Design and Prototype of a 5-DoF Robotic Surgical Instrument

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Design and Prototype of a 5-DoF Robotic Surgical Instrument

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for the Degree of Bachelor of Science.

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Abstract

This research presents the design and prototype development of a 5-degrees-of-freedom instrument for robot-assisted minimally invasive surgery to demonstrate novel kinematic capability. Five stepper motors drive winches mounted distally from the end effector, actuating each joint independently through cables. We describe the mechanical and kinematic design of the system with considerations for surgical use and fabrication techniques. Additionally, we implement a control system and describe the results of kinematic testing. We highlight aspects of manufacturing necessary to produce a surgery-ready iteration. Future work involves further testing, modifying the design to use industrial and biocompatible materials, and integrating the instrument with a surgical manipulator.

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Leadership Statement

This work was a collaborative effort between multiple WPI students and advisors. To maintain strong project management practices, team members took leadership over different aspects of the project:

Cameron Crane: Lead the design and manufacturing of the elbow and cable tuning.

Calvin Page: Lead the design and fabrication of the wrist and forceps mechanism.

Josh Kleiman: Lead the design and fabrication of the base plate and tensioning system.

Nicholas Johannsen: Developed the control system and conducted kinematic calculations.

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1 Introduction

Compared to traditional open surgery, Minimally Invasive Surgery (MIS) allows for expedited patient recovery by reducing patients' postoperative trauma. However, it demands high technical precision and dexterity to operate through small incisions in a target area. Specially designed robotic surgical manipulators offer surgeons means to execute Minimally Invasive Robotic Surgery (MIRS) with enhanced reliability. A major challenge for these robotic tools is access and operation in obstructed areas from a static entry point. To overcome this, researchers have previously proposed various kinematic designs with increased Degrees of Freedom (DoF) that enable these tools to manipulate tissues obstructed by other organs or obstacles.

This paper presents design improvement and prototype development of a 5-DoF robotic surgical instrument intended for Robot-Assisted MIS. The system is designed to be affixed to an existing surgical manipulator and teleoperated from a control station. Our proposed design is inspired by a 3-DoF instrument developed by Adam Powell, Sajid Nisar, and Charles Manger [1]. Additionally, in this research, we prototype the proposed design to validate desired capabilities and performance. We justify the tool's kinematic design with references to existing surgical robotic systems. Furthermore, we describe the fabrication of the surgical instrument using both polymer-based rapid prototyping materials and biocompatible commercially viable materials.

This surgical instrument's design was developed through a startup-inspired rapid prototyping methodology to maximize progress given a small development window. A control system was then implemented and the prototype was tested with consideration for commercial use and broader impacts. The surgical instrument is driven by five actuators mounted at the tool's distal end, capable of actuating each DoF independently. The instrument's design employs cable-driven transmissions to retain all mechanical elements in a concise tubular housing. This design element seals the mechanism from debris and allows it to be easily sterilized, supporting the system's use as a surgical device. Additionally, the tool, if manufactured with industry tolerances, has potential to hold movement, speed, and precision levels conducive to the requirements expected from a surgical tool.

We implement a controller to improve the system's stability and create a control system capable of coordinating movements of interacting mechanisms. Then, we explain the results of experimental evaluation regarding the developed prototype's workspace, and kinematic validation. Furthermore, we comment on how these evaluations relate to the tool's ability to function effectively in an in vivo environment and the greater ethical impacts of such robotic devices.

Future work involves integrating the instrument as an end-effector for a surgical manipulator to conduct grasping experiments, developing a commercial prototype, and conducting additional tests. Considerations for future testing include the tool's operating force limitations and structural resilience under repeated operating loads.

This paper describes the background literature explored to develop the surgical tool. Next, we describe our methodologies and our proposed instrument design. Then we describe the control and kinematic layout of the tool and the experimental methods used to test them. Finally, we discuss the performance of the device and impacts it may have on society.

2 Background Literature

Robotic surgery leverages electromechanical precision and accuracy to offer surgeons superior control over their tools during medical procedures. These advanced systems are currently employed to conduct human-teleoperated robot-assisted surgery [2]. Often, a physician will operate using a series of joystick-adjacent input tools that control specific motions on the robot arm and tool. Surgery robots used in MIRS often are made up of two main components, a robotic arm and a manipulation tool. The robotic arm moves around the outside of the body and positions to the manipulation tool during operation. The tool contacts and enters the body, it is often small in diameter and long to reach the operating area with minimal collateral. These surgical instruments typically expand upon the abilities of surgeons by either attaining better stability and precision than the human hand or by operating in areas it would be difficult for a hand to reach and operate in.

Healthcare Applications of Surgical Robots

Both teleoperated and fully autonomous robotic surgical systems are available across a myriad of clinical scenarios. MIS is a category of procedure involving patients' operation using slender tools and an endoscopic camera inserted through a small incision called a port rather than a large incision. MIS is becoming increasingly popular, a report states that almost every surgeon at Yale Medicine performs a MIS to some degree [3]. MIRS uses surgical instruments connected to robotic arms controlled by a teleoperated controller console.

There are alternatives for most types of open surgery that do not always require a wide field of vision. Some typical surgical applications currently used in modern practice include gynecological, prostate, tumor removal, and single-site gallbladder surgery [4].

Due to the small incisions that MIRS can afford, patients experience less blood loss, reducing the need for blood transfusions. Robotic surgery can also reduce the time required to stay in the hospital after the procedure, allowing the patient to return to everyday life quicker than with alternative options, and opening ward space for a new person who may need to stay. Robotic surgery also allows the surgeon to perform maneuvers and actions that would not have been possible otherwise. Due to the range of motion and compact size of many surgery-enhancing tools, there are angles and maneuvers doctors can now perform, such as suturing small or remote areas. Many robotic systems take advantage of 360-degree rotations, allowing sewing to occur in tiny areas with minimal additional space for changing directions. Additionally, robotic surgery can increase the uniformity of sutures, which helps with healing and scar tissue development. [5]

Prior to the COVID-19 pandemic, the number of robotic surgeries performed increased yearly, including a jump of 30% in 2019 [6]. Additionally, nationwide robotic surgeries have a 97% success rate [7], which is consistent with traditional surgery. However, some differences include reduced patient recovery time and slightly longer operating times [8].

All effective surgical robots must incorporate a design that aligns with the ergonomic needs of the surgeon. One critical component is having a user interface that is intuitive, easy to use, and provides the user with clear access to each part of the patient's body. To accomplish this, most or all controls should be located between the user's mid-thigh and mid-chest [9]. Furthermore, technology such as haptic feedback, audio feedback, and virtual reality can be implemented to improve the usability of the surgical robot. In each scenario, it is crucial to include safeguards to detect errors in the surgery and recover from them without compromising patient safety. Developing a system that prioritizes ergonomics for the user is crucial in maximizing the effectiveness and safety of the robotic instrument.

Supply Costs: Manufacturing and Materials

The benefits of using robots in surgery are challenged by the increased costs. In a recent study, robot-assisted surgeries averaged a cost of $2678, or 16%, more than their counterpart traditional laparoscopic surgeries. The majority of these costs were from longer operating room times and increased supply costs [10]. These increased supply costs for surgical robots originate from the complex, precise associated manufacturing processes and the need for specialized materials to fulfill design requirements.

The production of surgical robots requires complex manufacturing equipment capable of satisfying high-precision design requirements. The equipment and processes required often depend on several factors, such as the robot's size, range of motion, degree of autonomy, number of articulated joints, and applications. For example, incorporating advanced technology such as computer vision or haptic feedback can increase costs. However, regardless of the specific requirements, the manufacturing processes for all surgical robots must be precise to ensure accuracy during surgery. Therefore, the manufacturing equipment required to build surgical robots often costs significantly more than similar equipment in other industries.

Surgical robots are made of a combination of various medical-grade materials depending on the robot's application. For example, the robot's arm would require a high-strength, lightweight material such as titanium, which also is very corrosion-resistant [11]. Additionally, medical-grade plastics for casings and non-load-bearing components are often necessary. Furthermore, biocompatible coatings are often required for components that come in direct contact with the patient's body.

Existing Surgical Robots

Surgical robots have been around since the 1980s and have been in standard practice since the early 2000s. Hence, multiple robots are currently standard practice in the medical industry. Each system exhibits different strengths and weaknesses making them valuable for different applications.

Micsurge Surgical System

This system boasts a seven degrees of freedom drive mechanism, providing surgeons versatility for left and right-handed control. Its advantages significantly improves surgeons' perception of the surgical field by incorporating bimanual haptic force and partial tactile feedback, allowing for more intuitive control over surgical instruments. Control is further enhanced by the use of tracked handheld forceps, which enable precise instrument manipulation.

The system employs advanced technologies such as force reflection, a controlled Remote Center of Motion (RCM), and a robust control system to ensure precision and safety during operations. It features two surgical arms equipped with haptic feedback to give surgeons a more immersive experience, mirroring human touch. One of the arms is outfitted with two endoscopic High-Definition cameras that work together to create a stereoscopic 3D image of the surgical site, providing unparalleled depth perception and clarity. The system is designed with safety measures to address potential risks, such as the loss of RCM—a situation that could be hazardous. Force-torque sensors are integrated to halt power to the system, preventing any unintended movements in such events.

The manipulator's design of mounting to the side of the bed limits its portability, which is a major consideration for facilities that require flexible operation room setups. We would address this drawback by making our manipulator compatible with a mobile robotic arm.

Raven Surgical System

This Raven system is engineered for direct mounting on either side of the patient, offering a versatile approach. It features removable surgical instruments, which allows for the replacement of tools during operations, enhancing efficiency and adaptability in the surgical environment. The system uses seven degrees of freedom, encompassing movement in each XYZ plane, rotation about each axis, and a grasp function, enabling precise manipulation and control over surgical actions.

At the heart of this system is a drive-driven mechanism, consisting of a drive manipulator, a driven manipulator, and an integrating unit to enhance performance. Capable of utilizing up to four arms, the system ensures a broad range of movement and flexibility. The actuation of these arms is facilitated by a sophisticated spherical mechanism, responsible for maintaining the Remote Center of Motion, though its complexity presents challenges in manipulation.

Notable limitations of the system include the use of Phantom Omni devices as drive manipulators. These multipurpose devices, while versatile, are not specialized for medical robotics, presenting a learning curve for surgical teams. Additionally, the manipulators are noted to be uncomfortable to use, which can pose challenges for surgeons during lengthy procedures. A limitation of this system is its reliance on cable-actuated mechanisms that lack haptic feedback, reducing the surgeon's ability to feel and respond to the physical properties of the surgical site. Moreover, the system does not allow for the changing of tools during surgery, which limits operational flexibility and responsiveness.

SOFIE Surgical System

The SOFIE Surgical System integrates haptic feedback and sophisticated software control for an enhanced surgical experience. The system employs driven manipulators that have been designed specifically for robotic surgery, ensuring precision and reliability during operations.The SOFIE Surgical System has a user-friendly interface, which has been developed for surgeons comfort and ease of use. This attention to ergonomic design allows for intuitive control and interaction with the system, facilitating a smoother surgical process. The system has 6 degrees of freedom and uses a series of internal gears to drive manipulation.

However, the SOFIE Surgical System does present certain limitations that affect its application range. The design of the tool orientation results in a limited workspace, restricting the system's utility to a relatively narrow scope of operations. This constraint limits its adoption for more diverse surgical procedures. Additionally, the proximity of the instrument module to the actuator poses a challenge for sanitization, raising concerns about maintaining sterility and preventing contamination during surgery. Additionally, the system at this time has not been tested on patients.

