Design and Modelling of a Miniature Instrument for Robotic Surgery

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science

Mechanical & Industrial Engineering
University of Toronto

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Master of Applied Science
Mechanical & Industrial Engineering
University of Toronto
2017

Abstract

The da Vinci® Surgical System, the world’s most prominent form of robotic surgery, provides significant advantages over conventional surgery yet currently it cannot be used for surgical applications involving small operating volumes due to the existing instrument sizes (5-8mm shaft diameter). This research explores the feasibility of creating and accurately controlling a robotic instrument with a 2mm diameter and a three degree-of-freedom wrist. A unique wrist joint composing of a two degree-of-freedom bending notched-nitinol tube pattern is developed along with a proposed kinematic model. A base mechanism for controlling the wrist is designed for integration with the da Vinci Research Kit. A basic teleoperation task is successfully performed using two of the miniature instruments. The performance and accuracy of the instrument suggests that creating and accurately controlling a 2mm diameter instrument is feasible and the design and modelling proposed in this work provides a basis for future miniature instrument development.
Acknowledgments

I am grateful to my supervisor Dr. James Drake and Program Director Thomas Looi at the Centre for Image-Guided Innovation and Therapeutic Intervention (CIGITI) for giving me the opportunity to conduct this research and for providing an environment that encourages learning new skills and contributing to multiple projects.

To Kyle Eastwood, for supporting every step of my research; from defining the project, to teaching me how to use lab equipment and providing endless technical advice. You were an ideal mentor during my master’s and I aspire to be as knowledgeable, creative and dedicated as you.

To Vivek Bodani, who offered invaluable clinical knowledge and experience and always provided a selfless perspective. Also, thank you for your extensive training on the da Vinci Research Kit and the continued support.

To all members at CIGITI, for supporting cooperation, teamwork and teaching each other new skills. Thank you also for providing support for my papers and presentations, as well as all our interactions that made my master’s so enjoyable.

To my family, for always supporting me throughout my education. I would not have achieved my goals without your ongoing support.

To Midori, for your endless love and encouragement.
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Chapter 1
Introduction

1 Introduction

1.1 Chapter Summary

This chapter reviews the history of robotic surgery followed by an in-depth review of the most prominent surgical robotic system today, the da Vinci Surgical System. Robotic surgery provides key advantages over conventional minimally invasive surgery through its teleoperation framework and wristed instruments. The current clinical applications of the da Vinci are limited to operations within adults in the abdomen and pelvis. Studies which have applied the da Vinci to applications involving smaller operating volumes than its current applications have reported on a common finding; the current instrument sizes are too large. This motivates the development of a smaller instrument which can be used on the da Vinci platform to ultimately provide the benefits of robotic surgery to more clinical applications. The da Vinci Research Kit is a surgical robotics research development platform which enables the customization of a retired clinical da Vinci system and will provide a method of testing the new custom da Vinci instrument. The criteria of the new instrument include a 2 mm shaft diameter and matching the capabilities of existing instruments.

1.2 Brief History of Robotic Surgery

Since 1961, with the introduction of the first industrial robot, Unimate, robotics has been used to extend the manipulation capabilities of humans. [1] The first use of a robot to assist in surgery took place in 1985 where the Unimation Puma 560 was used for the accurate and steady placement of a needle for brain biopsy. [2] Following the development of a telepresence system for space applications, SRI explored the concept for surgery in which a surgeon could observe and operate on a patient from a remote location, as if the surgical site was directly in front of them. [3] This led to further development with the specific goal of improving surgical capabilities on the battlefield by allowing the surgeon to operate from a safe distance. The first telesurgical procedure of this nature took place in 1994. [1] As this first telepresence surgical system was being developed, minimally invasive surgery (Figure 1) also started gaining significant interest due to its faster recovery times, reduced scarring and improved patient
outcomes. The advantages provided by the telepresence surgical system approach seemed to be a potential solution to the challenges associated with minimally invasive surgery, specifically the fulcrum effect, lack of hand-eye coordination, reduced visualization and ergonomics. [3] Further development of the telesurgical system led to the commercialization of multiple systems, with the da Vinci Surgical System developed by Intuitive Surgical emerging as the leader. In 2000, the da Vinci obtained FDA approval for general laparoscopic procedures and became the first operative surgical robot in the United States. [1]

