the surgical tool. To accomplish this, each component should be durable enough to endure the effects of cable tension without material deformation. Several metals will need to be studied, allowing for the material with the most suitable properties to be selected for the surgical tool. Some of these qualities evaluated will include ductility, yield strength, and hardness. However, prototypes should be 3d printed and appropriate plastic materials should be researched.

To achieve its desired function, surgical tooling should meet objectives set by its users. Surgeons hope that MIRS systems will allow for the tool to enter the incision at a right angle without needing a presurgical device set up. Surgical systems should also facilitate an unrestricted surgical workspace even when the affected organ is several inches from the incision and the ability to change tools rapidly utilizing a quick-release mechanism (Nisar et al., 2020). These functional goals are necessary to ensure the system is easy to use and set-up. Having a large workspace will provide the end effector an appropriate amount of space to complete surgical tasks. The objectives will also help surgeons operate efficiently, as speedy tool change is required for a newly developed surgical system.

Considerations with the mechanical placement of components within the surgical tool are also essential for its feasibility. For instance, the size of the end effector is critical. Since incisions for MIS are often less than 1.0 cm, the end-effector needs to be small so it can fit through the incision. The shaft of the surgical tool should also be smooth preventing sutures from getting stuck. The surgical tool and the end effector must also be located several inches away from the actuator; this design measure allows for components of the surgical tool that touch the patient’s flesh to be sanitized and for the electrical components to be unaffected by the cleaning chemicals.

One concern is the relevance of the DoF added. It is critical the DoF added to the wrist increase the range of ability within existing surgical functions or adding the possibility to complete new surgical functions. Surgical functions include suturing, knot tying, cutting, grasping, stapling, transportation, and others. Based on the information presented in *Section 2.3*, it will be beneficial to add DoF to the wrist. Thus, each potential DoF in the wrist should be considered. However, some DoF in the wrist should not be added since they are already provided by the driven robotic arm. See *Table 3.1* and *Figure 3.1* for these considerations.

From these tables, it is evident research can be done to add DoF in multiple directions in the wrist. However, it is important to avoid redundancy in the function of each DoF. Furthermore, these DoF should help the tool reach around

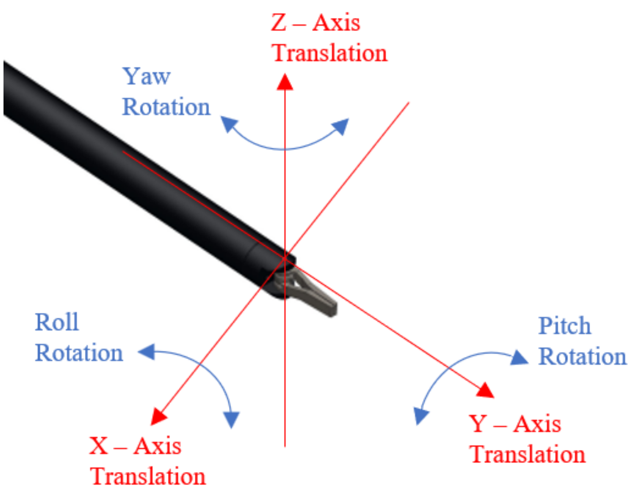


Figure 3.1: DoF Considerations of Wrist on a 3-D Coordinate Plane.

Table 3. 1: Considerations for Which DoF can be Added to the Current Prototype.

Degree of Freedom	Movement Attained	Considerations for Future Designs
X- Axis Translation	**No**	**Adding this DoF**
Roll Rotation	**No**	**Adding this DoF**
Y-Axis Translation	Yes. Given from the translation in the driven manipulator.	Not Applicable
Pitch Rotation	Yes. Given from rotation at the shoulder.	Not Applicable
Z-Axis Translation	**No**	**Adding this DoF**
Yaw-Rotation	*Yes. Given from the rotation at the wrist in the current prototype.*	*Increase the angle of rotation from 180 degrees to a greater angle.*

organs and bones to get to the surgical workspace. These DoF will create greater manuverability for operations on organs where there are bones or other organs between the affected organ and the incision. The system needs to be simple and easy to improve. There have been multipe prototypes leading to the present day model. These designs have been updated because the design and kinematics were intuitive enough to be reviewed and updated.

Analysis like that in *Table 3.1*, a presentation of the known DoF for the current prototype, can be done for the DoF added in the future. Another issue is adding DoF is usually related to adding cables. Adding cables increases the chance cables tangle and fray. Careful thought about the possibility of utilizing channels or additional tubing to avoid cable deformation needs to occur. Cable deformation will lead to a loss of force between the actuator and end effector leading to inconsistent performance of the tool, and failure of the tool. Research on different kinds of joints, materials, existing prototypes and surgical systems, and other relevant technology should be completed to find the best solution to add degrees of freedom. This research, all considerations mentioned in this section, and analysis of redundancy of DoF are critical to adding 2 DoF to the surgical tool. The tool will be designed in PTC Creo, a computer-aided design application.

3.2 Objective 2: Ensuring Safety by Considering Forces and Materials Involved

The surgical tool needs to be high strength to promote a safe environment for the patient, the surgeon, and their surroundings. This security can be attained by calculating the loads on each component of the surgical tool. Knowing the magnitude of these loads is important so that organs are not damaged during suturing or stitching operations. The recommended maximum loads for the following measurable quantities should be considered:

Table 3.2: Considerations for the Force on the surgical tool.

Quantity	Maximum Load
Driving force at the lcm needle	5 N (Source: Minor & Mukherjee, 1999)
Mean Gripping Force	10 N (Source: Piccigallo et al., 2010)
Torque at the Shoulder Joint	$(Force\ Applied\ on\ the\ End - Effector) \times (Sum\ of\ All\ Link\ Lengths)$ (Source: Piccigallo et al., 2010)
Torque required for Needle Insertion	146.258 N-mm (Source: Liu, 2010)
Strength of the Cable	110 Nt (Source: Liu, 2010)

Additionally, the tendon will exert a large amount of force on the pulley and any pins securing the pulley to the surgical tool. These forces contribute to deformation in the materials used to build the surgical tool, and potential failure of the tool. Thus, fatigue life should also be considered in calculations of the surgical tool before it is prototyped. Appropriate tendon materials should be researched to allow for the surgical tool to safely endure these forces.

Before the tool is prototyped, full kinematic analysis should be completed to ensure the surgical tool will work for MIRS. These analyses include static, dynamic, and structural testing. To ensure the tool is an improvement upon existing surgical tooling, the following qualities should be measured and compared to existing surgical tooling: shaft diameter (mm), wrist DoF (number of DoF and directions/ rotation), gripping force (N), torque of the orienting needle (Nmm), the speed of each of the rotational motion (roll, pitch, and yaw in degrees per second), the maximum possible angle of rotation or the maximum translation length for each DoF.

After these design elements are considered, the model can be manufactured and tested. The best way to test the prototype is using a suture practice kit to see the surgical tool's ability to complete tasks like knot tying, cutting, grasping components with the forceps, using retractors, stapling, and transporting laparoscopic instruments. Multiple trials should be completed for these tasks, allowing for there to be information on how often the surgical tool will be successful in completing desired tasks during surgery.

Chapter 4: Results and Discussion

4.1 Functional Requirements of the 5 DoF Model

This chapter proposes a 5 Degree of Freedom (DoF) Model and presents theoretical and mathematical analysis of the tool. It meets most of the major objectives presented in *Chapter 3* and has the mechanical specifications required to meet its user's needs. Functional goals that are not met in this model are discussed in *Chapter 6.2*, as attainment of these goals is only necessary when the material selection and manufacturing process begins. Innovative surgical tooling needs to be able to extend around organs to reach surgical workspaces that are obstructed by bones, organs, and airways. This increased surgical workspace provides the opportunity for the surgical tool to complete a greater breadth of operations than existing surgical tooling. The proposed tool attains these abilities when the added elbow pivot and wrist DoF are utilized.

Static force analysis presented in *Chapter 4.4* shows the appropriate transmission forces required in each actuator. Furthermore, explanation of the model is presented in *Chapter 4.3*. The mechanical specifications within the model show the design is simple, allowing for further innovation and testing on the existing model of the 5-DoF tool.