Da Vinci Surgical System

The da Vinci Surgical System is the industry standard and one of the most widely used surgical systems. A notable aspect of the system is its trolley-based design, which facilitates easy docking and enhances the system's mobility, allowing for streamlined setup and integration in a surgical environment. This system is built with metallic cables known for their high fatigue life, ensuring durability and long-term reliability. The system has comfortable hand and body placement during manipulation, reducing surgeon fatigue and enhancing precision during procedures. The system is equipped with advanced stereoscopic vision systems, providing surgeons with enhanced 3D visualization of the surgical site, significantly improving the accuracy and safety of surgical interventions.

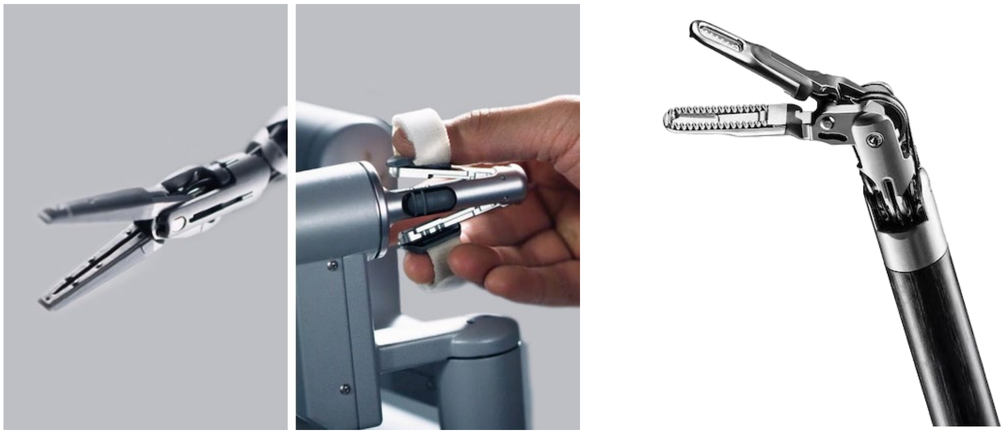

Figure 2.1: The left figure depicts the full da Vinci endo wrist next to its control mechanism at the operation station. The right figure shows a closeup view of the toolhead for the da Vinci endo wrist. [12]

The da Vinci Surgical System boasts a simpler design compared to its competitors, without compromising on functionality. It offers seven degrees of freedom (3 directional, 3 rotational, and 1 in the grip), allowing for intricate maneuvers and precise control over surgical instruments. Its driven manipulator is specifically designed to filter out any unintended shaking from the surgeon's hands, ensuring steady and controlled movements.

Figure 2.2: The figure above shows the full da Vinci surgical system. The left figure depicts the remote base station where the surgeon operates. The right image shows the full multi arm system with attached toolheads. [12]

Comprising a surgeon console, a patient-side cart, EndoWrist surgical instruments, and a 3D Vision system, the da Vinci integrates key components for a comprehensive surgical solution. It can be configured with either three or four robotic arms, employing a double parallelogram mechanism to maintain a remote center of motion, which is crucial for minimizing trauma to the patient and enhancing surgical precision. The system has Detachable surgical instruments allowing for necessary tool replacement after a specified number of operations. This ensures that the instruments can remain efficient, without major maintenance. Additionally, the da Vinci EndoWrist is the company's most versatile toolhead commercially available. It has degrees 6 degrees of freedom but does not achieve roll in the tip.

The limitations of the system include the system's large cost and size. These limitations pose challenges for small and medium-sized hospitals, making it less practical for these facilities to adopt this advanced technology. Additionally there are rotational limitations in the end of the manipulator limiting the systems versatility. Our team would overcome these challenges by making our tool compatible with smaller arms, have additional rotational movement, and be as cost effective to build as possible.

Limitations and Arm Considerations

Understanding the limitations of the current systems is critical for developing a problem statement that is accurate and reflects the needs of the field. Surgical manipulators are composed of both the tool head and the robotic. Since our team aims to develop a new kinematic layout for a tool head, we must address those concerns in our designs. This approach differs from our consideration of the limitations of robotic arms as we would need to select an arm with the ideal characteristics to mount our tool head rather than design one ourselves.

Current Limitations of Surgical Toolheads

- Device Uses Phantom Omni devices as drive manipulators, multipurpose devices that are not specialized for medical robotics
- Tools cannot be changed during surgery
- Based on the tool orientation, there is a limited workspace. Making the system fit for only a narrow scope of operations
- Uses cable-actuated mechanisms with no haptic feedback
- Operating cost is high

Current Limitations of Surgical Manipulators

- Device is actuated by a spherical mechanism for RCM that is complicated
- Drive manipulators do not remain in comfortable positions easily, making it challenging for surgeons to use them
- The instrument module is in proximity to the actuator such that it cannot be sanitized
- Operating cost is high
- Robotic arm size is large, making it impractical for small and medium-sized hospitals to use the surgical system

To best create a toolhead that is more effective in the field then already existing systems we would need to solve the challenges related to the toolhead in our design and select a robotic arm that addresses the above concerns.

Cable-Driven Robotic Arms for MIRS

The field of MIRS presents unique challenges and requirements that shape how a surgical robot operates. In many industries, including automotive, aerospace, and manufacturing, it is common to see both parallel and serial manipulators in use. Parallel manipulators have all of their links connected to the robot's base and supporting the end effector. Serial manipulators' links are in a chain, one after another, much like how a human arm has a chain of muscles from the shoulders to the wrist. Parallel robots are infeasible in MIRS due to extreme size requirements. Most serial manipulators, such as Universal Robotics' UR20, shown in Fig. 2.3, mount actuators directly to joints. Despite offering great precision and force capabilities, this type of arm is too large and heavy to be used effectively in MIRS.

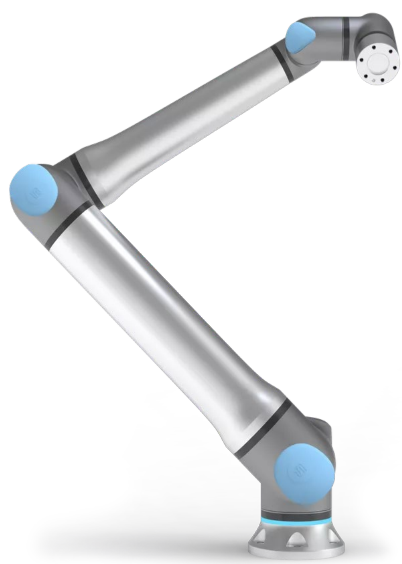

Figure 2.3: Universal Robot's UR20 Serial Manipulator [13]

Cable-driven robotic arms, as depicted in Fig. 2.4, are often used in MIRS products and research. These robots differentiate themselves from typical serial manipulators by migrating motors from within the arm to the base of the robot. Force is transmitted with tension via cables embedded within the arm. Tendon-driven robots, another similar type of robot, are commonly characterized by their use of flexible tendons and continuous, bending linkages as opposed to cable-driven robots with pulleys, solid linkages, and cables. This paper will focus on the design of cable-driven robots. These approaches to constructing a serial manipulator affect the size and capabilities of the robot while migrating much of the weight of the robot from the arm to the base.

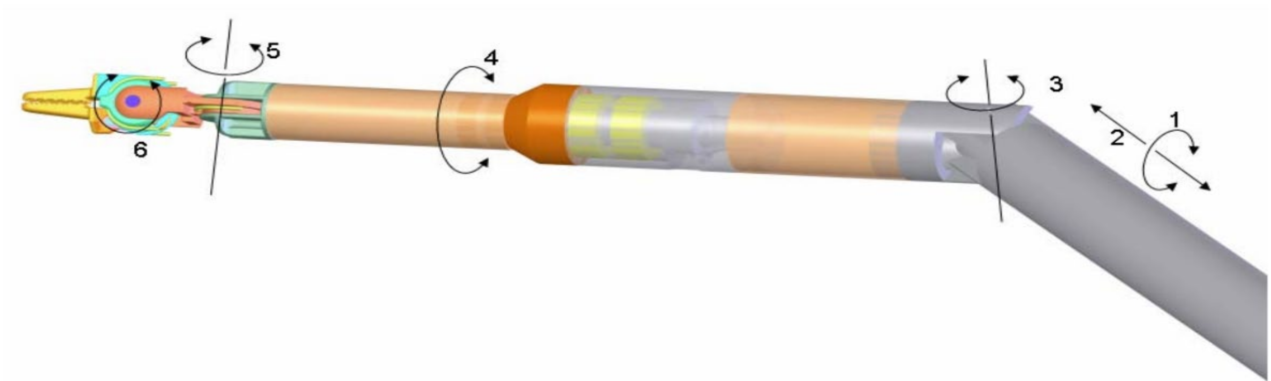

Figure 2.4: 6-Degree of Freedom Cable-Driven Robot [14]

Cable and tendon-driven robotic arms do not need to make room for or support the weight of motors. This characteristic drastically decreases the size and weight of the arm, leading to a more nimble architecture. The thin geometry of an arm is, therefore, primarily constrained by strength requirements and the space required to route wires and pulleys. These attributes allow robotic surgery to be minimally invasive by utilizing smaller incisions and enhancing maneuverability within tight, delicate anatomical spaces.

Biocompatibility and sterilization are major considerations for any tool used in surgery. Parts and materials with the potential to interact with a patient must be safe and have a feasible sterilization process. The design of cable-driven robots relocates parts typically placed along the arm over to the base of the robot instead. This relocation allows motors and other electronics, such as encoders, to be freely designed without conforming to biocompatibility or sterilization standards. Instead, thin cables and pulleys take up this challenge.

Although cable-driven robots have key advantages that allow them to be an appealing choice for MIRS, drawbacks relating to performance and complexity are present. Cable-driven mechanisms face high backlash due to the delicate balance of minimizing cable friction and slack [15], [16]. Additionally, wearing on cables over time can increase maintenance costs and degrade performance. Furthermore, cable-driven robot joints, especially those farther from the base of the robot, are more limited in the magnitude of force they can exert compared to their typical direct motor drive counterparts.

With their distinct advantages and limitations, cable-driven robots are well-suited for MIRS applications. Their reduced size and mass enhance maneuverability. Moreover, the isolated placement of motors simplifies cleaning procedures and addresses biocompatibility concerns. Thus, the design features of cable-driven robots offer a promising path forward for MIRS.

Control of Serial Cable Driven Robots

Surgical robotic arms require specially considered control systems to achieve the necessary power and precision needed to operate on the human body. However, the kinematic and dynamic control strategies are still similar to those used in other industrial robotic arms. Mathematical models of the arm’s dynamics and kinematics are created to plot smooth trajectories within the robot's workspace. Adding more degrees of freedom through joints increases the complexity of control systems and the robot’s configurations. In a certain practical sense, the role of a control system is to convert motor inputs into output positions, motions, trajectories, and forces at the end effector. One common strategy involves creating a kinematic transformation matrix using the Denavit-Hartenberg, or ‘D-H’ convention. This approach relates the robot's joints' motion to the position of the robot's end effector. For dynamic considerations, a similar approach can be conducted to produce a Jacobian matrix, which can relate joint kinematics to the force of the end effector [17]. Depending on the desired result, both kinematic and dynamic control elements need to be considered to fulfill design and operating parameters.

On a lower level of control operation, control laws to control the position, force, and velocity of the actuators in joint space are also necessary for predictable output. A standard approach uses a PID control loop, which leverages tunable coefficients to improve or adjust actuator performance based on the desired outcome and sensor feedback. For surgical robotic applications, control systems generally demand high optimization to be extremely precise and steady during surgery. Surgical robots may also operate in unusual environments. One example discussed in “Inducing Performance of Commercial Surgical Robots in Space” by Timothy Sands explores medical robots' unique considerations when operating in space. When robotic joints and arms no longer experience the force of gravity, their control systems must be adapted. Whether operating in air under Earth’s gravity, working inside a fluid tank, or on the International Space Station, the control system design and overall mechanical design of a surgical robotic system must consider its operating environment [18].