Figure 1: Laparoscopic Surgery, a form of minimally invasive surgery whereby instruments and a camera are passed through small holes rather than creating a large incision as in open surgery. The challenges introduced include the presence of a fulcrum at the entry ports to the patient which reduces hand-eye coordination and the need for a 2D video image for visualization. Image from US Air Force by Samuel Bendet [Public domain].
1.3 da Vinci Surgical System

1.3.1 System Overview

The da Vinci Surgical System made by Intuitive Surgical Inc. is the current world leader in surgical robotics technology. In 2016, approximately 753,000 surgical procedures were performed with over 4,000 da Vinci Surgical Systems worldwide. [4] The da Vinci is based on a master-slave teleoperation framework in which the surgeon sits at the master console which can control a series of robotic arms positioned at the patient (Figure 2). The surgeon’s console consists of a stereo vision system, two robotic manipulators to track the surgeon’s hand and finger movements, and a series of foot pedals. The surgeon’s hand movements are mimicked by instruments positioned within the patient and attached to the robotic arms. The patient-side manipulators can pivot about the entry point to the patient’s body via a remote centre of motion. Various EndoWrist instruments with unique end-effectors can be rapidly interchanged on the patient-side manipulators. These instruments have a common and important feature which differentiates them from conventional laparoscopic instruments in that they have a wrist at the end of the instrument, providing a total of 7 degrees of freedom (DoF); 3-DoF for position, 3-DoF for orientation and the final degree of freedom for actuating the end-effector. With 7-DoF, virtually any position and orientation made by the surgeon’s hands in free-space can be matched by the instruments attached to the patient-side manipulators. With one of the patient-side robotic arms controlling a stereo endoscopic camera, the end result is an immersive interface for the surgeon in which it appears as though they can see inside the patient and their hands are the end-effectors of the patient-side robotic arms.
1.3.2 EndoWrist Instruments

The EndoWrist instruments are one of the most important elements of the da Vinci system as they increase the surgeon’s dexterity. They have a total for four degrees of freedom; roll, pitch, yaw, and opening/closing the jaws. The pitch and yaw can articulate up to 80 degrees providing better range of motion than the human wrist. Error! Not a valid bookmark self-reference. shows two different EndoWrist instrument designs, the 8-mm and the 5-mm versions. In general, these instrument designs attempt to achieve as compact articulation as possible as close to the tip as possible. The more compact the wrist is the less space required to articulate. In reducing the shaft diameter from 8 to 5 mm, a less compact joint design is implemented, as described by Marcus et al. [5] Rather than two discrete and orthogonal pin joints as used for the 8-mm instruments, the 5-mm instrument uses a multi-disk design which takes on a continuum shape.
during articulation. Also, the 8-mm wrist design integrates the actuation of the separate forceps into the wrist joint whereas the 5-mm wrist design requires an offset from the joint. This offset results in less compact articulation.

Figure 3: EndoWrist Instruments, Left: 8-mm Large Needle Driver, Right: 5-mm Needle Driver. Note that the transition from black plastic to metal marks the base of the wrist joint for the 5-mm instrument but not for the 8-mm instrument.

1.3.3 EndoWrist Compactness Measurement

The compactness of a wristed instrument with an end-effector will be described in this thesis as the distance from the base of the forceps to the outer wall of the instrument shaft when articulated to 80 degrees, as shown in Figure 4. For instruments with wrists that take on a continuum shape, the compactness measurement (CM) can be solved as the following:

\[ CM = \text{shaft radius} + \text{joint bending radius} + \text{distance from joint to the base of the forceps} \]

The 5-mm EndoWrist has a compactness of \(2.5 + 9.5 + 8.3 = 20.3\) mm which is larger than the 8-mm EndoWrist compactness measurement of 16.7 mm in Figure 4.
Figure 4: Compactness measurement (CM) of the 8-mm EndoWrist in millimetres. The measurement is taken from the base of the forceps to the outer wall of the instrument shaft.

1.4 Benefits and Limitations of the da Vinci

Most of the benefits and limitations associated with using the da Vinci Surgical System apply to all forms of robotic surgery. Presently, from a clinical standpoint, da Vinci surgery is synonymous with robotic surgery due to its dominance within the market.