With the surgical tool's simple design and proper material choice, it is light weight. The design also shows the small size of the motors used to actuate the surgical tool. The compactness of the tool makes it easy to move, and consequently, easier to operate with. It also allows for surgery to be more inexpensive since fewer people will be required to move the surgical tool during the preparation for surgery.

The prior objectives are obtained by the following design specifications:

1. The tool can be released from its motors with a quick-release mechanism.
2. The shaft's diameter is 14 mm, and the forceps are 18 mm long and 3.375 mm wide.

- The 14 mm diameter of the shaft limits the incision length to a maximum of 17 mm.

3. The shaft of the surgical tool is a smooth cylindrical body with openings that allow the joints to move. Future innovations of the tool will not have openings or pulleys sticking out of the sides of the shaft when components are miniaturized. This will prevent the surgical tool from damaging human organs it encounters.
4. The shaft's length is 490.75 mm.
5. The design intent of the surgical tool allows for it to enter the human flesh at a location approximately 245.375 mm away from the nearest electrical component of the system, halfway between the forceps and the motor.
6. The maximum gripping force of the forceps is 5 Nt. Appropriate actuators need to be selected to ensure this force is attainable.
7. The total mass of the actuators is 410 kg; one motor weighs 82 kg.

4.2 The Considered Designs

In this section, three potential designs for the 5 DoF tool are discussed, and the rationale for the design selected is presented. Each of the designs utilizes the three DoF from the original prototype, numbered 1, 4, and 5 in *Figure 4.3*. These DoF are the shoulder roll, wrist pivot, and close respectively. These DoF are discussed briefly in *Chapter 2.2* and will be discussed further in *Chapter 4.3*. Thus, the added joints will contribute to DoF 2 and 3 in *Figure 4.3*.

In *Figure 4.3a*, a universal joint is added in the middle of the existing shaft. The universal joint adds two translational DoF, both called elbow pivot, perpendicular to each other. These DoF provide the opportunity for more movement in the shaft past this joint, denoted as the elbow. Utilizing a universal joint also allows for the shoulder roll DoF to impact the position of the wrist without impacting the translational movements of the universal joint. The joint is able to rotate while keeping its "input" or portion of the shaft closest to the motors and "output" or portion of the shaft closest to the wrist oriented at the same angle and in the same direction. However, consistent roll from the shoulder will result in variable roll at the wrist. Calculations for this would need to be done and need to be accounted for.

Variable wrist roll may not be optimal for stitching, as a consistent wrist roll, and a wrist roll DoF that moves independently from the shoulder, are desirable for the surgical tool. While the simplicity of having both added DoF in one location makes the universal joint appealing, it is very hard to actuate and control. Its yoke and cross, shown in *Figure 4.1*, would be challenging to connect pulleys to. Connecting pulleys to the yoke would likely inhibit one of the two translational degrees of Freedom. For these reasons, the universal joint was considered but not used in the elbow of the 5 DoF model.

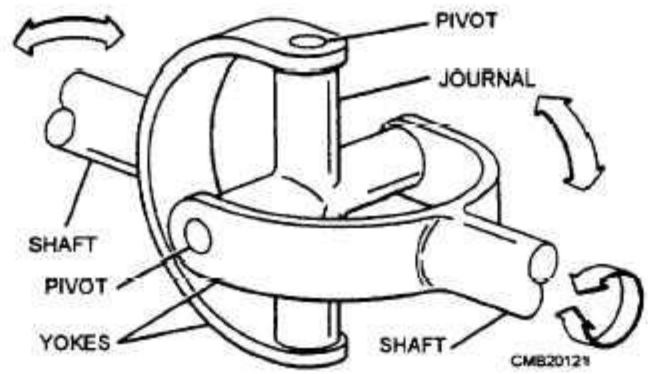


Figure 4.1: The Universal Joint. The cross within the joint is formed by the perpendicular intersection of the two journals at the center of the joint (Source: Cross and Roller Universal Joint, n.d.)

In *Figure 4.3b*, a rotational joint is added in the middle of the existing shaft, adding the one elbow pivot DoF, and a rotational joint is added at the wrist (wrist pivot). The joint added at the wrist adds a second wrist pivot DoF perpendicular to the original wrist DoF. Like the DoF layout where the universal joint is added, this orientation provides the opportunity for a larger surgical workspace and greater mobility past the universal joint. There is also increased translational motion within the wrist that moves independently from the shoulder roll DoF, as the added joint in the wrist allows for the forceps to rotate a total of 180 degrees, up to the end of the shaft. This 180 degree movement is shown in *Figure 4.6*.

However, despite this added wrist motion, if the elbow pivot joint is rotated at a 90 degree angle, the shoulder roll becomes a translational degree of freedom in the wrist. The shoulder roll will simply move the wrist in a circle within the X-Z plane. This motion is shown in *Figure 4.2*. Roll at the wrist is essential and it is desirable to have the wrist and shoulder roll independently of each other. Because the DoF layout with two added rotational joints did not provide the necessary roll DoF, this DoF layout was considered but not utilized in the final design.

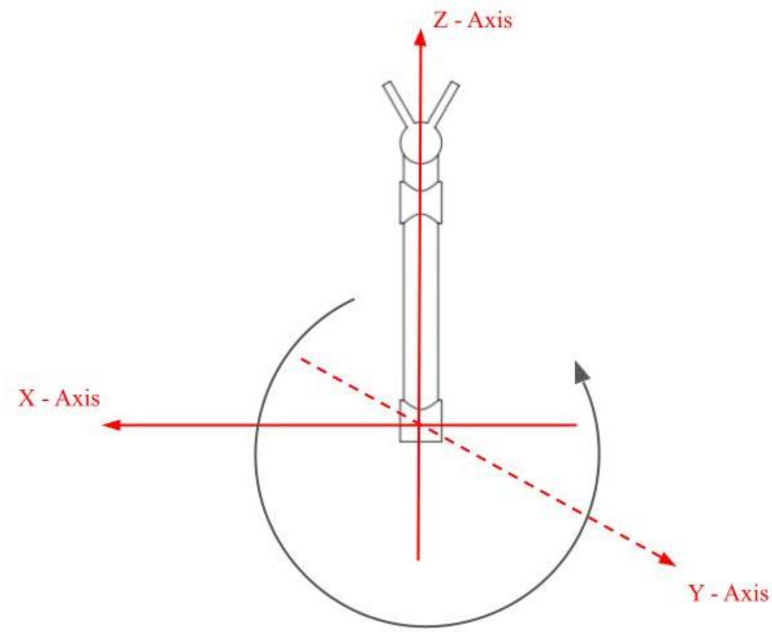


Figure 4.2: Diagram of X-Z Movement in the DoF Layout Utilizing Two Rotational Joints. In the diagram, the origin is set at the center of the elbow joint. The portion of the tool shown is the section between the elbow joint and the end of the forceps.

Figure 4.3c shows the DoF Layout for when a rotational joint in the middle of the shaft and the ability to roll is added at the existing tool. These DoF are known as elbow pivot and wrist roll, respectively. Like the prior DoF layouts, the elbow joint increases the size of the surgical workspace past the middle of the shaft and allows for greater mobility of the wrist in translational directions. The rotational joint at the elbow allows for the same motion in the X-Z plane given in the second DoF layout. The third DoF layout allows the tool to utilize this circular motion while being able to roll its wrist independently from the shoulder; this characteristic is a requirement for MIRS tooling those the prior two designs lacked.

Furthermore, in the development of SOPHIE surgical system, it was determined the four DoF layout for a surgical tool *elbow pivot – wrist roll – wrist pivot – close* was beneficial for several reasons. The third layout is the only potential design that contains these DoF, as DoF two through five are the same as the layout for the tool for SOPHIE surgical system. Consequently, the arguments for the orientation of DoF in SOPHIE surgical system are the same as arguments for the third potential design since DoF one is the same in all three potential designs.

Dr. van den Bedem's paper discusses the *elbow pivot – wrist roll – wrist pivot – close* orientation utilized in the third design is favorable because there will be lower amounts of friction and backlash in the tool than other DoF layouts. Backlash is defined by sudden movements by the tip of the surgical tool that are potential damaging to the patient. Dr. van den Bedem also discussed this DoF orientation is backdrivable, so the pulleys and gears can all move in either direction with this orientation. For these reasons, I selected the third DoF layout for my 5 DoF model.