One problem discussed by literature specifically on cable-driven surgical robotics is managing ‘backlash.’ Backlash occurs when motor hubs, axles, pulleys, and belts either deform or slip due to high load or are not precisely machined, leading to kinematic instability, especially under load. These problems are compounded amongst serial kinematic chains like most surgical robotics arms. Furthermore, affixing actuators in the base of the robot and relying on cable or belt transmissions to operate a joint introduces new margins of error and opportunities for backlash. Even a reasonably well-constructed arm can still struggle with backlash contextualized in the surgical resolution of movement. For some applications, these sources of error can be systematically reduced by minimizing acceleration magnitudes and tuning the motion trajectories of the arm. However, in the application of surgery, this is often not enough. Instead, higher-level control systems are devised using data-driven statistical analysis. These techniques use machine learning, Gaussian process regression, or other techniques to model backlash and factor it into the control laws of a robotic arm [19].

A final consideration of robotic control systems is how they are operated. While some surgical robots are developed to be fully autonomous, other semi-autonomous systems have a surgeon physically wielding a set of controls. The physical controls often resemble the surgical robot’s instrument, allowing the surgeon to intuitively conduct operations through the robot. Depending on the specific application of the surgical robot, the user controls also differ. Other advanced control systems, such as haptic feedback, improve user success and precision [20].

Design for Manufacturability

Design for Manufacturability (DFM) is a concept used in product development that emphasizes manufacturing considerations during the design phase. Through a variety of methods, it seeks to optimize manufacturing and assembly processes, enhance product quality, and reduce production costs by proactively addressing manufacturing constraints and requirements. This is accomplished by designing products to have minimal complexity and streamlined assembly procedures.

When selecting parts for a design, DFM calls for using the minimum number of parts, selecting standard components over custom components, and re-using components from other products made on-site where possible. Using the minimum number of parts required for a design simplifies the manufacturing and assembly processes, and reduces the costs associated with procurement, inventory management, and quality control. Selecting standard parts over custom parts is preferable because they are less expensive and more available, yielding lower lead times. Re-using parts from other products made on-site helps reduce the total number of unique parts in the warehouse, which reduces procurement and inventory management costs [21].

Modular design principles facilitate dividing the product into subassemblies that can be independently manufactured, assembled, and repaired. This allows for greater flexibility and scalability in production processes while reducing the effects of bottlenecking. This also enables design teams to independently redesign one component without necessarily redesigning the whole product [21].

Common design considerations that help streamline the assembly process include incorporating error-proofing mechanisms, avoiding fasteners where possible, selecting optimal materials for the fabrication method, and having low tolerances where possible. Error-proofing mechanisms ensure assembly tasks are performed correctly by design, minimizing the risk of errors and defects and inherently, reducing the need for rework and quality inspections. This is accomplished by designing parts to only fit together one way. Fasteners should be replaced by tabs or snap fits where possible to reduce assembly time and total number of parts [21].

In recent years, advancements in manufacturing technologies, such as computer-aided design and rapid prototyping with 3D printers, have further expanded the scope of DFM. These technologies enable engineers to design intricate geometries, optimize material usage, and rapidly prototype designs, thereby accelerating the product development cycle and reducing the time-to-market [22].

DFM plays a critical role in modern product development by enhancing the efficiency, reliability, and cost-effectiveness of manufacturing processes. It considers manufacturing processes early in the design stage, employing modular design, strategic part selection, and streamlined assembly methods.

3 Methodology

To develop this surgical instrument, an existing concept review, prototyping philosophy, part sourcing strategies, and team dynamics needed to be established. Methodologies were chosen with the timeline, resources, and design aspirations in mind. These strategies were pivotal in guiding the design process of this project to successful completion.

Existing Concept Review

An extensive review of the existing concept created in previous literature was completed. This was done by reviewing the design in Computer-Aided Design (CAD) software and 3D printing portions of the concept. This allowed the team to gain a clear understanding of the architecture proposed by the concept, including its cable configuration, surgical capabilities, kinematic layout, and general scale. These key properties guided the design of the proposed instrument.

Prototyping Philosophy

The design process of this project followed the "Fail Fast" philosophy often used by startups in industry. This philosophy is characterized by relentlessly prototyping, iterating, and testing assumptions to ensure that minimal resources are spent on dead-end ideas [23]. Fig 3.1 shows prototypes from each subsystem that each provided valuable insight on required improvements. As the project's duration was roughly seven weeks, such a strategy was necessary to properly utilize the bandwidth and time of all four team members to develop a working prototype. Through each subsystem iteration, the goal was to achieve functionality while minimizing complexity where permissible. This focus ensured that the instrument remained reliable and manufacturable. Each subsystem was developed and prototyped in parallel and integrated together as soon as feasible.

Figure 3.1: Prototypes from each subsystem

Part Sourcing Strategies

Successful prototyping was dependent on the strategic selection of the procurement methods and fabrication processes used for each component. Relying too heavily on commercially available parts would limit design while increasing risk of supply chain delays and relying too heavily on parts fabricated in-house would complicate design and require longer manufacturing time. We proactively assessed whether each component should be fabricated in-house or sourced as a pre-build component, prioritizing rapid manufacturing of each subsequent design iteration.

Components that are custom in nature or have compelling arguments relating to cost or lead time were fabricated in-house using the equipment at Kyoto University of Advanced Science (KUAS). When determining the fabrication method, we considered the size and strength requirements of the component. Resin printers often have smaller build plates than Fused Definition Modeling (FDM) printers, and resin is significantly more expensive than Polylactic acid (PLA). Therefore, resin printing was used for smaller parts requiring finer details and higher strength requirements, while FDM printing with PLA was used for the larger components whose detail did not need to be as accurate.

Standard components with a compelling cost or lead time were sourced as pre-built. Common components such as standard screws, nuts, and bolts were readily available in inventory at KUAS, while more uncommon components were ordered from an external vendor. Most parts were available within two to three days, while some parts had lead times of one to two weeks. Components that were needed for upcoming iterations were proactively identified to prevent bottlenecks. Components that needed to be sourced for imminent prototypes were sourced in-person. For example, when alternative cable options were desired, we walked to a nearby fishing store and purchased fishing cable.

Team Dynamics

To enhance team workflow, individual members were assigned responsibility over one of the following subsystems: controls, base plate, elbow, and wrist roll/forceps. Each member was tasked with keeping their subsystem on schedule and delegating relevant assignments accordingly. Subsystem owners collaborated to integrate their respective subsystems into the final prototype. Assignments not directly related to a particular subsystem were delegated based on team member availability and strengths.

4 Proposed Instrument Design

Figure 4.1: Five DoFs instrument prototype with its unique kinematic layout that includes both shoulder and wrist roll.

The tool outlined in Fig. 4.1 is composed of two main subsystems, the base plate and the arm. The base plate houses the system's electronics and motors, while the arm would be the component of the tool inserted into the body interacting with the work area. Separating the base plate for the arm has benefits regarding the functional size of the tool, sterilization, and the ability to actuate the tool remotely. The base plate houses the actuators, electronic components, tensioning systems, and shoulder roll mechanics. The arm contains the mechanical elements needed to move the remaining joints. Containing tensioners and actuators in the distal end allows for optimized arm diameter and more effective sterilization.

Kinematic layout

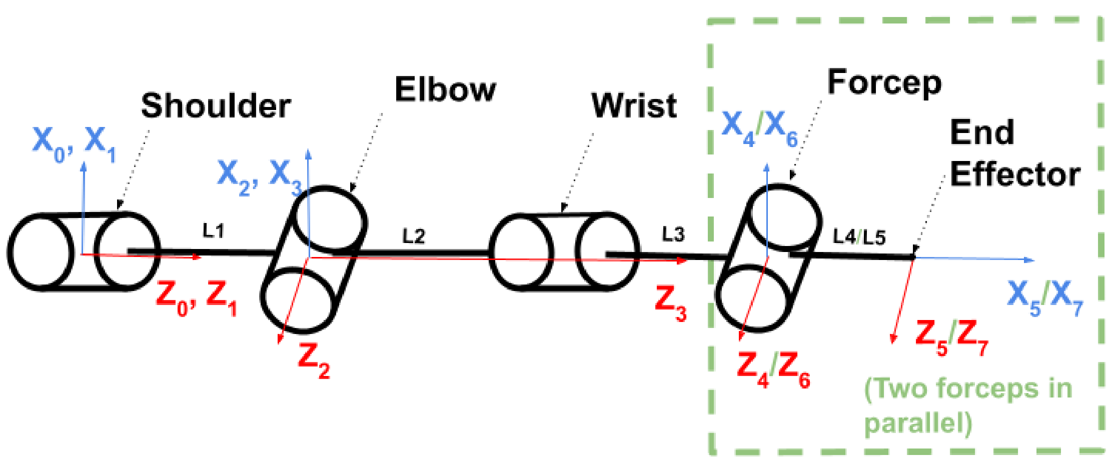

Figure 4.2: Kinematic diagram of the instrument.

Fig. 4.2 shows the kinematic layout of the surgical instrument. The shoulder is attached to the base plate, which is the end attached to the manipulator. Since the robot uses a forceps tool, and each end of the forceps is controlled independently through an actuator, the system has two end effectors. For simplification, only one side of the forceps is drawn. In practice, the program solves for each end effector position separately. Despite being a 5-DoF system, only 4-DoF need be considered for kinematic analysis. The positions of each end effector are expressed in reference to frame 1, which is the base frame of the surgical instrument.

Base plate

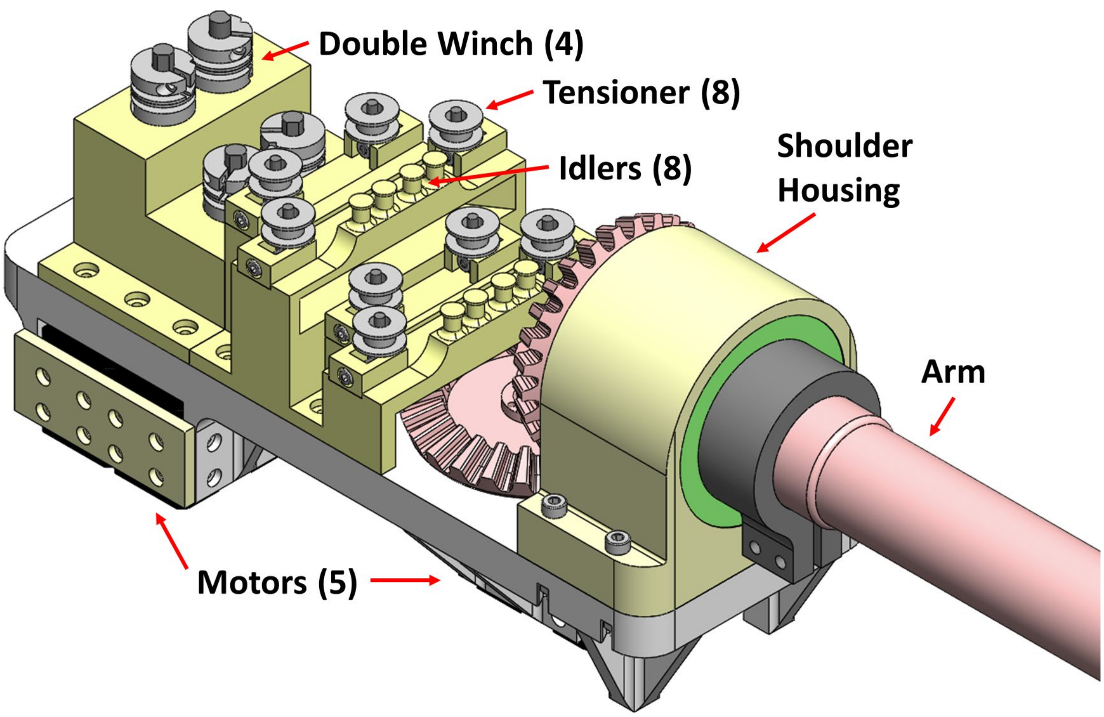

Figure 4.3: Isometric view of base plate.