1.4.1 Benefits

The main advantages provided by the da Vinci system compared to conventional minimally invasive surgery include improved dexterity, motion scaling, elimination of hand tremor, improved visualization and improved ergonomics. [6]

1.4.1.1 Dexterity, Motion Scaling & Elimination of Hand Tremor

Dexterity is increased through the use of wristed instruments. Conventional manual instruments do not have the additional two degrees of freedom seen at the end-effector as with the da Vinci instruments. Manual instruments with more than the conventional 4-DoF exist however tend to be more challenging to control. The da Vinci system achieves intuitive control of the higher DoF wristed instruments by restoring hand-eye coordination which is made possible through the
robotic teleoperation framework. Motion scaling, which is the ability to scale down large movements made by the surgeon to smaller movements made by the instruments, as well as tremor abolition are also made possible with this framework. The wristed instruments combined with motion scaling and tremor abolition has shown an increase in dexterity by nearly 50% compared with laparoscopic surgery. [7]

1.4.1.2 Improved Visualization & Ergonomics

With a separate console for the surgeon, visualization of the surgical field can be done in a unique way. The surgeon positions their head in a display which provides a separate image for each eye. Combined with a stereo endoscope which is a unique type of endoscope containing two cameras, the surgeon can perceive the surgical field in 3D. This provides an improved sense of depth compared to a 2D image which is used for conventional laparoscopy. 3D vision has shown to reduce skills-based errors by 93% as well as enhance dexterity by 10–15%. [7]

In a similar way, ergonomics of the surgeon are improved with the separate surgeon console. Because laparoscopic surgery requires the surgeon to control instruments manually and directly above the patient, this can lead to awkward stances and fatigue during long operations. [6] With the da Vinci system, the surgeon is able to be seated comfortably throughout the operation.

1.4.1.3 Additional Benefits

Additional benefits of the da Vinci include a faster learning curve, removal of innate handedness as well as data logging. In an in vitro study, inexpert surgeons were able to perform tasks more quickly and more precisely with a da Vinci than with conventional laparoscopy. [8]. This is likely attributed to the restoration of hand-eye coordination of the da Vinci versus learning how to operate with a fulcrum as in laparoscopy. The da Vinci system has also been shown to eliminate innate handedness, specifically that performance was comparable regardless of which hand was used to perform a task. [9] Lastly, the robotic system enables the ability to log data from surgeries. Combining this with machine learning may introduce an artificially intelligent surgical assistant which can predict when complications may arise and offer steps to avoid them.
1.4.2 Limitations

Limitations of the da Vinci system include increased cost, no force feedback, large footprint within the operating room, need for specialists, and system malfunctions.

1.4.2.1 Cost

The primary limitation to the da Vinci system is the cost. In 2017, purchase of the system cost US$0.6-2.5 million with $700-3,500 per procedure for instruments and accessories as well as $80k-170k per year in service costs. [10] Turchetti et al. conducted an economic review of the system in 2012 in which they compiled cost comparisons of da Vinci surgery and laparoscopic approaches for 12 different surgical operations. [11] Robotic surgery was always more costly ranging from 1.09-10.79 (median of 1.23) times that of manual laparoscopic approaches.

1.4.2.2 Lack of Haptic Feedback

In laparoscopy, surgeon’s can infer the amount of force applied on tissue based on its resistance. Presently with the da Vinci system, there is no force feedback. This is most consequential when surgeons are attempting to identify tissue consistency as well as for knot tying, often resulting in breakage of the suture. [6]

1.4.2.3 Large Footprint, Need for Specialists & System Malfunctions

Given that the system is fairly large and requires three separate components, a significant amount of space within the operating room is required for da Vinci surgeries. Additionally, operating the system requires surgeon’s who are specifically trained as well as technical staff who monitor the system to avoid negative consequences during system malfunctions. Because the system is quite complex, system malfunctions are possible. System malfunctions are most often related to malfunctions of the instruments such as broken/dislodged tension wires or not recognizing an attached instrument. [6] It should be noted that the negative effect of these malfunctions is minimal other than additional operating room time.