The paper also discusses how one rotational joint, or elbow, rather than two, is optimal for stiffness and movement of the tool. Rigidness would be lost if two elbows were added to the surgical tool; this further proves why the third layout is better for adding two DoF than the second layout (Bedem, 2010). The rotational joint is much simpler to connect pulleys and tendons to than the universal joint. Consequently, actuating two separate mechanisms that each add one DoF is much more feasible than actuating a universal joint. This further defends the third layout compared to the first layout.

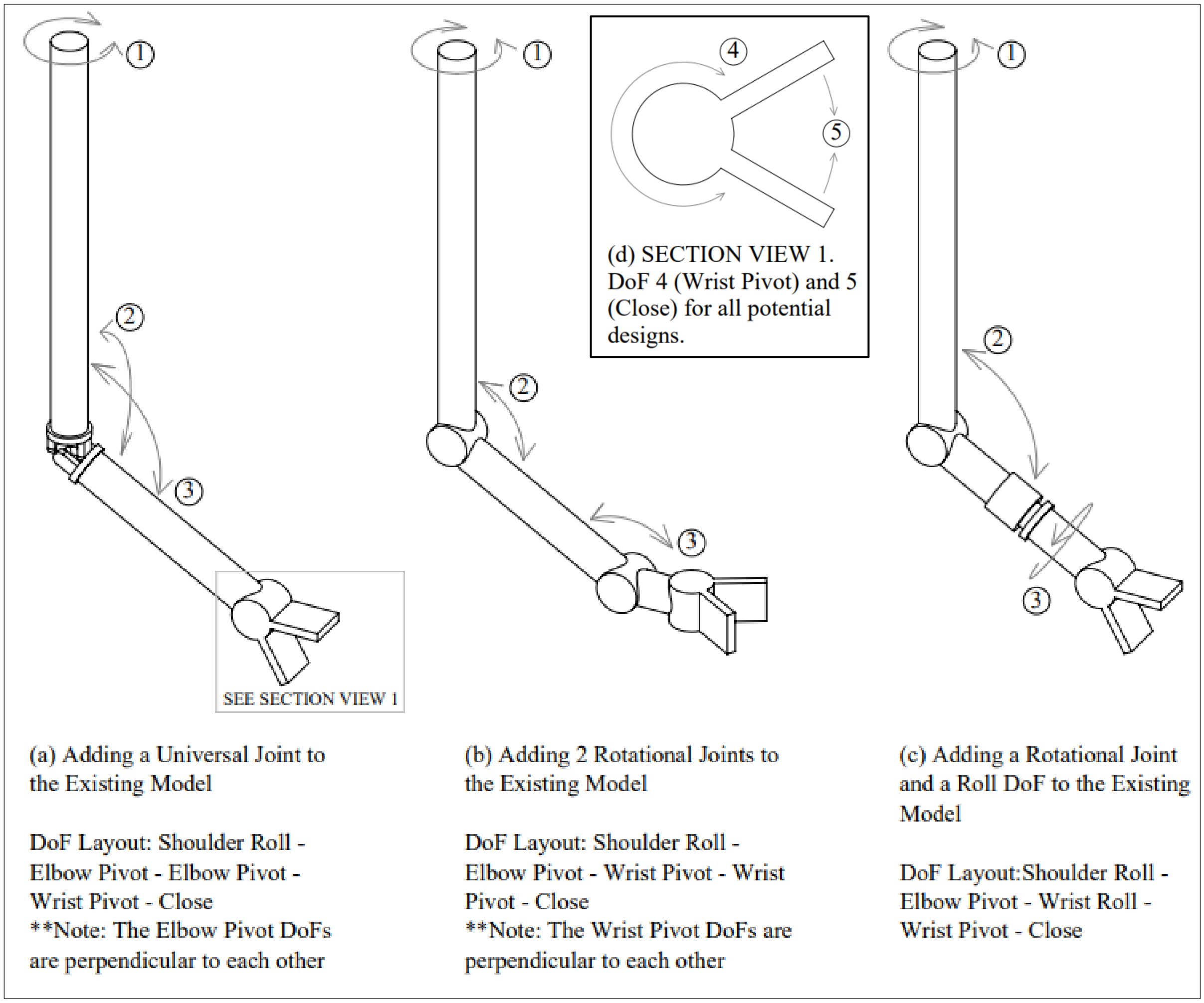


Figure 4.3: DoF Layouts Considered for the Realized Design.

4.3 The Proposed Model

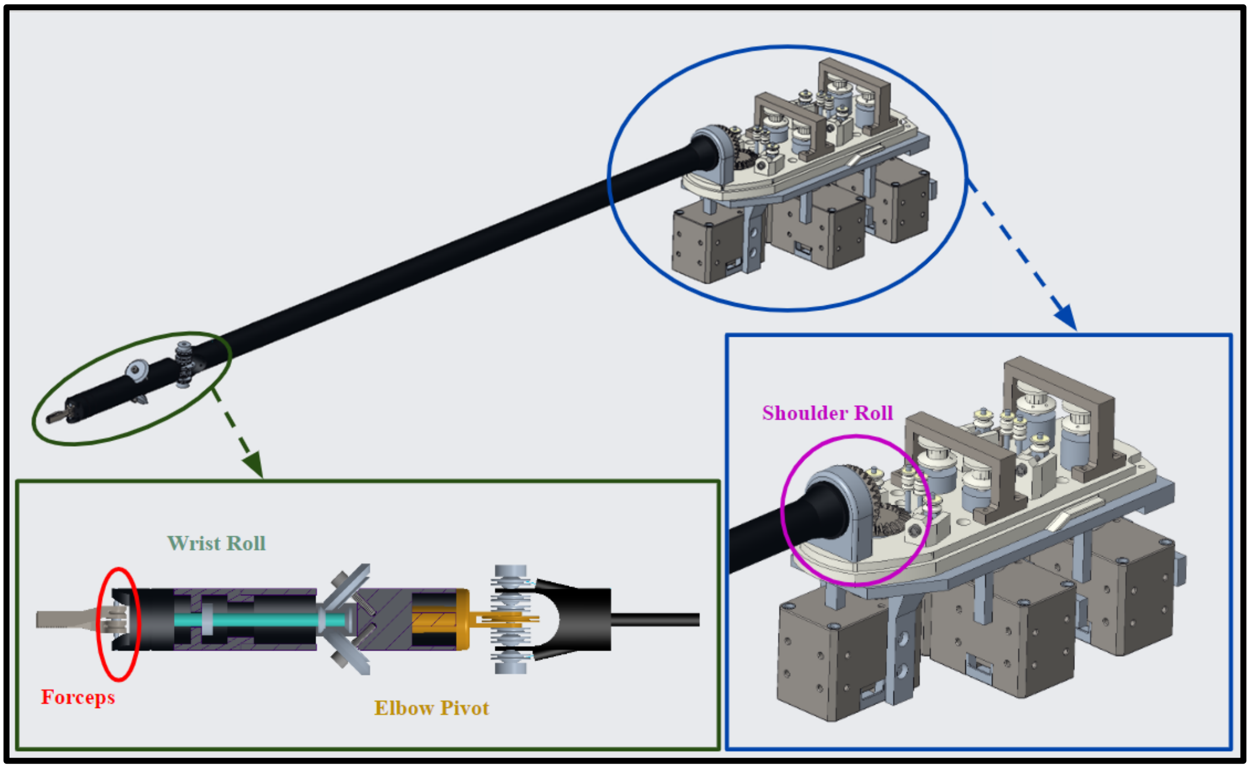


Figure 4.4: A Three-Dimensional View of the CAD of the Realized Model. Actuated by 5 servomotors, it utilizes tendons and gears to attain five degrees of freedom (DoF): shoulder roll, elbow pivot, wrist roll, wrist pivot, and close. The sectioned views show the mechanical elements of how different components of the tool move.