The tool has five joints that allow it to achieve its range of motion. These joints are referred to as the shoulder, elbow, wrist, and inner and outer forceps, as shown in Fig. 4.1. The joints are operated by motors fixed to the bottom of the base plate. The design uses gears to drive the shoulder roll, and tensioned cables to drive the other four joints (Fig. 4.3). Every motor is equipped with a clamping hub and D-shaft to transmit torque.

The shoulder is driven through bevel gears (Fig. 4.4). The shoulder completes 85.7% of a revolution for every revolution of the driving motor, determined by the ratio of teeth between their two corresponding gears G1 and G2: G1/G2 = 24/28 = 0.857. G1 is fixed to its shaft with a clamping hub, ensuring rotational motion from the shaft is translated into the gear. The shoulder is supported by a housing and held in compression with a clamp. Axial bearings are located on either end of the housing to support the axial load, while radial bearings are embedded within the housing to support the radial load.

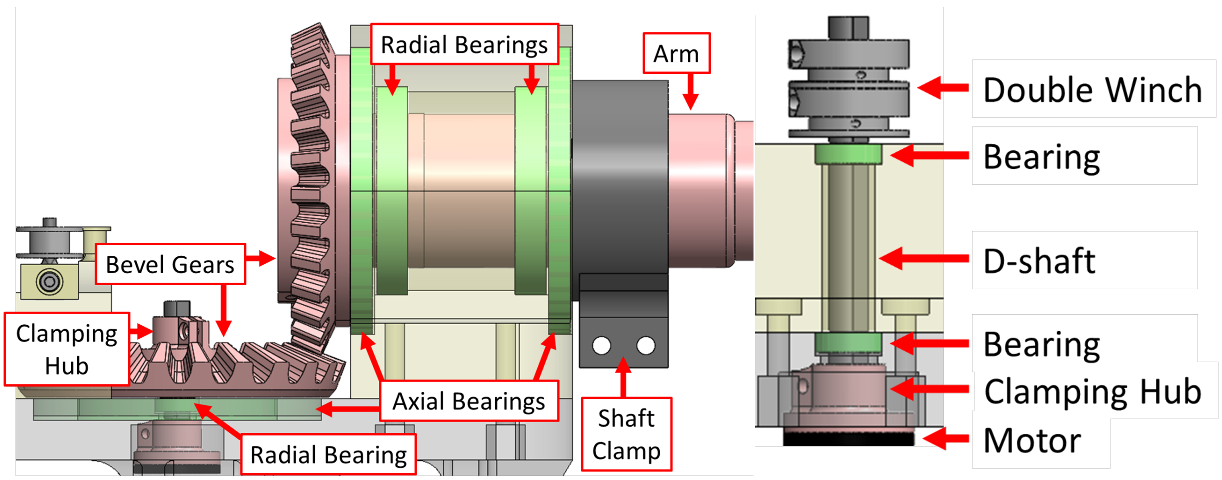

Figure 4.4: Side views of shoulder (left) and driving shafts (right)

The other four joints are cable-driven, with each cable's driving shaft being supported by two bearings to handle the radial load. There is also a double winch system clamped at the top of each shaft (Fig. 4.4). This system allows large magnitudes of tension to be applied on the cables wound in opposite directions around their winches. When the shaft rotates, one spool unwinds while its counterpart winds, increasing tension in one end of the cable and driving the cable loop in that direction. This system also enables each end of the cable to be independently tensioned using their respective tensioner and idler mechanisms. A fully-tensioned system allows for precise cable movement, and therefore, precise actuation of each joint.

Each cable loop passes from the driving shaft to the joint and returns, passing through the tensioning system in both directions. The tensioning system consists of tensioners and idlers for each side of the four cable loops. The tensioner consists of a free-spinning pulley on a dead axle, capable of translating along one axis to adjust the length of the cable loop, and therefore, tension. The idler is used to position the cable to enter or exit the shoulder (Fig. 4.5).

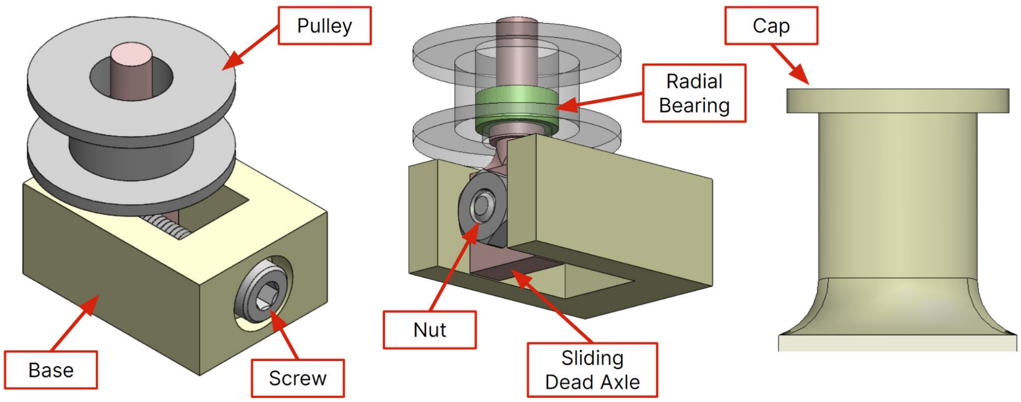

Figure 4.5: Tensioner (left) and idler (right) design

Each cable is routed to have its own independent path, unobstructed by other cables or components (Fig. 4.6). Furthermore, the cables are routed on two different heights (Fig. 4.7) to allow for straight cable paths into the arm, reducing entanglement on the base plate.

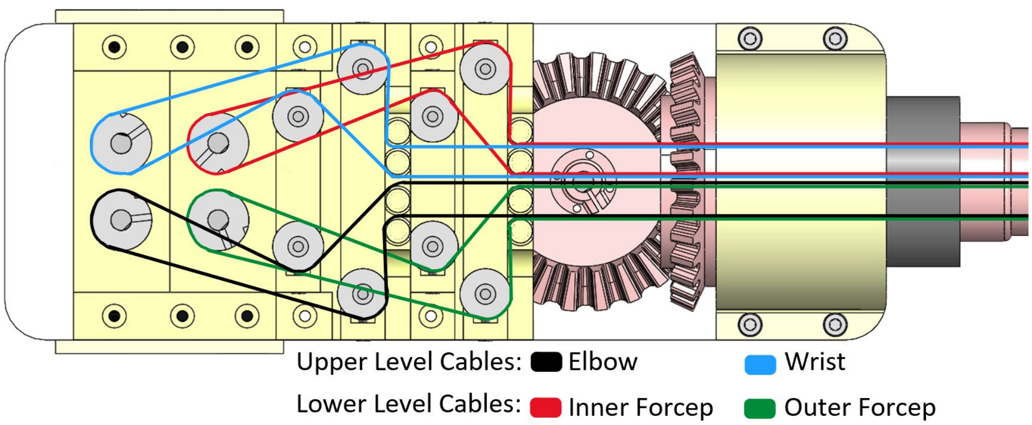

Figure 4.6: Top view of cable paths on base plate

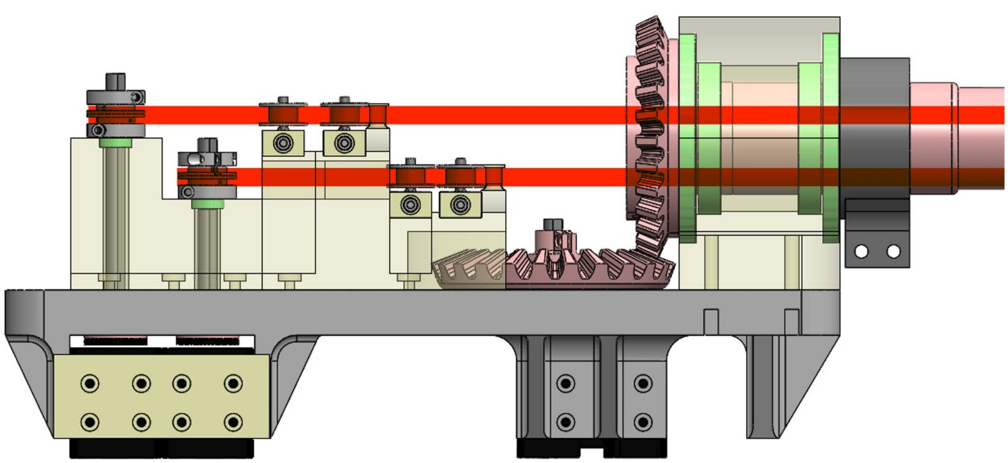

Figure 4.7: Side view of cable paths on the base plate

Large components in the base plate subsystem were fabricated using FDM printers with PLA. Meanwhile, smaller components requiring fine detail and high strength such as the clamping hubs, double winches, and tensioners were fabricated using resin printers. The D-shaft, bearings, and fasteners were standard, externally-sourced components. For this prototype, the cable is a polyethylene braided fishing line rated for 50 lbs. The final base plate prototype is shown in Fig. 4.8.

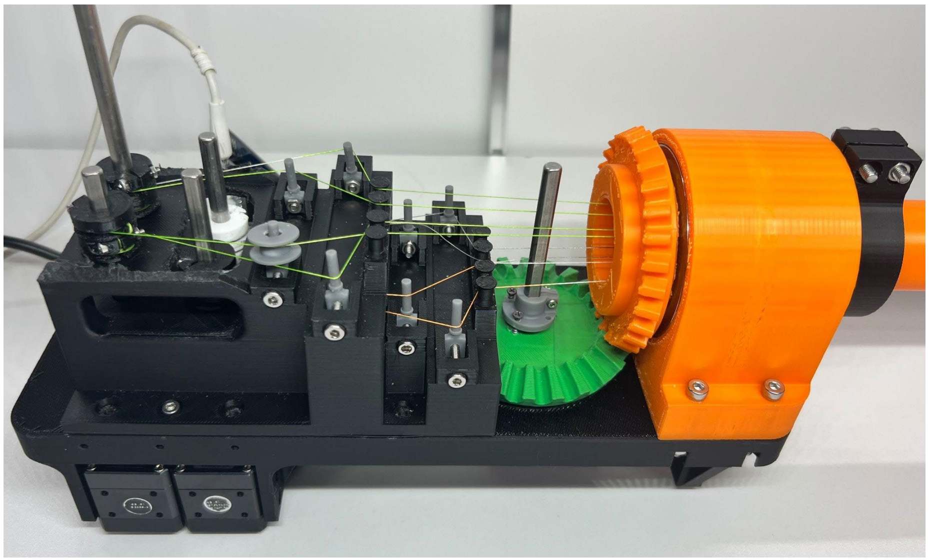

Figure 4.8: Final base plate prototype

Elbow

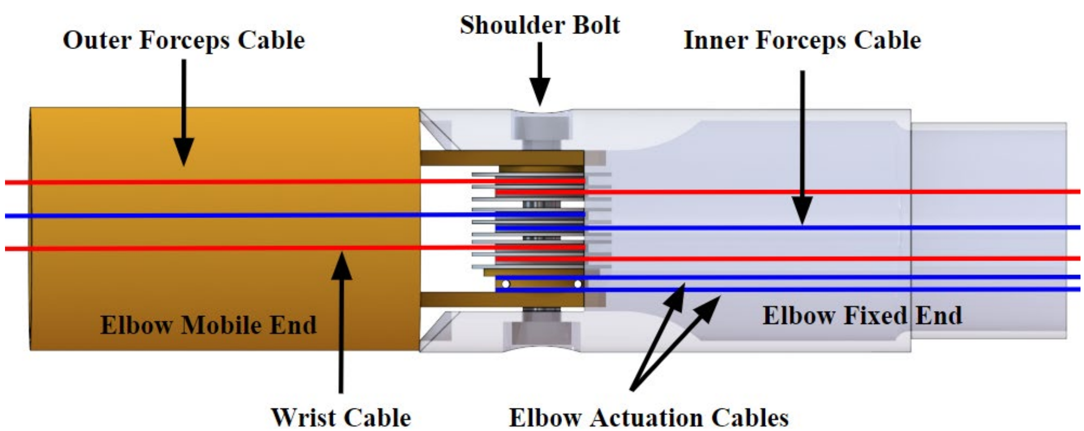

Figure 4.9: Elbow top down view with transparent fixed end. Pulleys in the center for organization of the cables needed to actuate the wrist and forceps.