1.4.3 Weighing the Pros & Cons

The financial cost of performing surgeries robotically have the potential to be offset by reduced patient length of stay, reduced complications, fewer readmissions and lower infection rates. However, all of these potential offsets in hospital costs have not been fully realized at present.
There have been multiple studies exploring whether the da Vinci outperforms the alternative forms of surgery. When comparing it with laparoscopy, the results are somewhat inconclusive. In a study comparing conventional laparoscopy with the da Vinci, Maeso et al. found that the da Vinci often resulted in longer surgery times but shorter hospital stays for certain procedures. The da Vinci was also associated with fewer Heller myotomy-associated perforations and more surgical conversions when used to perform gastric bypass. [12] From a separate study, Brody et al. found that the da Vinci resulted in fewer conversions and shorter hospital stays and longer operative times. [13]

Where the robotic technology has a clear advantage is the added dexterity. From Turchetti et al. “There is emerging evidence from established centers that robotic surgery facilitates the performance of certain advanced operations, especially those that involve procedures in confined places and those requiring complex intracorporeal hand suturing” [11]. This result is supported by Chandra et al. stating that “The ability to minimize instrument pathlength may be considered a surrogate for the ability to perform meticulous dissection in a compact area with a minimum of collateral tissue damage. Thus, experts would derive the greatest benefit from robotics likely in operations that have these characteristics, such as prostatectomy (narrow pelvis, dissection near neural structures) or hepatobiliary surgery (dense complex anatomy).” They also suggested that surgeons who are not proficient in laparoscopy may use the robotic technology to perform certain complex tasks minimally invasively which would otherwise be done with an open approach. [14]

To summarize, while the da Vinci may not outperform conventional laparoscopy outright, it has the ability to improve outcomes when high dexterity is required in confined volumes. Regarding the cost of the equipment, Turchetti et al. suggest that “If the reported benefits of robotic surgery, especially the facilitated execution of complex interventions with improved task quality and patient outcome, are confirmed by prospective studies, then the high initial investment in the robotic technology may be more than justified.” [11] Ultimately, the ceiling on robotic surgery is very high. Its potential to outperform existing forms of surgery as well as provide surgeons with new capabilities and information is significant. As the technology is still relatively new, further development of these systems is required to achieve its full potential.
1.5 Current Clinical Applications

The da Vinci is advertised to be used in the following surgical applications: cardiac, colorectal, general, gynecologic, trans-oral, thoracic and urologic. In 2016, the most common applications were the following: 44% was in gynecology, 33% was in general surgery, and 19% was in urology. Table 1 lists the specific surgeries and procedures the da Vinci is advertised for.

Table 1: List of da Vinci surgeries advertised on davincisurgery.com

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<th>da Vinci Mitral Valve Prolapse Surgery</th>
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<td>da Vinci Coronary Artery Disease Surgery</td>
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<tr>
<td>Colorectal Surgery</td>
<td>da Vinci Colectomy (Colon Resection)</td>
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<tr>
<td></td>
<td>da Vinci Rectal Resection (Rectal Cancer Surgery)</td>
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<tr>
<td>General Surgery</td>
<td>Bariatric Surgery (gastric bypass and sleeve gastrectomy)</td>
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<td>Heller Myotomy (surgery for patients with achalasia – swallowing disorder)</td>
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<td>Gastrectomy (stomach cancer surgery)</td>
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<td>Hernia Repair</td>
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<td></td>
<td>Cholecystectomy (gallbladder surgery)</td>
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<td>Nissen Fundoplication (acid reflux surgery)</td>
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<td></td>
<td>Pancreatectomy (Benign)</td>
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<td></td>
<td>Pancreatectomy (Cancer)</td>
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<tr>
<td>Gynecologic Surgery</td>
<td>da Vinci Hysterectomy (Benign)</td>
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<td>da Vinci Single-Site Hysterectomy (Benign)</td>
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<td>da Vinci Hysterectomy (Cancer)</td>
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<td>da Vinci Endometriosis Resection</td>
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<td>da Vinci Sacrocolpopexy</td>
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<td>Head &amp; Neck Surgery</td>
<td>da Vinci TransOral Robotic Surgery</td>
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<td>Thoracic Surgery</td>
<td>da Vinci Lobectomy</td>
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<td></td>
<td>da Vinci Prostatectomy (prostate cancer surgery)</td>
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<td></td>
<td>da Vinci Partial Nephrectomy (kidney disease/cancer surgery)</td>
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<td></td>
<td>da Vinci Cystectomy (bladder cancer surgery)</td>
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<td></td>
<td>da Vinci Pyeloplasty (urinary obstruction surgery)</td>
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</table>

1.6 Potential Future Clinical Applications

Ninety-six percent of da Vinci surgeries currently take place within the abdomen or pelvis of adults. As described previously, the main advantage of the da Vinci which has significant clinical impact is the added dexterity which is particularly useful in applications involving complex procedures within small operating volumes. Gynecological and urological applications are two examples however there are many other surgical applications with this same requirement that the da Vinci is currently not used for. Three specific examples which will be explored here are neurosurgery, otolaryngology, and pediatrics. The studies discussed here evaluated the potential
use of the da Vinci system but concluded that there were technical limitations when applying the system to these other applications.