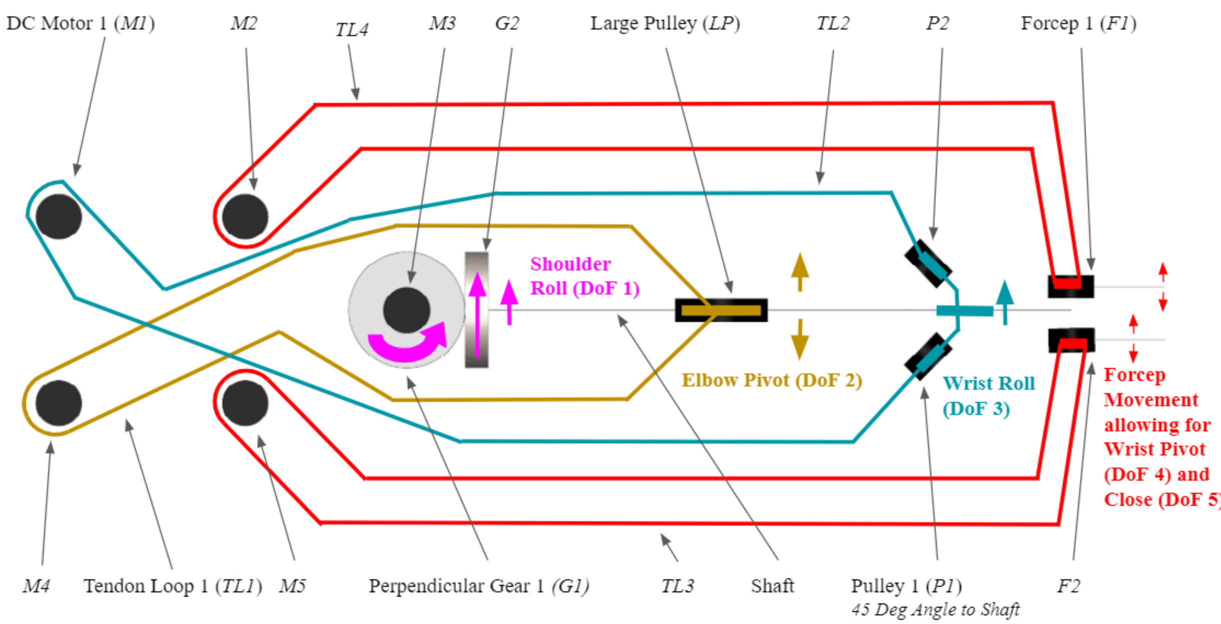


Figure 4.5: Actuation of Each DoF.

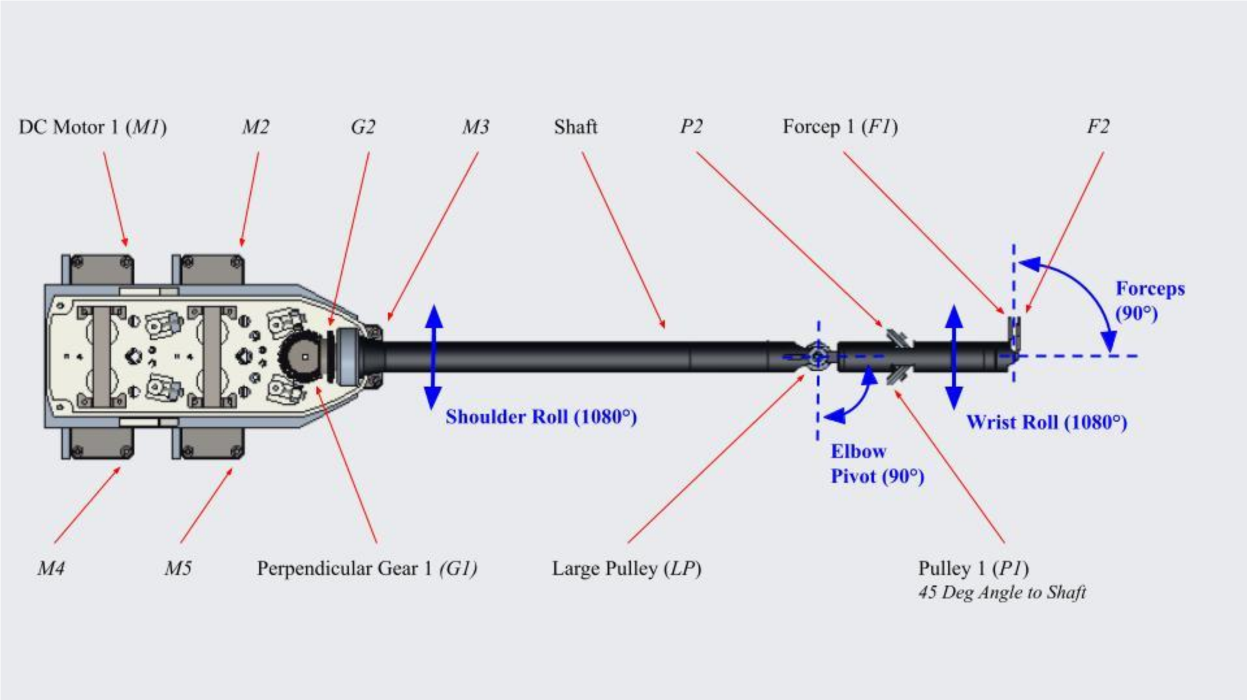


Figure 4.6: An Image of the Surgical Tool with Its Components Labeled and Arrows Representing DoF. Each of the given degree values for the DoF can be reflected about the transverse axis of the shaft. Thus, the tool can move the respective degree amounts in both directions. Each forcep is actuated individually, but the movement of the forceps contributes to the wrist pivot and close DoFs. The shaft in this figure is not the proper length; it has been resized to show all components from the top view of the tool.

This section discusses each DoF in detail and how it is actuated. *Figures 4.4 and 4.5* provide detailed information regarding the orientation of mechanical components in the assembly, and the connection of tendons to the pulleys and to different parts in the assembly. However, it is important to note *Tendon Loops 1, 3, and 4* (*TL1*, *TL3*, *TL4*, respectively) all sit within the shaft, while *Tendon Loop 2 (TL2)* sits immediately outside of the shaft. The layout of the DOF discussed in this section are shown in *Figure 4.3c*. The degrees in the figure are numbered in the order they are discussed in this section.

The first DOF is shoulder roll, allowing for the entirety of the tool to rotate about the axis of the shaft. The roll movement occurs when *DC Motor 3 (M3)* spins and consequently spins *Perpendicular Gear 1 (G1)* that is fixed to the motor. The teeth of *G1* are aligned with *Perpendicular Gear 2 (G2)* such that for each revolution of *G1*, *G2* completes approximately 85.7% of a revolution in the opposite direction. Since the *Shaft* is fixed to *G2*, the shaft rotates the same angular distance as *G2*. The percent 85.7 is given by taking the ratio of the number of teeth in the two gears: $\frac{G1}{G2} = \frac{24}{28}$ = 0.857.

The shoulders' rotation's benefits are discussed in depth in *Chapter 4.2*. This rotation allows for greater movement of the surgical tool in 3-dimensional space, rather than simply in the X-Y plane shown in *Figure 4.2*. The shoulder can rotate up to three full revolutions in each direction from the tool's natural position.

The next DOF is elbow pivot. The DOF adds the ability for the end of the surgical tool to be moved about its elbow in one direction. The potential path of movement of the wrist is defined by an arc that is the radius of the portion of the shaft between the elbow and the wrist. However, when this DOF is utilized at the same time as shoulder roll, this section of the shaft has a great range of mobility, as the elbow's translational can be utilized in any direction. Elbow pivot can be utilized such that the two portions of the shaft can be colinear to each other, perpendicular to each other, or oriented at any angle in between.

The elbow pivot DOF is actuated by *DC Motor 4 (M4)*. A tendon is attached to the pulley on top of the motor such that two pieces of wire extend away from the pulley; the two tendons form *Tendon Loop 1 (TL1)*. Each of the pieces of wire within *TL1* are connected to opposite sides of the *Large Pulley (LP)*. When the motor spins, one of the sections of tendon in the loop is shortened while the other is extended. This moves the pulley. However, the pulley has a slip fit on the axle (the axle is fixed to the portion of the shaft closer to the actuators) between the two pieces of the shaft so it can spin, but it is fixed to the portion of the shaft closest to the wrist; when the pulley moves, this section of the shaft moves about the central axis of the large pulley. The components highlighted in gold in *Figure 4.4* represent *LP* and the part within the portion of the shaft closest to the wrist that is fixed to *LP*.