The tool controls the pitch of the end effector through the actuation of the elbow joint. The elbow has two main components: the fixed end and the mobile end. The fixed end, depicted in gray in Fig. 4.9, connects directly to the shaft actuated by the shoulder. The fixed end is secured such that movement of the shoulder corresponds to movement in the elbow. The mobile end connects to the wrist and forceps through a pressure fit. The fixed and mobile ends of the elbow attach with a shoulder bolt located at the proximal end of the elbow's fixed end. The mobile end has radial bearings nested in the extrusions used to fix it to the bolt. Additionally, three free-rotating pulleys with nested bearings are attached to the bolt to assist with tensioning and organizing the cables for the wrist and forceps. These pulleys are each separated by a central wall to have two separate channels to control the location of both halves of the cable responsible for the joint actuation.

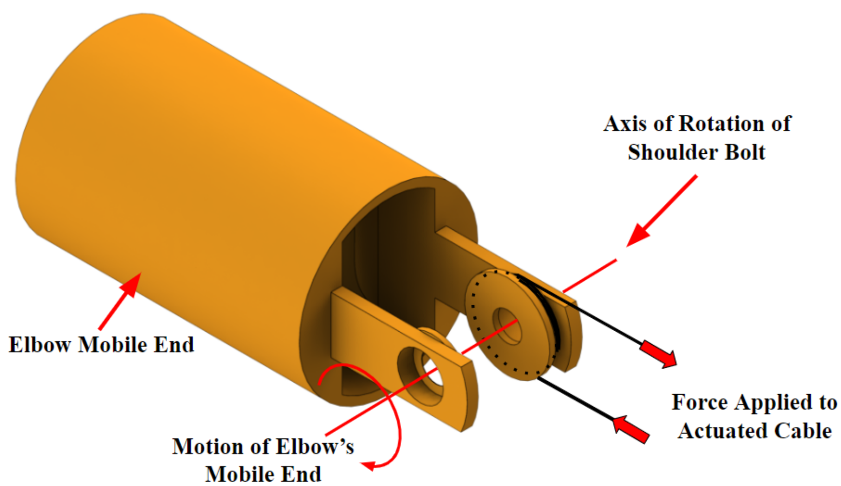

Figure 4.10: Isometric view of the mobile end of the elbow.

Wrapping each cable routed through the elbow around an axle is necessary to maintain tension in the cables for the wrist and forceps. As the elbow moves through its workspace, the cable length needed to actuate the wrist and forceps changes. Wrapping the cables around a central axle fixes the cable length between the base plate and the axle. When the cables wrap around the axle, any additional length change the cable needs will result from winding or unwinding around the pulley while keeping the cable in tension, as depicted in Fig. 4.10. Having the pulleys and the mobile end rotate about the same axis of rotation limits the amount of string elongation that occurs when the elbow actuates, as no additional offset distance is added to the cable when it moves through its workspace.

The elbow actuates using cables fixed to the winch embedded in its mobile portion. A single cable is routed through the holes of the winch and secured such that there are cables of equal length on either side of the winch. Each cable is wound in opposite directions around the winch, showing cable tension and its corresponding rotation, thus creating a double winch. When one-half of a cable experiences tension, it imposes torque on the winch. Thus, the elbow rotates in the direction corresponding to the tangential tension force of the cable. The rotation of the winch also causes the other end of the cable to wind in the opposite direction around the winch. The elbow will remain fixed when both cables are in equilibrium and full tension.

Wrist Roll and Forceps

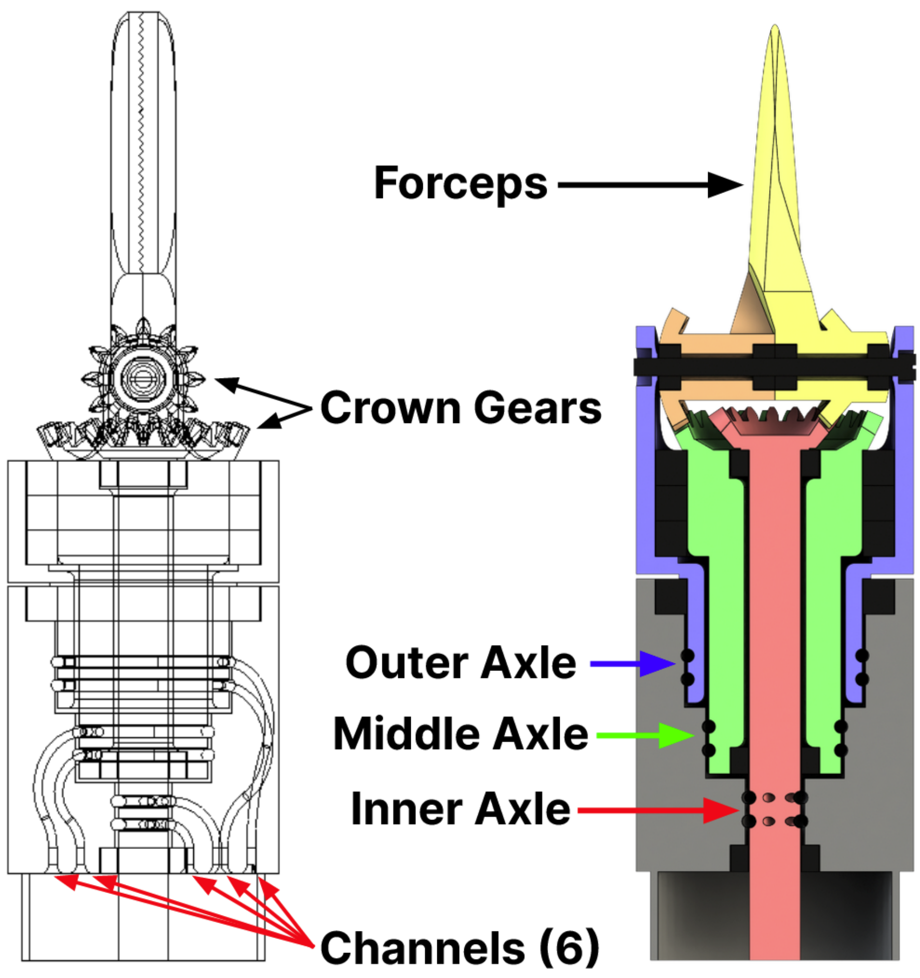

Figure 4.11: Wireframe side view (left) and cross section front view (right) of wrist roll and forceps.

Adopting the ability for a joint's axis of rotation to be collinear with its link surfaces is a fundamental challenge with cable-actuated serial manipulators and adds important capability to a surgical device. On a sufficiently short link, this motion will rotate, tangle, and elongate any cable loops that traverse the joint in the kinematic chain. In traditional serial manipulators, a slip ring can transmit electricity past such joints in the kinematic chain to power motors or other electronics. However, there is no equivalent to a slip ring to transmit mechanical power through tension force rather than electricity. This cable elongation issue is illustrated in Fig. 4.12. To solve this issue, the proposed design, depicted in Fig. 4.11, includes cable loops that terminate before wrist rotation.

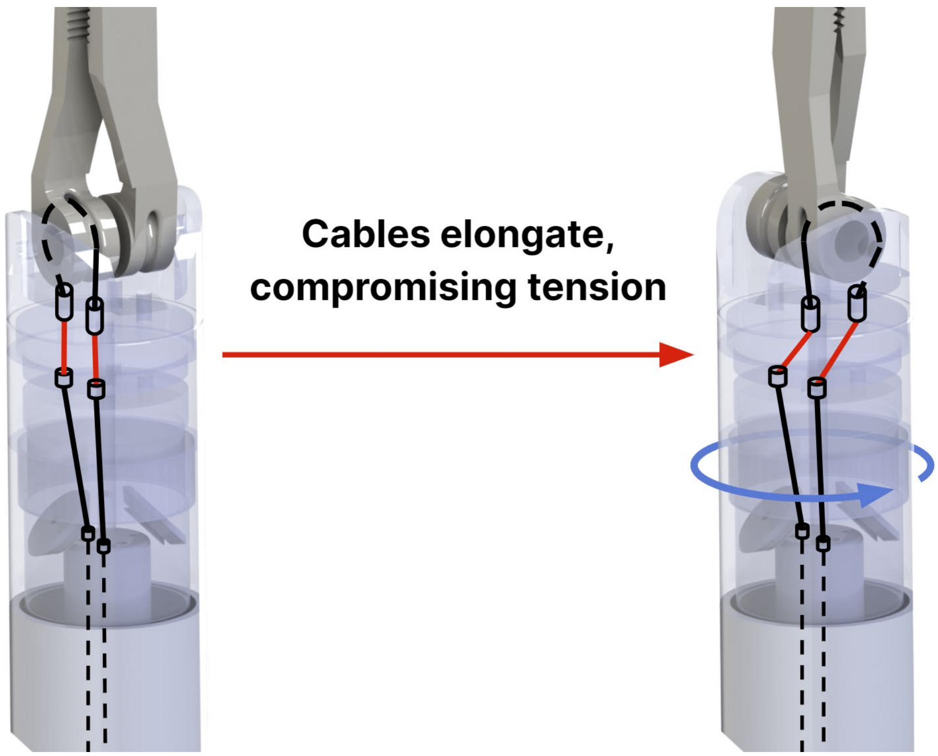

Figure 4.12: Cable elongation problem, illustrated when the wrist rotates from a properly tensioned position (left) to an elongated position (right)

This design terminates the wrist roll and both forceps' cable loops at the same stage, where they each transmit force to one of three nested axles. The outer axle, as shown in Fig. 4.11, is the part that holds and rolls the forceps. The middle and inner axles have a crown gear [24] on their opposite ends that mesh with a corresponding crown gear on each of the forceps, enabling their actuation.

This wrist roll and forceps architecture solves the cable loop twisting problem at the expense of introducing interactions with each of these degrees of freedom. As the wrist rolls, it orbits the forceps around their crown gears, actuating them along with the wrist. Fortunately, these interactions are straightforward to compensate for within control code.

Constraints of size, readily available bearings, and the method used to direct each cable to its respective cable loop primarily drove the implementation of the wrist roll and forceps systems. Larger 20mm ID bearings hold both the wrist roll and middle axles in place, despite their nested placement, to reduce part count and keep the design compact. 6mm bearings hold the inner axle to the middle axle and the elbow piece. 2mm bearings facilitate smooth rotation of the forceps.

As seen in the wireframe side view of Fig. 4.11, channels direct cables from the elbow joint to tangentially join their corresponding double winches on the nested axles. These channels, achieved with resin SLA printing, have a nominal diameter of 1 mm and direct each cable to its respective winch.