1.6.1 Neurosurgery

A study from 2015 was conducted by Marcus et al. evaluating the use of the da Vinci in a keyhole transcranial endoscope-assisted microsurgery on a cadaver. The diameters of the various keyholes drilled were 20-30 mm. The 12 mm endoscope could not be passed through the keyhole simultaneously with two instruments, regardless of whether they were the 8-mm or 5-mm instruments. Instead, the endoscope was positioned outside of the keyhole, limiting the illumination, magnification, and width of view. The 5-mm instruments were easier to pass down the keyhole due to their smaller diameter however their wrist design makes them less compact than the 8-mm instruments, making them less dexterous. The study also reported that instrument clashes prevented dissection deep within the operating volume. Compared to existing rigid tube shaft instruments, the robotic instruments used in the study increased dexterity. Improved ergonomics, an immersive 3-D view, motion scaling, tremor filtering and lack of haptic feedback were also noted. Additionally, the authors commented on the limited range of 5-mm instruments, with no bipolar forceps or suction-irrigation available. They concluded with the following: “Keyhole transcranial endoscope-assisted microsurgical techniques are technically challenging approaches that may greatly benefit from surgical robotics. However, the most widely used surgical robot worldwide today, the da Vinci platform, is neither safe nor feasible to use in keyhole neurosurgery.” The factors associated with this result were the system’s multiple large and bulky arms, limited selection of instruments and lack of haptic feedback. [5]

1.6.2 Otolaryngology

A case report from 2005 by McLeod et al. discussed the use of the da Vinci for applications in ear, nose & throat procedures. The report details the first da Vinci-assisted excision of a vallecular cyst in a human. A laryngoscope, the 12-mm stereo endoscope and a single 8-mm instrument were passed down the patient’s throat. The second instrument was not used due to limited space. The authors discuss how otolaryngologic endoscopy is challenged by anatomical constraints and limited degrees of freedom of the instruments. They suggest that surgical robotics may help overcome these limitations but from their clinical case, there are several shortcomings
of the da Vinci including the large size of the instrumentation and the difficulty of the setup process for airway surgery. [15]

Prior to this study, the same research group used the da Vinci within a laboratory setting on porcine, cadaveric head and neck airway models. In this paper, they discuss the limitations of the existing size of the instruments (8-mm) and camera for maneuvering within the oropharynx, resulting in collisions. From these observations, they make specific reference to the development of smaller instrumentation to facilitate the incorporation of surgical robotics into otolaryngology. The authors also state that “Such advances might revolutionize the way we perform certain surgical procedures in the head and neck and might elevate minimally invasive endoscopic surgery to a higher level.” [16]

These findings were supported in a later study which assessed the da Vinci within the smaller pediatric airway by Rahbar et al. in 2007. Five patients underwent endoscopic repair of laryngeal cleft. Both the 5-mm and 8-mm instruments were tested. For three patients the repair could not be performed using a robotic approach due to limited transoral access. Challenges mentioned of the robotic system for airway surgery included: “(1) obtaining a safe, adequate means to administer airway anesthesia; (2) obtaining proper exposure of the larynx to perform the surgery; (3) the need to introduce the robotic arms into a single port of entry (oral cavity or pharynx) and overcome limitation of movement; and (4) the lack of availability of suction instruments.” The advantages included: “(1) improved optics, with 3-dimensional visualization; (2) tremor filtration; and (3) increased freedom of instrument movement, which allows for delicate handling of tissues and increased surgical precision.” The authors concluded with: “We believe that the development of smaller instruments and further advances and modifications in device technology will facilitate the incorporation of robotic equipment into otolaryngology.” [17]