The last DOF before the forceps is the wrist roll DOF. This degree of freedom allows for the forceps and the axis they are attached to rotate independently from the rest of the tool. The wrist roll DOF is helpful for stitching. The wrist can rotate up to three revolutions in either direction from the tool's resting position. Stitching is an essential function of an MIRS tool, making this DOF required.

The wrist roll DoF is actuated by *DC Motor 1 (M1)*. Two pieces of wire, within *Tendon Loop 2 (TL2)*, are connected to *M1*. The other ends of these tendons are connected to *Pulley 1* (*P1*) and *Pulley 2* (*P2*). The tendons wrap around these pullies two times and then are spun around the rod highlighted in teal shown in *Figure 4.4*. When the motor spins, one side of the tendon loop is pulled and causes the tendon that is wound on the rod to unravel. To unspool the tendon from the rod, it needs to rotate. The rotation of the rod causes the wrist roll since the rod is connected to the wrist but no other portion of the shaft. The rod's rotation also causes the tendon connected on the other side of the rod to be wound onto the rod. At the connection between the wrist and the rest of the shaft, there is a slip fit hole for the shaft to pass through. A bushing is fixed to the shaft and rests on the 2.5 mm thick surface for the bushing within the hollow shaft.

The wrist pivot and close DoF are created by the forceps. Wrist pivot is the forceps ability to move together or individually about the axis they are connected to. The end of the forceps move in an arc with a radius of the arc being the length of the forceps. The forceps have the ability to sit parallel to the transverse axis of the shaft, perpendicular to the transverse axis of the shaft, or at any angle in between. *Figure 4.6* shows the angles the forceps can be oriented at. Within this pivot motion, there is the opportunity for the forceps to move together or independently from each other. When the forceps move independently from each other, they can be open, when the forceps are apart from each other, and closed, when the two forceps are together. The close DoF is helpful for gripping thread, tools, and other components. The wrist pivot DoF is needed for stitching.

The concept of actuation for each forcep is the same. Therefore, I will discuss the actuation of *Forcep 1 (F1)*. The components used for this actuation are *Tendon Loop 4 (TL4)*, and *DC Motor 2 (M2).* The corresponding components for the actuation of *Forcep 2 (F2)* are *Tendon Loop 3* (*TL3*) and *DC Motor 5 (M5)*, respectively. A diagram of the connection between the tendon loops, motors, and forceps is shown in *Figure 4.5*.

Two ends of the tendon extend from the pulley on top of *M2*. Each of the strands extend to opposite sides of *F1*. When the motor is spun, one of the portions of the tendon attached to *M2* is extended and the other is shortened. This corresponds to pulling the forcep in the direction of where the tendon is being shortened.

In *Figure 4.4*, there are six small pullies shown adjacent to the large pulley. These pullies all rotate about the same axle, and the smaller pullies can spin freely on the axle. These pullies are utilized for the tendon loops extending past the elbow towards the wrist, *TL2*, *TL3*, and *TL4.* Since there are two lengths of the tendon extending towards the wrist in each of these loops, two pullies are needed for each loop. Within their respective paths through the shaft, each of the tendon lengths is wrapped around its own pulley twice. Wrapping the tendons around the pulley allows for these tendons to change their length based on the bend in the elbow pivot DoF. The ability for these tendons to change their length is essential because the distance between the actuators and the wrist varies when the elbow is pivoted at different angles. Having these pullies change the length of the tendons allows for each motion within degrees of freedom to occur independently from the elbow pivot DoF.

4.4 Mathematical Analysis

This section presents the static force analysis of different components of the surgical tool. Each respective subsection, *Chapter 4.4.1: Shoulder Roll*, *Chapter 4.4.2: Elbow Pivot*, *Chapter 4.4.3: Wrist Roll*, and *Chapter 4.4.4*: *Forceps* provide the static analysis for a DoF or component within the tool. Although it is not a DoF, the forceps are considered instead of wrist pivot and close. The ability of the forceps to move independently from each other contribute to these DoF. This analysis allows one to see the forces in the actuator required to move each component with the desired force of 3 to 5 Newtons. Static Force Analysis involves setting the actuating torque equal to the driven torque since the tool will be in equilibrium. The actuating force will need to be considered individually and solved for each DoF when considering a driven force of 5 newtons, the maximum desired force in each DoF.

The following variables are utilized in the analysis presented in the section:

S_1 represents the length of the tool from the side of the driven perpendicular gear closest to the wrist to the center of the elbow rotational joint.

S_2 represents the length of the tool from the center of the elbow rotational joint to the end of the forceps.

θ is the angle formed between the 2 components of the shaft.

r_{G1} is the radius of the actuating perpendicular gear or the gear that is connected to *M3*.

r_a is the actuating radius or the radius required to create torque within the motor.

r_d is the driven radius or the radius of the element required to move the respective component for that DoF.

r_{LP} is the diameter of the large pulley.

F_a is the actuating force.

F_d is the driven force.

T_a is the actuating torque.

T_d is the driven torque.

l_f is the length of the forcep.

r_f is the radius of the cylindrical portion of the forcep holding the tendon.

4.4.1: Shoulder Roll

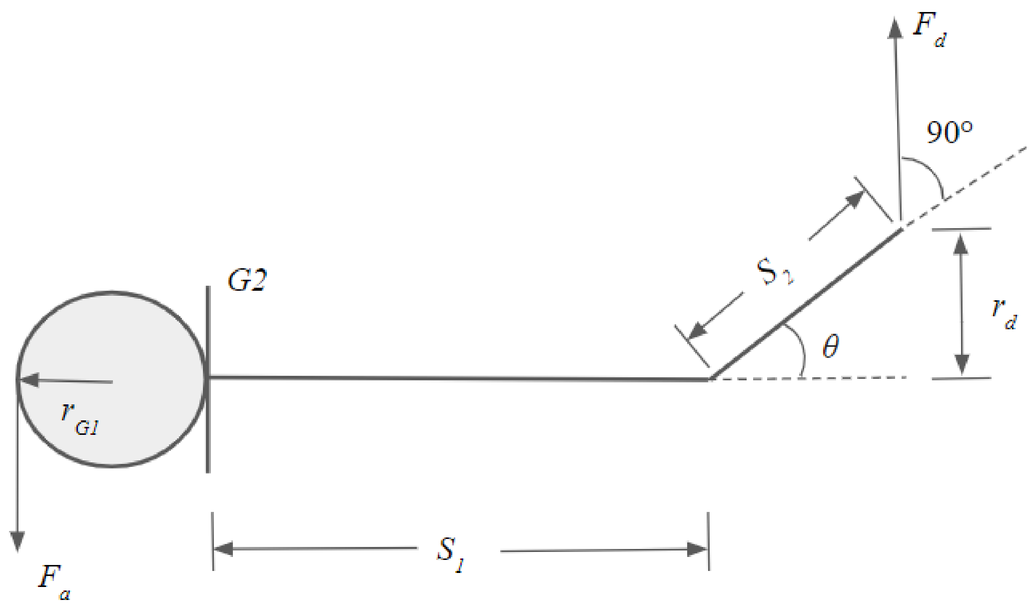


Figure 4.7: Schematic for the Static Force Analysis of the Shoulder Roll DOF.

$T_d = T_a$ (1)

$F_d\, r_d = F_a\, r_a$ (2)

For this DoF, (3)

(a) $r_d = S_2 Sin(\theta) except\ when\ \theta = 0.\ when\ \theta = 0, r_d =$ 7 mm since 7 mm is the radius of the shaft. For this example, I will consider $\theta = 90\ deg$ since that will create the largest driven radius and require the greatest actuating force to move the tool.

(b) $r_a = r_{G1}$

$F_d S_2 2\ Sin(\theta) = F_a\, r_{G1}$ (4)

$$F_a = \frac{F_d\, S_2\, Sin(\theta)}{r_{G1}} \tag{5}$$

Known values in this equation are: (6)

(a) $F_d = 5\, Nt$

(b) $S_2 = 106.756\, mm$

(c) $\theta = 90\, deg$

(d) $r_{G1} = 12\, mm$

$$F_a = \frac{(5\, Nt)(106.756\, mm)Sin(90)}{(12\, mm)} \tag{7}$$

$$F_a \approx 44.48\, Nt \tag{8}$$

To actuate the shoulder roll DoF, an actuator that can produce approximately 44.48 Nt of force is required.