The bearings, nested axles, and forceps are all fastened by dropping them into the outer axle forceps holder part and sliding a shoulder bolt through the forceps. The shoulder bolt is secured with a captive nut and prevents any parts from sliding out of the assembly while also acting as the axis of rotation for both independently moving forceps.

This proposed design for wrist roll and forceps actuation effectively solves the challenge posed by wrist roll in a cable-actuated arm without compromising functionality or range of motion. Additionally, it can be manufactured with commercially available parts and ensures smooth motion with minimal friction.

Implemented Design for Manufacturability

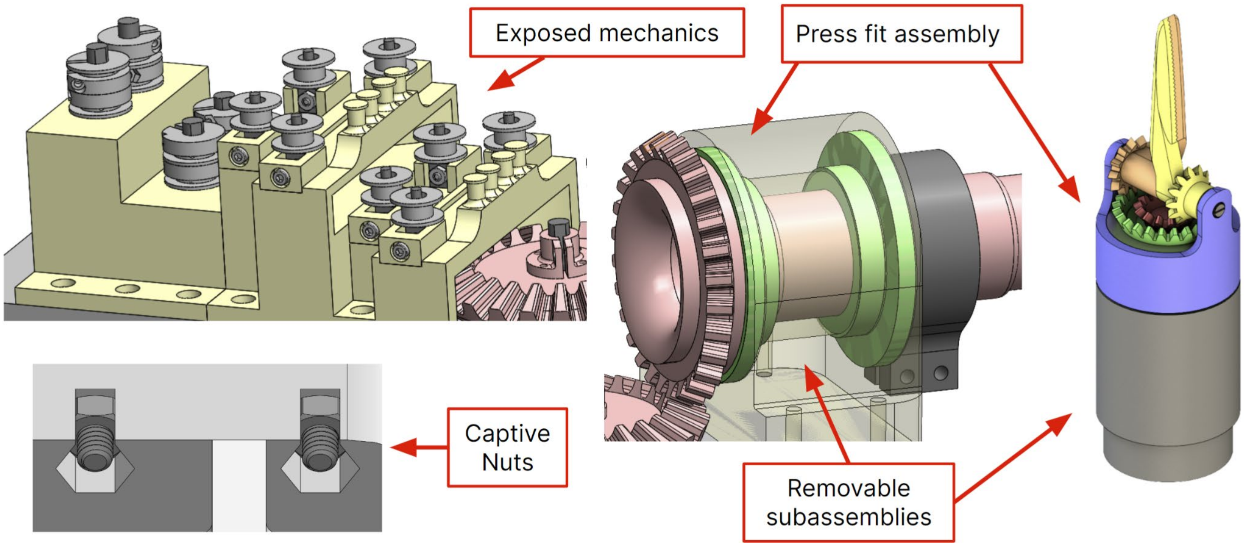

Figure 4.13: Examples of Design for Manufacturability (DFM) integrated into the instrument's design

The proposed design prioritizes easy manufacturing and assembly of the instrument (Fig. 4.13). One example of this is the exposed double winches, tensioners, and idlers on the base plate which allow the cables to be wired from the top. In previous iterations, these mechanisms were covered and the cables were wired through openings on the side, which made it difficult to set up and tension the cables. Another example is the use of captive nuts to attach components onto the top of the base plate. This method involves creating a recess corresponding to the size of the hexagonal nut on the bottom side of the base plate, toleranced to prevent the nut from spinning within the recess. As the bolt is rotated from the top, the captive nut is unable to spin and therefore, pulls itself up within the recess. Additionally, the nested gear and shoulder roll designs allow for their components to be press-fit into place. This technique reduces the number of fasteners required in these assemblies because components are held in place by other components. By designing these subassemblies such that there is only one way that they will fit together, it serves to error-proof the assembly process. Lastly, the use of subassemblies throughout the design allows for components to be manufactured, assembled, and repaired independently.

5 Kinematic Modeling and Control

With five degrees of freedom and actuators to control, this instrument requires a sophisticated control system to intuitively control its motion in surgery. A C++ program to control motor movements was developed. A forward kinematics model observes the current joint and cartesian space coordinates of the instrument. These models and programs were necessary to achieve complex motion such as compensating for forceps movement while rotating the wrist.

Design Interim Control System

Development of the mechanical prototype necessitates the development of a control system to verify design functionality. In this section, we discuss developing the mechanism's kinematic model & the implementation through a basic teleoperated control system for testing. The instrument was analyzed in accordance with the Denavit-Hartenberg or "D-H" convention to generate kinematic frames. These kinematic frames were used to compute a symbolic transformation matrix that relates the transformation from the first (base) kinematic frame to the end effector of one side of the forceps. This forward kinematic relationship calculates the pose of the robot for any joint-space position. Control of the robot is facilitated by the robust DYNAMIXEL low-level control libraries, but requires special consideration for certain joints, particularly the wrist roll.

Control Hardware & Libraries

The robot uses the coreless DYNAMIXEL XH430-W350-R motors to actuate its joints. These motors were selected for their accessibility and low backlash (0.25°). The Robotis OpenCM 9.04 microcontroller controls the motors with its associated expansion board, the OpenCM 485 EXP. The OpenCM 9.04 platform is favorable for its compatibility with the DYNAMIXEL product system, external power supply to power the motors, and accessible interface with the Arduino IDE. One major advantage of using DYNAMIXEL motors is support from the "Dynamixel2Arduino" library. This library provides tools to control each motor's torque response and kinematics, which are fundamental tools necessary for higher-level control systems. Having these tools immediately available allowed for development efforts to focus on kinematic and other control options.

Forward Kinematic Model

To analyze the kinematic relationships of the robot, we adhered to the D-H convention of frame assignment. The base frame, Frame 1, was first chosen arbitrarily with the z-axis along the joint. To assign subsequent frames, we followed the D-H methodology of identifying the joint axis and their common normal vectors. Ultimately, we identified 6 frames. Frame 1 is the base frame at the center of the shoulder joint. Frame 2 is located in the elbow. Due to the orientation of the wrist joint, Frame 3 also has its origin in the elbow joint of the robot. Frames 4 and 6 are in parallel, and exist in the same point, but attached to different joints. Each of these frames is attached to one half of the forceps, and as discussed in section 3.3, offer no differences between their transformation outside of the joint variable. Frames 5 and 7 correspond to each of the robot's two end effectors at either end of the forceps.

Forward kinematic modeling is a key and often first step in kinematic modeling of a mechanism. The forward kinematic model analyzes the current angular positions of each joint and calculates the pose of the end effector in the workspace. To do this, we need to make use of transformation matrices. These transformation matrices relate the transformation between one frame and the other, including smaller discrete elements, such as the following frame's cartesian position and rotational orientation, to ultimately describe the pose of the next frame in reference to the current frame. Using MATLAB to assist with computation after solving a generic form, transformation matrices were generated to relate each kinematic frame with respect to the one before it in the kinematic chain.

These intermediate transformation matrices are then multiplied to create a transformation matrix from the first kinematic frame to the last in the kinematic chain. In the case of this instrument, this transformation matrix describes the pose of the end effector in relation to the base frame at the center of the shoulder joint. This process was then repeated a second time to generate a second transformation matrix for the second end effect at the other half of the forceps. Since the robot has two end effectors, forward kinematics must be calculated for each one to completely describe the pose of the system.

Forward kinematic modeling is a useful testing tool due to its ability to analyze each joint's current angular positions and calculate the end effector's pose in the workspace. Using the MATLAB symbolic toolbox, we calculated the homogeneous transformation matrix for the kinematic chain by obtaining intermediate transformation matrices from the D-H parameters in Table 5.1.

Table 5.1: D-H Parameters

Link	θ	d (mm)	a (mm)	α
1	θ_1*-90°	L_1	0	-90°
2	θ_2*	0	0	90°
3	θ_3*	L_2+L_3	0	-90°
4/5	$\theta_{4/5}$*-90°	0	$L_{4/5}$	0°

Afterward, the position vector expressions were implemented in C++ so the OpenCM microcontroller could calculate the cartesian positions of each end effector. Eqs. (1) to (3) calculate the cartesian end effector positions, shown with abbreviations for trigonometric functions and joint variables, (e.g. $c_1 = \cos(\theta_1^*)$). While a simple analysis, this model provides the operator with a tool to test the accuracy and precision of system motions.

$$x = c_1s_2(L_2+L_3)-L_{4/5}c_{4/5-90}(s_1s_3-c_1c_2c_3)-L_4c_1s_2s_{4/5-90} \quad (1)$$

$$y = L_{4/5}*c_{4/5-90}(c_1s_3+c_2c_3s_1)+s_1s_2(L_2+L_3)-L_{4/5}s_1s_2s_{4/5-90} \quad (2)$$

$$z = L_1+c_2(L_2+L_3)-L_{4/5}c_2s_{4/5-90}-L_{4/5}c_3s_2c_{4/5-90} \quad (3)$$

The simulator shown in Fig. 5.1 shows the results of the kinematic model.

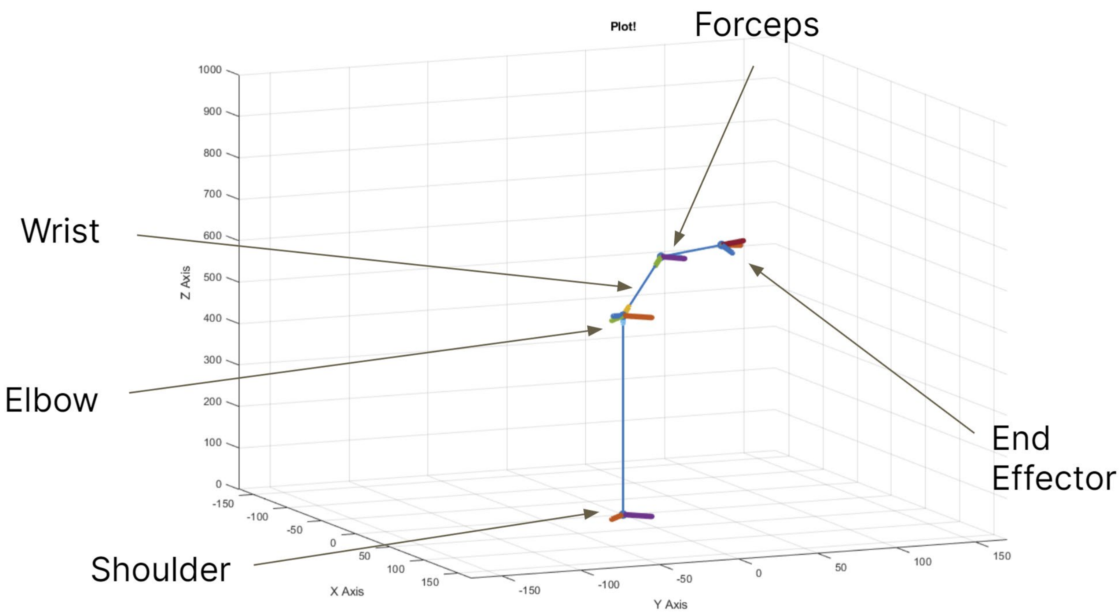

Figure 5.1: Kinematic simulator

Control

To test the robotic instrument, a teleoperated control program was created in C++ to run aboard the OpenCM 9.04 microcontroller. The program offers several different operations and utilities for testing purposes. Most valuable of these are the position control modes. First, a joystick-style motion control mode to step the positions of each joint in small increments. This mode can help the user visually manipulate the instrument into a certain pose. Additionally, the position input control mode prompts the user for a target joint position and then actuates the selected joint to the specified angle. Moving the joints of the robot is the core functionality of the program.

While the DYNAMIXEL libraries facilitate moving the instrument's joints, the program still must model the transmission ratios to each joint, as well as other "compensation" to account for non-independent motion. In the case of the wrist-forceps assembly, the program compensates for the motion of the wrist by moving the forceps' crown gears at the same rate. Preventing relative motion between the forceps' crown gears and the wrist link is critical to avoid undesired position change.