1.6.3 Pediatrics

In 2007, Meehan et al. reported on a robotic repair of a bochdalek congenital diaphragmatic hernia in a small neonate. The patient was 2.2 kg and taken to the operating room at 6 days of life. The da Vinci was used due to its articulating instruments as sutures needed to be placed precisely and securely for the procedure. An abdominal approach was elected as it was decided that there would not be enough room for the robotic instruments entering through the chest. The instrument trocar had to be retracted outside the abdominal cavity in order to gain extra
instrument length for the 5-mm instruments. The procedure was successful however significant discussion in review of the surgery was allotted to the considerable length that the 5-mm instruments must extend outside of the trocar in order to operate. This length is extremely important for operating in very small children and should be minimized. The authors added that the articulating instruments helped considerably in placing the sutures and tying the knots but also that reducing the viscera took excessively long due to limited instrument articulations which occurred largely due to the size of the operating volume. [18]

1.6.4 Summary of da Vinci Application Studies

The reviewed studies which involved using the da Vinci surgical system for a different application than what it is advertised for all had similar findings. Each study described the advantages of using the robotic system, specifically the enhanced dexterity through the articulated instruments while also describing how the instrument size is a limitation for operations within small volumes or openings. The studies conducted by McLeod et al. took place prior to the 5-mm instrument line. Marcus et al. describe how the 5-mm instruments are less compact when articulating than the 8-mm instruments however they are still preferred in certain cases due to their reduced shaft diameter. Based on the evidence from these studies there is a clearly defined need for smaller instrumentation for operating in small volumes. These applications could arguably benefit from robotic surgery more than the current da Vinci surgical applications yet are limited by the existing instrument sizes. Widespread use of the da Vinci for these clinical applications is likely limited until new smaller instruments are introduced.

1.7 Research Question

1.7.1 Developing a Miniature Robotic Instrument

From the reviewed studies which applied the da Vinci to new applications involving smaller operating volumes, the main challenge faced was the size of the existing instruments. This research aims to address this by answering the following question: Is it possible to develop a robotic instrument that is significantly smaller than existing EndoWrist instruments while maintaining similar capability? Such an instrument would have to have a significantly reduced shaft diameter compared to current instruments (5, 8 mm) while also matching the degrees of freedom (4) and range of motion (80° articulation) of current instruments. Additionally, the
instrument’s wrist should articulate more compactly than existing instruments. These criteria are listed in Table 2.

<table>
<thead>
<tr>
<th>Table 2: Criteria for development of a new miniature instrument</th>
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<tr>
<td>Shaft diameter</td>
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<tr>
<td>Degrees of freedom</td>
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<tr>
<td>Range of motion</td>
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<td>Compactness</td>
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A shaft diameter of 2 mm is selected based on the existing instrument sizes of 5 mm and 8 mm and setting a challenging criterion that, if successful, could allow a significant number of new applications to benefit from robotic surgery. One clinical example with particularly restrictive instrument sizes is endoscopic neurosurgery. For these procedures, instruments must be less than 2.5 mm to be passed down the working channels within the trocar. This is one of the potential applications which could benefit from the development of a 2 mm robotic instrument.

Achieving a smaller size, while matching the degrees of freedom, range of motion and compactness will take priority over the instrument’s stiffness or ability to transmit forces for initial instrument development. The instrument’s force transmission capability will be assessed following the initial development of the instrument to inform how the instrument could be used for tissue manipulation.

1.8 Existing Miniature Instruments

A study in 2011 by Catherine et al. reviewed the various designs used to achieve distal active articulations for minimally invasive surgery. [19] Included in the review is a table outlining actuation technology, diameter, length, bending angle, radius of curvature, number of DoFs and torque. Only two devices had properties of <4 mm shaft diameter, <14 mm joint bending radius, and ≥2 DoF. A device developed by Yamashita et al. is a 2-DoF bending manipulator with 3.5-mm shaft diameter. [20] The manipulator uses rigid links with a unique combination of rolling and hinged joints for articulation and can achieve a relatively high bending torque of 27.9 N mm. The joint is fairly complex and requires 9 pieces to achieve one degree of freedom. Reducing the shaft diameter further is expected to be challenging due to the complexity of the joint. Additionally, the link offsets between the joints appear large reducing the compactness. The
device also requires that the end-effector is passed down the lumen of the joint yet the joint has
discrete bends which does not easily enable the use of end-effectors being passed down the
lumen as their bending radii must be very small.