4.4.2: Elbow Pivot

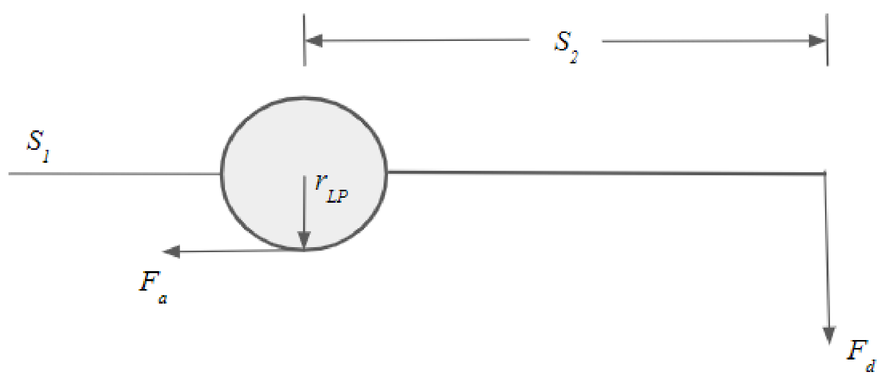


Figure 4.8: Schematic for the Static Force Analysis of the Elbow Pivot DOF.

$$T_d = T_a \tag{1}$$

$$F_d\, r_d = F_a\, r_a \tag{2}$$

For this DoF, (3)

(a) $r_d = S_2$

(b) F_a is equal to the force in the tendon. We assume that the diameter of the pulley connected to the motor is negligible.

(c) $r_a = r_{LP}$

$$F_d\, S_2 = F_a\, r_{LP} \tag{4}$$

$$F_a = \frac{F_d\, S_2}{r_{LP}} \tag{5}$$

Known Values in this equation are: (6)

(a) $F_d = 5\, Nt$

(b) $S_2 = 106.756\, mm$

(c) $r_{LP} = 5.5\, mm$

$$F_a = \frac{(5\, Nt)(106.756\, mm)}{6.5\, mm} \tag{7}$$

$$F_a \approx 82.12\, Nt \tag{8}$$

To actuate the elbow pivot DoF, an actuator that can produce approximately 82.12 Nt of force is required.

4.4.3: Wrist Roll

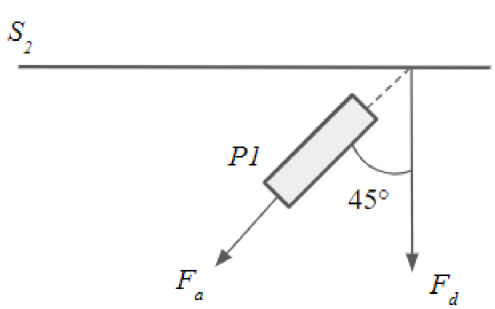


Figure 4.9: Schematic for the Static Force Analysis of the Wrist Roll DOF.

For this DoF, (1)

(a) The Calculation is different because pulling the tendon off the central rod directly moves/ rotates the surgical tool. Thus, radii do not need to be considered.

(b) Assume that the diameter of the pulley connected to the motor is negligible, allowing the force in the tendon to be the same force generated by the motor (*F_a*).

Based on the Figure, (2)

(a) $F_a\, Cos(45) = F_d$

$$F_a = \frac{F_d}{Cos(45)} \quad (3)$$

Known Values in this equation are: (4)

(a) $F_d = 5\, Nt$

$$F_a = \frac{5\, Nt}{Cos(45)} \quad (5)$$

$$F_a \approx 7.07\, Nt \quad (6)$$

To actuate the wrist roll DoF, an actuator that can produce approximately 7.07 Nt of force is required.

4.4.4: Forceps

The movement in the forceps contributes to both the Wrist Pivot and Close DoFs. The diameter of each forcep is the same, so the static forces within each forcep are the same.

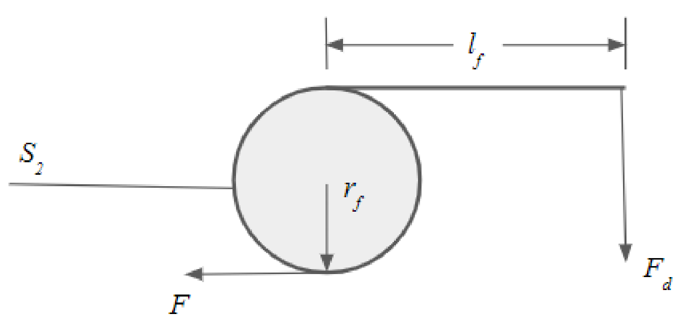


Figure 4.10: Schematic for the Static Force Analysis of the Forceps.

$$T_d = T_a \quad (1)$$

$$F_d\, r_d = F_a\, r_a \quad (2)$$

For this DoF, (3)

(a) $r_d = l_f$

(b) $r_a = r_f$

(c) Assume that the diameter of the pulley connected to the motor is negligible, allowing the force in the tendon to be the same force generated by the motor (F_a).

$$F_d\, l_f = F_a\, r_f \quad (4)$$

$$F_a = \frac{F_d\, l_f}{r_f} \quad (5)$$

Known Values in this equation are: (6)

(a) $F_d = 5\ Nt$

(b) $l_f = 18\ mm$

(c) $r_f = 2.234\ mm$

$$F_a = \frac{(5\ Nt)\ (\ 18\ mm)}{2.234\ mm} \quad (7)$$

$$F_a \approx 40.29\ Nt \quad (8)$$

To actuate the forceps, an actuator that can produce approximately 40.29 Nt of force is required.

4.5 Practical Evaluation

An imaginary prototype has been realized in the Computer Aided Design Software, PTC Creo. The imaginary prototype will need to be 3-D printed and tested. The proper actuators should be selected to actuate the tool. Testing for the mobility of each DoF and motion, including the shoulder roll, elbow pivot, wrist roll, and forceps, of the tool should be completed. When these experiments are done, the actual force each DoF and motion of the tool can apply should be

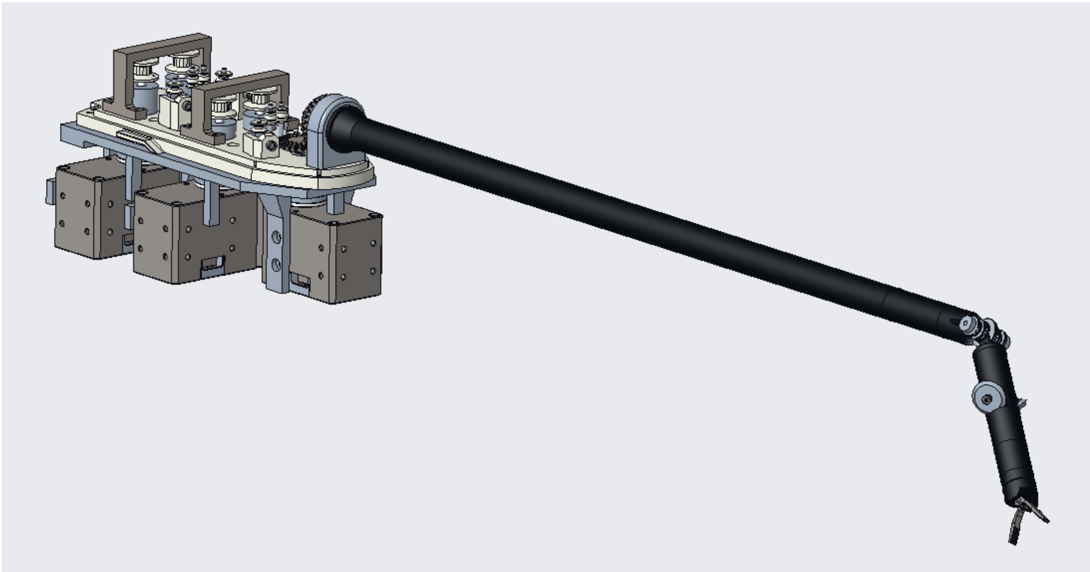


Figure 4.11: An image of the CAD of the 5-DoF Surgical Tool. The forceps are separated in the image to show their ability to move, allowing for the close DoF. Similarly, the elbow pivot and shoulder roll DoFs are utilized in the image to create a larger surgical workspace.

measured and be compared to the desired force each DoF in a surgical tool produces, 3 to 5 Newtons. The maximum gripping force in the forceps and the maximum torque at the shoulder joint are to be considered too. Completing these tests will allow us to determine if the actuators selected for the prototype are appropriate for the realized tool. If certain movements the tool is designed to complete cannot be completed, then the design needs to be re-considered. Testing the tool will prove if the technological concepts utilized to design the prototype are suitable for the tool.