Another place compensation motion is necessary is the elbow. In Fig. 5.2 below, the green cable represents one of three that pass through the elbow to drive the forceps and wrist. Despite the idler pulley in the elbow, motion in the elbow still causes the string loop (closed with the pink dashed line for reference) to shift. The amount it shifts, highlighted in red, must be accounted for as motor compensation. Since the program does not use external sensors and instead relies on the motor encoders to measure joint position, the compensation factor is necessary to convert between joint and motor positions while avoiding unwanted motion.

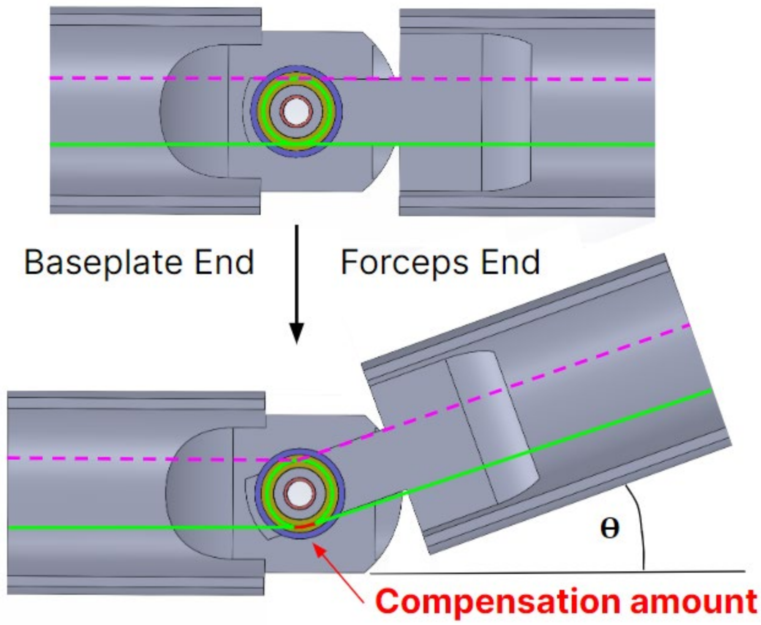

Figure 5.2: Visual representation of cable length compensation in the elbow joint.

6 Experiments and Results

Tests were designed to qualify and quantify the performance of this instrument prototype. The prototype produced numerous observations to gain insight into the nature of this design. All five joints demonstrated independent functionality and met or exceeded range of motion and precision expectations. These tests measured the extent to which this prototype performed.

Validation

The shoulder roll is limited only by the number of rotations allowed before the cables are fully entangled and fail. Ten consecutive rotations of the shoulder in the same direction did not limit the functionality of the cables or subsequent joints. The elbow joint rotated accurately up to its mechanical hard stop at around 90 degrees. The wrist roll is limited in its range of motion by the number of winds that can fit within the internal channels on its double winches. The wrist roll demonstrated two full rotations from its prototype. Both forceps are capable of reaching their mechanical hard stops, regardless of the wrist roll's position.

Individual Joint Testing

Each degree of freedom underwent individual testing to assess their accuracy. A position θ, representative of the edge of each joint's relevant workspace, was determined. For example, the elbow has a mechanical hard stop at around 90 degrees. Therefore, 80 degrees was selected to sufficiently measure both undershoot and overshoot up to 10 degrees. All joints began their testing by starting at a neutral position in the middle of their range of motion (0 degrees). Then, the joint was commanded to the goal angle of θ, back to 0, to $-\theta$, and finally back to 0. This experiment was repeated five times per joint. The observed angle of the joint at each goal angle was measured to determine the accuracy of the mechanism and software tuning as shown in Fig. 6.1. The value of θ for each joint is as follows in Table 6.1.

Table 6.1: Value of θ in degrees used for testing each joint

Joint	Shoulder	Elbow	Wrist Roll	Outer Forcep	Inner Forcep
θ	180°	80°	90°	80°	80°

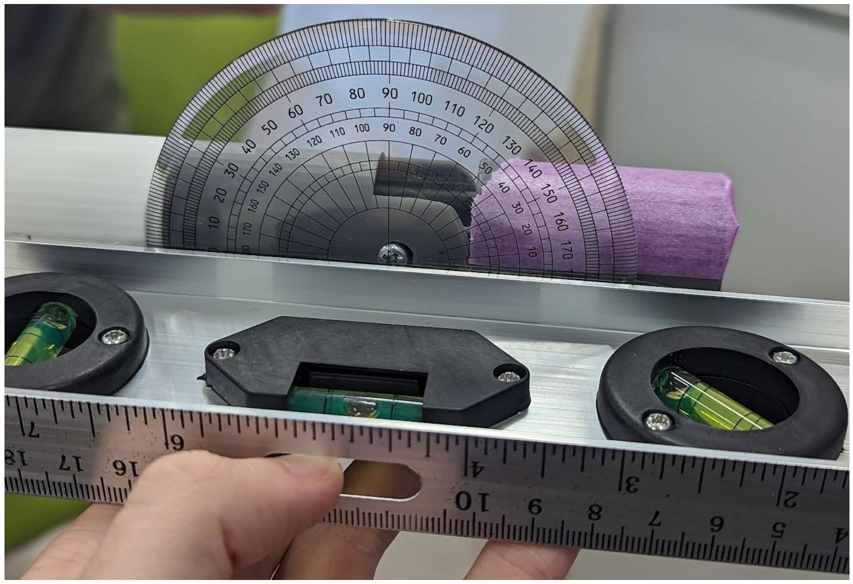

Figure 6.1: Individual joint testing setup

The results of this testing showed varying accuracy among joints. Fig. 6.2 communicates the average percentage error between the goal position and the actual position of each joint. The wrist and shoulder demonstrated the highest accuracy, with 0.50% and 0.58% errors, respectively. The elbow and inner forceps displayed lower accuracy, with 2.61% and 2.89% errors, respectively. The outer forceps was the least accurate, with an error of 5.61%.

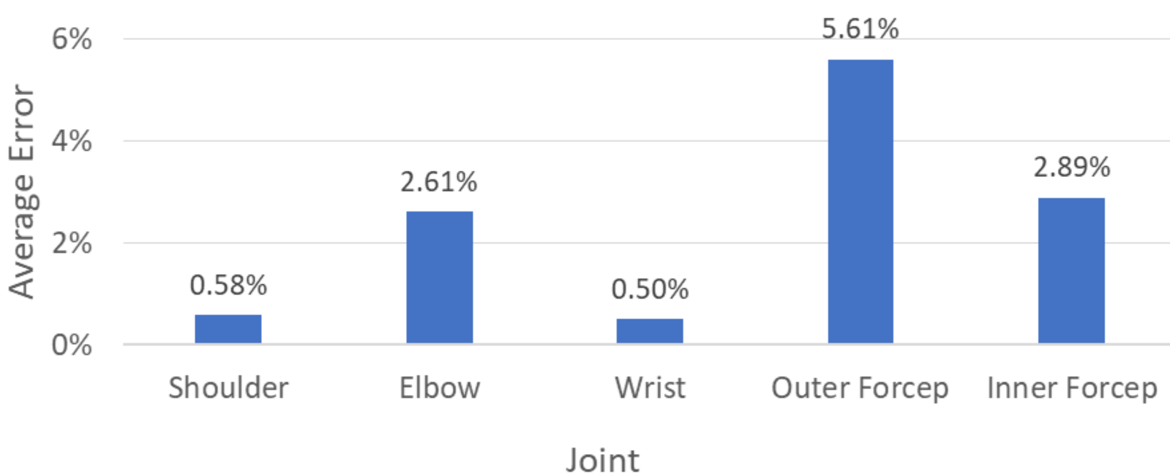

Figure 6.2: Average error of each joint goal

Wrist Roll Compensation

Due to the nested axle design of the forceps and wrist roll mechanism, rotating the wrist requires compensation to ensure the forceps do not change position, as discussed earlier. A grape was placed in the grasp of the forceps, and a 180 degree rotation was commanded. This test, pictured in Fig. 6.3, was successful; the grape rotated without translating and the forceps maintained a firm grip on the grape.

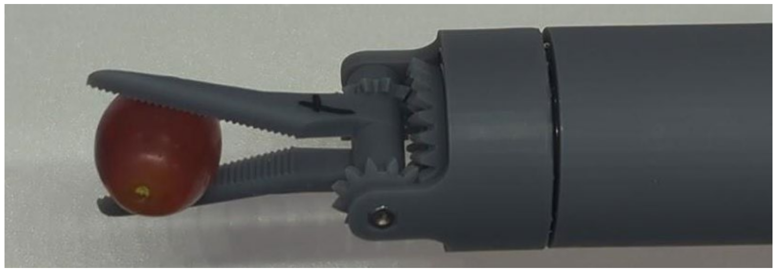

Figure 6.3: Wrist roll compensation test with grasp.

System Testing

All five joints were connected and tested using the control algorithms validated previously. When routed around the pulleys in the elbow, the cables responsible for wrist and forceps actuation remained in tension despite the angle of the elbow. The tool had the ability to grasp a grape and manipulate it behind an obstructing object by actuating the shoulder, as seen in Fig. 6.4. This validated how the tool would distally remove the grape without contacting the obstruction. The tool grasped and moved the grape without releasing or crushing it through its entire motion.

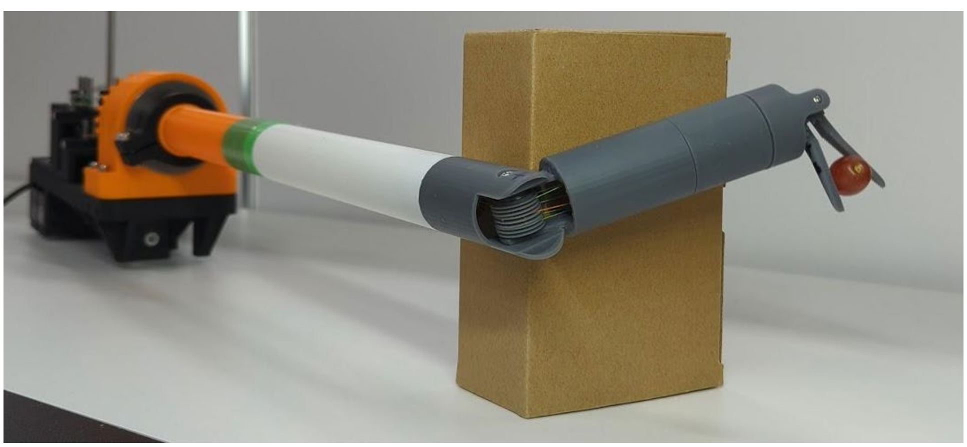

Figure 6.4: Device manipulating a grape behind an obstacle.

During system testing, a phenomenon was identified in which actuation of the forceps sometimes caused actuation of the elbow. The identified relationship limited the tests of this specific prototype, and potential reasons for this correlation are expanded upon in the discussion.

7 Discussion

Being a seven-week project conducted abroad in Kyoto, Japan, the timeline and logistics of the project were an exciting challenge to overcome. This section discusses achievements and limitations from the project. This discussion also advises next steps for future work.