The second device of interest has a 2.4 mm shaft diameter and was developed to deflect a laser
fiber. [21] The design uses a sliding curved joint type and is composed of alternating cylindrical
and spherical pieces which slide with respect to each other. Four wires are used for actuating the
joint and pass through holes in the wall of the cylindrical pieces. A hole through the spherical
pieces provides an inner lumen for the laser fiber. The main limitation associated with the joint
appears to be its relatively large bending radius of 12.7 mm. Introducing an end-effector to the
end of this joint would likely push the compactness measurement beyond the desired 15 mm. To
achieve 90° bending, the joint requires 25 components and is 19.9 mm long.

For both of these devices, the joints are integrated at the tip of a hand-held instrument, driven by
motors located at the handle. This complicates the control of all degrees of freedom of the
instrument. From the second paper by Harada et al., they specifically reported that operators
found it difficult to combine all movements to position the manipulator. The teleoperation
approach for controlling wristed instruments used by the da Vinci system solves this problem.

Three other miniature instrument designs of note include concentric tube robots, the I-Flex and
the Axsis robot. Concentric tube robots are composed of pre-curved super-elastic nitinol tubes
arranged in a concentric fashion. The robot’s overall shape, tip position, and orientation can be
controlled by rotating and translating the individual tubes relative to one another. [22], [23] The
key advantages of concentric tube robots include their small shaft diameter (<3 mm) and ease of
fabrication. Their primary limitation for this application is their poor compactness. Since the
solid curved tube must bend to a straight configuration without exceeding the material’s elastic
strain limit, the joint’s bending radius must be relatively large. The I-Flex developed by the Bio-
Inspired Technology (BITE) Group at Delft University of Technology consists of a series of
parallel cables positioned to form a ring with an external spring and an internal cable to constrain
the cables, similar to the Endo-Periscope III [24], [25]. The internal cable doubles as a method
for actuating an end-effector. The diameter of the joint is 0.9 mm and can articulate up to 90
degrees in all directions with an approximated CM value of 10 mm. This instrument has most of
the desired capabilities although joint stiffness is likely an issue as the backbone of the joint is
merely seven small cables. Details of the device only exist on the BITE group’s website and information on the instrument’s joint stiffness or force transmission abilities are not provided. The last miniature instrument of note is the Aaxis system developed by Cambridge Consultants with a 1.8 mm shaft diameter which can articulate with two degrees of freedom. [26] The joint appears to consist of a series of rolling friction joints with cables passed through them for control. This design appears to be limited by its compactness as the maximum achievable angle for each rolling joint is minimal.

1.9 Existing Research Platforms for Robotic Surgery Development

For development of a new instrument, commonly in the past an entirely new robotic platform is developed in order for a human to operate it. However, in recent years, development of teleoperated surgical robotic research kits have become available. In 2011, the RAVEN-II was developed at the University of Washington and the University of California and the system has been distributed to research centres around the world. [27] Similarly, Johns Hopkins University and Intuitive Surgical collaborated to develop the da Vinci Research Kit (dVRK) which released in 2013. The dVRK is an open-source version of the da Vinci Surgical System using the manipulators from retired clinical systems. [28] The Centre for Image-Guided Innovation and Therapeutic Intervention (CIGITI), the lab at which this research is conducted, purchased a dVRK in 2013, providing the option of using the system for this research. Multiple steps which are required for custom builds are bypassed by using an existing research kit including (1) building an actuation system for the instrument (2) writing the software to achieve reliable control of the actuators (3) integrating a human interface for teleoperation. Furthermore, since the da Vinci Surgical System is by far the most widespread surgical robotic system in the world, developing an instrument which is compatible with the da Vinci platform may accelerate its adoption in a clinical setting. For these reasons, the dVRK is used to accelerate the development of a custom miniature instrument.

1.9.1 The da Vinci Research Kit (dVRK)

The da Vinci Research Kit (dVRK) is an open-source robotics platform created to promote the development of new applications and technologies for surgical robotics [28]. The kit uses the robotic manipulators, head display and foot pedals from an early generation of the da Vinci
Surgical System. Open source electronics and software have been developed to provide the designer with full customization abilities of the system.

The concept of developing a custom instrument for the da Vinci platform is made possible in part due to the system’s design which allows for rapidly interchanging the instruments. The patient-side manipulator (PSM) has been designed with a standardized interface which can drive a connected instrument as well as allow for it to be easily swapped (Figure 5). This interface, known as the sterile adapter, has four mating disks each with a range of motion of ±170° and can actuate an attached instrument. This interface allows for new custom instruments to be designed to compliment the existing instrument line. With modifications to the dVRK’s code, these custom instruments can be teleoperated.