Once these tests are completed, the tool should be tested for functionality. A suture practice kit should be utilized to see if the tool can complete tasks like knot tying, cutting, and stapling. Analyzing the tool's ability to complete these tasks will also help determine that the added DoFs are able to complete their desired function.

Chapter 5: Broader Impacts & Ethics

5.1 Welfare of the Public

In this chapter, I consider the ethics of research on MIRS and, specifically, the 5 DoF surgical tool. The tool's potential impact on surgeons, patients, and society are discussed. Since the 5 DoF model is only in CAD software, so many ethical considerations will need to be taken into account in the future when physical prototypes of the model are produced.

The research completed on the surgical instrument was done in accordance with the American Society of Mechanical Engineers (ASME) Mechanical Engineering Code of Ethics. Specifically, the *Fundamental Principle I* and the *Fundamental Cannon I* were met. The research done to produce the 5 DoF surgical tool was both done to "enhance the human welfare" (*ASME*, 2012) and also done in consideration with the health and safety of all people. In *Chapter 1.1*, I discuss how developing a 5 DoF tool allows for safer surgery. The chapter discusses how there is less blood loss, lower wound infection risk, and lower post operative pain for the patient. These benefits can be attributed to the smaller incision size required for MIRS but also that robotic surgical systems are programmed to filter out shaking in the surgeon's hands. Ultimately, these improvements from traditional surgery lead to a safer operation for the patient.

MIRS also benefits the general welfare of the public because it facilitates the ability to have more patients in the hospital. The known benefits of MIRS, lower blood loss and less post-operative pain, allow for shorter hospital stays. Since patients will be in the hospital for shorter times, the beds they would have been staying in after a traditional surgery will become available sooner. Having open beds will be useful to have the resources to complete more MIRS surgeries but these beds may need to be utilized during times of high infection rate. During the COVID-19 pandemic, there was a shortage of space in hospitals. Thus, performing operations in a way that patients can shorten their stay will be beneficial.

MIRS can also lower hospital readmission rates. According to the Policy Department for Economic, Scientific and Quality of Life Policies, MIRS has the potential to reduce hospital readmission rates by 50% from traditional surgery operations. Patients often return to the hospital within a few days of surgeries due to both minor and, less frequently, major complications within a few days of their surgery. Specifically, for a hernia surgery, one in six patients return to the hospital due to complications from the operation (Dolic et al., 2019). The ability to reduce complications will make surgery safer for patients and facilitate the availability of hospital beds for patient's with other ailments.

Shorter hospital stays also allow for a less expensive surgery since spending multiple nights in a hospital often costs money. The lower cost of operation will also allow for greater accessibility to MIRS. Traditional surgeries is often expensive, so its lower cost and often quicker recovery time, makes it more accessible than traditional surgery methods. Furthermore, the goal of remote operation from different locations or even continents allows for the patient to be operated on by a surgeon in a place with access to more MIRS training. If this goal is attained, MIRS will be even more accessible to patients than it already is.

Utilizing the 5 DoF surgical tool will also allow for a greater scope of operations to be done with MIRS. Specifically, operations that require the tool to go through the ribs or pelvis will be able to be done with MIRS when these operations could not be done with MIRS in the past. The ability to complete each of these operations with MIRS will further contribute to the benefits related to health and safety MIRS provides.

5.2 Intellectual Property & Research Collaboration

While researching and designing the 5 DoF tool, copyright and citing prior surgical systems was prioritized. My research processes followed Fundamental Cannon 5 of the ASME Mechanical Engineering Code of Ethics. I researched how to improve surgical tooling for Al-Zahrawi, da Vinci, and SOFIE surgical systems; all of the respective sources were cited during the design process, as this tool is a continuation of the 3 DoF tool for Al-Zahrawi Surgical System.

Furthermore, the 5 DoF tool will be shared through WPI's database and at the International Symposium on Artificial Life and Robotics (AROB Symposium). The same principles of citing sources for shared work are to be followed when the design is improved upon. The CAD has also been shared with Nisar-Sensei for further improvement.

5.3 Ethics for Future Research

Because the current model of the tool is only in CAD and will need to be prototyped, there are significantly greater consequences for decisions made during the prototyping and testing phases of the tool's fabrication. Due to the nature of MIRS operations, failure can cause serious injury or even death. Thus, each design choice needs to be considered carefully. One choice that has been made was the dimensions for the radius and thickness of the pulleys. Increasing these dimensions will reduce the chance of deformation due to forces from organs. However, increasing these dimensions will also make the tool have a greater shaft diameter and be heavier; these are major disadvantages of making these components larger. Thus, the need for a small tool and the tool's ability to undergo forces from the human body need to be considered in future designs. Each design choice needs to be considered, as hasty decision making could lead to the design of a tool that deforms while during the operation, a tool that is too expensive to manufacture, or a tool that requires incisions comparable to those required for traditional surgery methods.

Future decisions that need to be considered include material selection and the manufacturing process. The cost and feasibility of these choices will determine if they are adequate for MIRS. Poor choices could result in death or MIRS procedures that are too expensive for the general public. Future researchers need to consider this carefully, so that many people have access to MIRS and so that each patient is safe. The last issue for MIRS is training of the surgeon. With da Vinci's FDA approval in 2000 and it being the only FDA approved system, there is still limited information on training for surgeons for MIRS systems. To ensure safety in MIRS systems, standardized training needs to be established for surgeons. Without this standardized training, MIRS still remains unsafe. In following ethical research practices, a major objective of MIRS is the safety and welfare of the people.

Chapter 6: Conclusion

6.1 Summary

The DoF layout for the tool selected was *shoulder roll – elbow pivot – wrist roll – wrist pivot – close*. This orientation is beneficial because its wrist roll is helpful for stitching, and the use of one rotational joint at the elbow allows for greater mobility of the tool's wrist while maintaining its rigidness. The forceps' ability to move is also helpful for stitching and grasping tools. The shoulder roll DoF operates with one gear adjacent to the motor rotating a gear fixed to the shaft, and consequently, rolling the shaft. Other elements within the tool move when they are pulled by a tendon in a tendon loop. Utilizing tendons makes the tool light weight, keeps the actuators far from where the tool enters the incision, and facilitates disinfection of the sections of the tool which enter the body.

6.2 Recommendations

After the design is tested per the recommendations presented in *Chapter 4.5*, cost, manufacturability, material considerations, and miniaturization should be considered together before the tool is manufactured. These elements should be considered together because they have a direct impact on each other, as the materials selected have a direct impact on the manufacturing process and cost. These factors also determine whether the tool can be used in hospitals or if the design is simply a proof-of-concept. Miniaturizing components depends on the materials selected and the manufacturing processes utilized. For instance, small, machined steel parts can be produced to a greater precision than 3D printed parts.

In considering these processing elements for future designs, a list of all the potential options for combinations of the materials and manufacturing processes used should be made. The feasibility of these design choices should be evaluated by the ability to miniaturize components, cost (of both the materials and for the manufacturing process), and safety of using the respective materials in a surgical tool. These design choices should be evaluated by both research and experimentation with advanced prototypes on suture pads. Research can be done by studying material properties, different machining processes, and other surgical tooling. One potential challenge in these studies may be that the manufacturing processes inhibit the ability to miniaturize the pulleys and other components to a diameter smaller than 10 mm, the diameter of the 3 DoF surgical tool. Miniaturizing the 45-degree pulleys and the rod will be most challenging.