Design Limitations

A primary goal of the project was to achieve the desired mechanical performance of the prototype, and therefore most of the project's development time was allocated to the redesign, prototyping, and assembly of the instrument. Innumerous improvements were implemented and problems were solved throughout the development of the project. However, limitations in the mechanical performance of the prototype were inevitably affected by the short development time. The largest unresolved issue with the prototype was the non-independence of the elbow with the forceps and wrist joints when it was not held down. Friction in the closed loop transmission cable geometry between the elbow and forceps and the compressed, coaxial pulley stack on the elbow axle led to unexpected coordinated actuation of the elbow with the wrist and forceps. Concern over the cable geometry and design was identified early in the project development, and modeling the relative motion of the joints in the control system to was planned to compensate for friction. While this compensation would seemingly overcome the foreseen challenges, the pairing of these joints due to friction meant that this relationship could not be compensated for with control software. In testing, when the elbow moves, it performs well for a limited number of degrees, but as the backlash is overcome in the wrist-forceps loop, it introduces friction in the cables that causes the forceps and wrist to actuate unpredictably. Although it may be possible to implement additional sensors to measure friction and correct this error, a mechanical solution would likely be better to implement. Because this issue was discovered in the project's closing weeks, it remains its primary limitation. Addressing this limitation should be a primary focus of future work on the instrument.

Another potential issue was identified in the shoulder joint of the instrument. Since the pulleys at the elbow rotate along with the shoulder, but the winches on the base plate remain stationary, the cables will entangle with each other at a singularity in the center of the elbow after the shoulder rotates 45 degrees. Additionally, like the issue identified with the shifting loop length of the wrist, the shoulder too will cause the transmission loop lengths to shift. However, the shifting length of the cable did not affect the performance of the prototype. It was found that both the shifting loop lengths of the shoulder and the entanglement of the cables were not present to the prototype's performance. After rotating the shoulder by 10 full rotations, all cable-driven mechanisms functioned identically to how they had before. However, future prototypes with reduced backlash, higher cable tension, and more rigid cable materials may find this problem to be a point of failure. It may be possible to affix the motors and winches to rotate with the shoulder, removing the twisting motion that causes the cables to entangle in the shoulder link in the first place. Future work improving the design should consider the significance of this problem and explore solutions as necessary.

Using the cable loops to drive joints two or three joints down the kinematic chain (from base plate, through the elbow, to forceps, for example) introduces significant challenges. It may be worth considering radical design changes, like introducing more motors to control each joint's winch directions independently as well as the length of the cable loop, changing the kinematic structure of the instrument, or exploring alternatives to cable-based transmissions altogether.

Mechanical Performance: Material and Manufacturing Limitations

While the use of rapid prototyping methods and materials enabled efficient design iteration, it led to mechanical performance challenges when testing the instrument. The design was produced with off-the-shelf nuts, bolts, bearings, and fishing line; SLA resin 3D printing; and FDM 3D printing. The design emphasizes the alignment of motion axes due to the serial kinematic design and numerous transmission axes. Slight deformation of assumed-rigid materials in this design introduces friction, wear, and inefficiency that may have limited the mechanical performance of the entire prototype. While this is an important consideration in any design, the exclusive use of rapid prototyping materials amplified these factors, resulting in a more significant impact. Future iterations of this surgical device should be manufactured with higher strength and precision metals and composites to overcome these mechanical challenges.

One of the largest challenges presented was keeping the device consistently and properly tensioned. Due to deformation and slipping, the design was unable to keep high tension in the transmission cables, especially during and after motion. One specific area identified was the motion hubs used to fix pulleys to the driven shafts. Both 3D printed set screw and clamping designs failed occasionally due to the high torque and stress exerted between the motor and the high-tension transmission cables. Metal hub components were unable to be sourced readily in

Japan, and the mechanical performance did not reach its potential as a result. Additionally, the process of setting up the tensioned cables was extremely time consuming and required substantial practice. One method to improve this process is to use pre-wound cables attached to fasteners that could be directly attached onto the base plate and tightened with a torque wrench.

While many aspects of DFM were implemented into the instrument design, additional aspects may be implemented to improve the design. For example, the design employed exposed mechanics for easier access during assembly, modular design to enable independent workflows, and press-fit assembly to reduce the number of fasteners and integrate error-proofing. Additionally, the team aimed to minimize the number of components, use standard components whenever possible, and avoid high tolerances. However, there are some aspects of DFM that require improvement in our design. For example, there is a high number of nuts and bolts in our design that could be replaced by tabs or snap fits to reduce the assembly time and total number of parts. Additionally, some components such as the long arm were divided into multiple components exclusively because of the size constraints of the 3D printers. Furthermore, there are many different sized fasteners used in the design, and these could be standardized to prevent assembly errors caused by using the incorrect fastener.

The design of this instrument, even when at an enlarged prototyping scale, necessitates a high level of performance and precision in assembly, alignment, and rigidity. These metrics are very difficult to obtain with the prototyping materials used and could be greatly improved by refining the tensioning system and implementing additional aspects of DFM. Future work on this project should consider alternative materials and manufacturing strategies to overcome these challenges.

Control Limitations

One area of the project burdened by the development timeline was the control system implementation. Planned and abandoned features once included inverse-kinematic control, additional motion compensation due to the non-independent nature of the later joints in the kinematic chain, macro commands to pick up objects in the workspace, and related experiments and results to validate these features. While some features, like inverse kinematic analysis, saw some success, shifting focus due to project goals and development time cut them from being implemented in the final product. The challenges of rapidly developing a functional prototype led to a limited amount of time to test, tune, and validate the control system once envisioned for the instrument. The experimental results and variance between different joint performance are due largely to poor tuning of control variables and the relatively simplistic strategy implemented to control them.

The control system used encoders on the motors at the base plate, leading to unaccounted for backlash. To calculate joint position, it measured the winch position and modeled the entire transmission. While theoretically sound in a perfect system, this measurement system cannot correct for backlash. Implementing additional sensors, especially joint axis encoders, would open new possibilities for control system correction of mechanical and design deficiencies. Particularly, they may allow for modeling and correction of not only the system's backlash, but the friction-induced unwanted motion between the elbow and wrist-forceps assembly. Future work on the kinematics and dynamics of the instrument is recommended to explore adding new sensors and implementing higher-level, data-driven control algorithms to address these issues.

Considerations for Surgical Application

Consideration must be given to size, material, and bio-compatibility for surgical applications. While the tool's arm diameter is within the useful range for minimally invasive surgery, miniaturizing the diameter would enable the arm to be used in additional surgery types requiring smaller incisions. Stronger, biocompatible materials that are able to withstand sterilization within an autoclave must be used on any instrument that is used in surgery multiple times. These considerations are extremely important to keep in mind when furthering the development of any aspect of a surgical instrument.

The arm that this device would be compatible with would need to be an arm that was designed to be mobile within the reasonable scope of a hospital. Additionally, it would need actuators designed specifically for MIRS and a simple but robust RCM. The arm would need to be easily sanitized and comfortable for surgeons to use it practically. Ideally the initial costs and actuation cost would be as low as possible for the low barrier of entry.

Our team believes the Al Zwhari Manipulator developed by Nisar et Al. (2019) fulfills the maximum amount of these requirements. The system is a reasonable size, cost effective to run and use, and has motors selected for the application. Its primary limitation is that, similar to this instrument, it has limited testing such that it was developed in a research lab and has not been used in a clinical setting.

8 Broader Impacts & Ethics

Surgical robots have an impact on people that spans across multiple walks of life. Bringing a surgical instrument to market has huge economic implications both with upfront investment and competition in the field. The roles of surgeons and nurses change when a robotic instrument revolutionizes surgical operations. The outcomes of patients profoundly impact real peoples' lives. With the great impacts that a robotic surgical instrument can have, it is imperative that the broader impacts and ethical ramifications of its development and use are considered.

Economic Considerations

Introducing robots to the workforce often entails considerable economic considerations and repercussions. When creating technology for the healthcare industry, there is an incredible moral value to reducing the cost of care so it can benefit the greatest audience. The goal of this research is to democratize MIRS by creating a functional prototype that is affordable. Producing a robot that has the functionality to complete its task effectively while simultaneously being easy and cost-effective to manufacture would allow more doctors access to the technology and thus treat more patients. Additional complications arise when you consider the cost of making a fully commercially viable prototype. In the final design's fabrication process, steps should be taken to select materials that will be both viable and cost-efficient.

Ensuring Patient Safety

Creating a design that implements fail safes and safety mechanisms to best ensure patient safety is of monumental importance when developing a surgical tool. Our team must take steps to reduce the possibility of creating inherent inadvertent biases through the design. To achieve this goal, it is important to consider all types of patients that the device may operate on and cater testing to the intended versatility.

Creating a device that operates with any level of autonomy has clear ethical implications. As engineers, we must take steps to reduce the possibility of mechanical malfunction. One method to do this is to follow the steps of the scientific method and not implore any unnecessary shortcuts that will devalue our design. Additional patient concerns become a larger factor as the machine approaches a functional clinical state. Additionally, we will consider potential ways in which the security of the device and the patient could be at risk. For example, if the device has the capability to record surgical data, we must address how that information would be stored and used. If patient health information is revealed during a procedure, we would need to consult the relevant HIPPA laws to ensure the patient's confidentiality.

Potential Impact on Healthcare

Broadly speaking, a commercial device could have overwhelming impacts on the medical community. Increasing the success rate and recovery time of surgery is one of the most prominent ways this device could impact the global community. Additionally, it could expand surgeons' accessibility by introducing opportunities for safe remote surgery. Remote surgery would allow doctors to perform life-saving medical procedures in real-time without being physically present. Removing doctors from the operating room can also reduce their exposure to harmful radiation and chemicals that may cause health complications in the future.

However, there is also an ethical consideration in dehumanizing medical practice. As robots take a more prominent role, the ability of a surgeon's experience and intuition to prevail when faced with new environments can fall short with autonomous systems. Therefore, standardized robot-assisted medical training, proper safety procedures, and training medical staff on how to recover or abort a robot-assisted surgery are required to conduct these operations.

9 Conclusion

To further the capabilities of MIRS, a prototype 5-DoF surgical instrument with novel kinematic layout is proposed. After being developed in multiple iterations, the motion proficiency of the final prototype was tested to validate the design and identify areas for future improvement. This architecture for a MIRS instrument shows strong promise, offering a compelling alternative to current designs with its distinct kinematic layout.

This 5-DoF robotic surgical instrument aims to eventually lead to improved surgical outcomes. Its enhanced dexterity and ability to work around obstacles hold promise by enabling minimally invasive access to previously inoperable areas, potentially enhancing surgical approaches and reducing reliance on extensive incisions. This translates to faster patient recovery, lower healthcare costs, and a potential for broader societal benefits through improved patient quality of life. While challenges remain in engineering, cost, and regulation, the instrument has the potential to provide another option for minimally invasive robotic surgery and contribute to a healthier society with further development.

10 Reflection

Following the completion of the project, the team met in retrospective meetings to reflect on the design process, limitations considered, research methods, and teamwork.

Design: Throughout the seven week project, the team embraced the "Fail Fast" design philosophy by continuously implementing design changes into new prototypes. This method helped us quickly identify various fundamental flaws in early prototypes, giving us time to resolve the problems in later prototypes.

Constraints: While our main goal was to achieve functionality, limitations relating to manufacturability and application were considered. Design for manufacturability principles heavily impacted design choices, and our limited rapid prototyping methods restricted the strength of the prototype. The instrument is designed for surgical application and therefore all materials on the arm must be autoclavable, and the arm must be able to enter a human and perform the desired operation.

New Knowledge: Team members acquired knowledge relating to design methods, CAD software, fabrication methods, control systems, and working in a research laboratory. Common methods used to acquire this knowledge include literature review and discussion with experts in the field, such as our advisor, Dr. Sajid Nisar.

Teamwork: Team members agreed to a project schedule, which was consistently reviewed and updated. The team held daily stand-up meetings to determine assignments and identify and resolve problems. Each team member led one subsystem, and tasks were distributed based on subsystem ownership. Tasks were then delegated by subsystem owners based on availability and individual strengths. Larger challenges such as design flaws or subsystem integration challenges were solved via team meetings as needed. Additionally, weekly progress updates meetings were held with the advisors.

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