Bibliography

"ASME Mechanical Engineering Code of Ethics." American Society of Mechanical Engineers, February 1, 2012.

Bedem, van den, L.J.M. "Realization of a Demonstrator Slave for Robotic Minimally Invasive Surgery." Phd Thesis 1 (Research TU/e / Graduation TU/e), Technische Universiteit Eindhoven, 2010. https://doi.org/10.6100/IR684835.

"Contact Types and Behaviours in Structural Analysis – Yasin ÇAPAR." Accessed December 10, 2022. https://yasincapar.com/contact-types-and-behaviours-in-structural-analysis/.

"Cross and Roller Universal Joint." Accessed December 13, 2022. https://constructionmanuals.tpub.com/14273/css/Cross-and-Roller-Universal-Joint-179.htm.

Cursi, Francesco, Weibang Bai, Eric M. Yeatman, and Petar Kormushev. "Optimization of Surgical Robotic Instrument Mounting in a Macro–Micro Manipulator Setup for Improving Task Execution." *IEEE Transactions on Robotics* 38, no. 5 (October 2022): 2858–74. https://doi.org/10.1109/TRO.2022.3171097.

Comanche County Memorial Hospital. "DaVinci Surgical System," August 2, 2018. https://www.ccmhhealth.com/davinci-surgical-system/.

"DLR - Institute of Robotics and Mechatronics - MiroSurge." Accessed November 3, 2022. https://www.dlr.de/rm/en/desktopdefault.aspx/tabid-11674/#gallery/28728.

Dolic, Zrinjka, Rosa Castro, and Andrei Moarcas. "Robots in Healthcare: A Solution or a Problem?," April 2019.

Hassan, Taimoor, Asad Hameed, Sajid Nisar, Nabeel Kamal, and Osman Hasan. "Al-Zahrawi: A Telesurgical Robotic System for Minimal Invasive Surgery." *IEEE Systems Journal* 10, no. 3 (September 2016): 1035–45. https://doi.org/10.1109/JSYST.2014.2331146.

Hong, Man Bok, and Yung-Ho Jo. “Design of a Novel 4-DOF Wrist-Type Surgical Instrument With Enhanced Rigidity and Dexterity.” *IEEE/ASME Transactions on Mechatronics* 19, no. 2 (April 2014): 500–511. https://doi.org/10.1109/TMECH.2013.2245143.

Huo, Xijian, Yiwei Liu, Li Jiang, and Hong Liu. “Design and Development of a 7-DOF Humanoid Arm.” In *2012 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, 277–82, 2012. https://doi.org/10.1109/ROBIO.2012.6490979.

IMV Corporation. “» Mechanism of 6 Degrees of Freedom Vibration Test System,” October 27, 2017. https://www.imv-global.com/news/mechanism-6-degrees-freedom-vibration-test-system/.

Li, Wenyang, Peng Chen, Yinlai Jiang, Dianchun Bai, Shunta Togo, and Hiroshi Yokoi. “Structure Design of a Tendon-Driven Robotic Arm Considering Safety and Durability.” In *2018 IEEE International Conference on Intelligence and Safety for Robotics (ISR)*, 71–76, 2018. https://doi.org/10.1109/IISR.2018.8535706.

Liu, Taoming. “Design and Prototyping of a Three Degrees of Freedom Robotic Wrist Mechanism For a Robotic Surgery System,” August 27, 2010.

Lynch, Kevin M. “2.2. Degrees of Freedom of a Robot – Modern Robotics.” Northwestern: Video Supplements for Modern Robotics. Accessed October 30, 2022. https://modernrobotics.northwestern.edu/nu-gm-book-resource/2-2-degrees-of-freedom-of-a-robot/.

Madi. “Everything About the Degrees of Freedom of a Robot.” Mecharithm, January 8, 2021. https://www.mecharithm.com/degrees-of-freedom-of-a-robot/.

Minor, M., and R. Mukherjee. “A Dexterous Manipulator for Minimally Invasive Surgery.” In *Proceedings 1999 IEEE International Conference on Robotics and Automation (Cat. No.99CH36288C)*, 3:2057–64 vol.3, 1999. https://doi.org/10.1109/ROBOT.1999.770410.

Nisar, Sajid, Asad Hameed, Nabeel Kamal, Osman Hasan, and Fumitoshi Matsuno. "Design and Realization of a Robotic Manipulator for Minimally Invasive Surgery With Replaceable Surgical Tools." *IEEE/ASME Transactions on Mechatronics* 25, no. 6 (December 2020): 2754–64. https://doi.org/10.1109/TMECH.2020.2991869.

Nisar, Sajid, and Osman Hasan. "State of the Art and Key Design Challenges of Telesurgical Robotics." In *Encyclopedia of Information Technology*, 6872–81. IGI Global, 2017.

———. "Telesurgical Robotics and a Kinematic Perspective." In *Encyclopedia of Information Technology*, 6882–93. IGI Global, 2018.

Piccigallo, Marco, Umberto Scarfogliero, Claudio Quaglia, Gianluigi Petroni, Pietro Valdastri, Arianna Menciassi, and Paolo Dario. "Design of a Novel Bimanual Robotic System for Single-Port Laparoscopy." *IEEE/ASME Transactions on Mechatronics* 15, no. 6 (December 2010): 871–78. https://doi.org/10.1109/TMECH.2010.2078512.

"Raven II - ROBOTS: Your Guide to the World of Robotics." Accessed November 3, 2022. https://robots.ieee.org/robots/ravensurgical/.

"Raven II Surgical Robot." Accessed November 3, 2022. https://rll.berkeley.edu/raven/.

Sang, Hongqiang, Chenghao Yang, Fen Liu, Jintian Yun, and Fa Chen. *Kinematics Rapid Modeling Method of Tendon-Driven Robotic Mechanisms Using the Tendon-Routing Matrix and Equivalent Radius Matrix*, 2016. https://doi.org/10.2991/icemie-16.2016.73.

Shang, Jianzhong, Christopher J. Payne, James Clark, David P. Noonan, Ka-Wai Kwok, Ara Darzi, and Guang-Zhong Yang. "Design of a Multitasking Robotic Platform with Flexible Arms and Articulated Head for Minimally Invasive Surgery." In *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 1988–93, 2012. https://doi.org/10.1109/IROS.2012.6385567.

"SOFIE." Accessed November 3, 2022. https://www.tue.nl/en/research/research-institutes/robotics-research/projects/sofie/.

Spong, M. W., S. Hutchinson, and M. Vidyasagar. *Robot Modeling and Control*. 2nd ed., 2020.

Takuma, Takashi. "Design of Tendon-Driven Mechanism Using Geometrical Condition." *MDPI*, actuators, 9, no. 3 (June 30, 2020). https://doi.org/10.3390/act9030048.

"Telesurgical Robotics and a Kinematic Perspective: Computer Science & IT Book Chapter | IGI Global." Accessed November 1, 2022. https://www.igi-global.com/chapter/telesurgical-robotics-and-a-kinematic-perspective/184384.

Understanding Universal Joint, 2015. https://www.youtube.com/watch?v=LCMZz6YhbOQ.

Wang, Wei, Jianmin Li, Shuxin Wang, He Su, and Xueming Jiang. "System Design and Animal Experiment Study of a Novel Minimally Invasive Surgical Robot." *The International Journal of Medical Robotics and Computer Assisted Surgery* 12, no. 1 (2016): 73–84. https://doi.org/10.1002/rcs.1658.

Wedmid, Alexei, Elton Llukani, and David I. Lee. "Future Perspectives in Robotic Surgery." *BJU International* 108, no. 6 Pt 2 (September 2011): 1028–36. https://doi.org/10.1111/j.1464-410X.2011.10458.x.

Xue, Ruihua, and Rong Liu. "Statistical Analysis of Da Vinci Procedure Volumes of 2021 in Mainland China." *Intelligent Surgery* 4 (September 1, 2022): 18–22. https://doi.org/10.1016/j.isurg.2022.06.003.

Yang, Yingkan, Jianmin Li, Kang Kong, and Shuxin Wang. "Design of a Dexterous Robotic Surgical Instrument with a Novel Bending Mechanism," September 16, 2021. https://doi.org/10.1002/rcs.2334.