As seen in Figure 5, the first three joints of the PSM perform the gross positioning of the instrument while the 4-DoF of the instrument primarily control the orientation and actuation of the end-effector. Each instrument has two main components, the tip, which is where the wrist and end-effector are located, and the base. The base is designed to convert the rotations of the four actuation disks into the desired movement at the instrument’s tip.

![Figure 5: dVRK’s PSM displaying 7-DoF and instrument interface. Top Left: Back of instrument base which mates with actuation disks, Bottom Left: Sterile adapter with 4 actuation disks, Right: Instrument mounted on PSM](image)
1.9.2 Custom Instruments for the da Vinci Research Kit

Since the creation of the da Vinci Research Kit, custom instruments have been developed for use with the system. CIGITI was among the first to do this with the creation of a concentric tube instrument in 2015 [29], [30] Other custom instruments for the dVRK include an instrument integrated with ultrasound and tactile sensing for better tumour localization [31] and a 3.3 mm snake-like continuum manipulator [32]. Two other custom instruments under development within CIGITI include a bone cutting device [33] as well as an instrument specific for performing cleft palate surgery [34]. From these custom instruments, three of them were developed specifically for miniaturization although not necessarily with the same criteria described for this research. The concentric tube instrument provides a small shaft diameter but with a large bending radius. The 3.3 mm snake-like continuum manipulator has a 0.7 mm endoscope channel and a 1.8 mm instrument channel. The instrument is restricted to planar bending and is not intended to replicate a “wrist”. The instrument for cleft palate repair uses a pin jointed wrist at a 5 mm shaft diameter with potential to be reduced further but introduces the challenge of increased friction since the pulleys at the wrist are removed. None of these instruments have achieved a 3-DoF wrist below a 3 mm shaft diameter and a 15 mm compactness measurement.

1.10 Developing a New Miniature Instrument: Thesis Layout

The design of a custom instrument for the dVRK can be separated into two components: 1) the wrist design and 2) a base mechanism which converts the rotations of the four disks into actuation of the wrist. The layout of the thesis is as follows: Chapter 2 defines a new miniature wrist design to achieve the defined criteria. Chapter 3 proposes a kinematic model for the new wrist design. Chapter 4 discusses the selection of specific design parameters and manufacturing of the instrument. Chapter 5 describes a unique actuation system to control the wrist via the standard base interface. Chapter 6 describes the experimental testing of the instrument. Chapter 7 discusses a teleoperation task using the instrument. Chapters 8 to 10 offer a discussion, conclusion and future work for this research.
Chapter 2
Developing a Miniature Wrist: Joint Selection & Design

2 Developing a Miniature Wrist: Joint Selection & Design

2.1 Chapter Summary

This chapter explores the most important component of the instrument, the wrist. Bending flexure joints, a technology for achieving articulation at a small scale is selected for the wrist joint. Existing notched nitinol tube designs, the most common form of bending flexure joints, are examined and certain characteristics of the wrist are selected including the use of square asymmetric notches and multi-degree of freedom bending. A new cutting pattern is designed to achieve these joint characteristics as well as reduce coupling across actuation cables. This leads to a new bending flexure joint design which is used for the instrument’s wrist.

2.2 Joint Selection

To create a smaller instrument, the focus is placed on miniaturizing the wrist. The instrument’s wrist requires intricate movement, high precision, and must be very small (2 mm diameter). In 2015, a review paper was published by Jelínek et al. on the “Classification of Joints Used in Steerable Instruments for Minimally Invasive Surgery.” [35] The joint types included in the paper included rolling (using friction, teeth or belts), sliding (using curves or hinges), rolling sliding and bending flexure. As part of this review, the different joint types were qualitatively evaluated based on their performance relating to joint geometry and motion. The seven categories of performance were preventing axial split, preventing transverse split, preventing slip, torsional stiffness, space efficiency (size vs. DoF), providing inner lumen and overall design complexity. The performance is evaluated as either good (+), neutral (0), or weak (-). The total grades could range from -7 to +7. All of the joint categories were evaluated based on either planar (2D) or spatial (3D: perpendicular & revolved) implementations. Table 3 shows the results, taken from the paper.
Table 3: Qualitative performance evaluation of joint types used in steerable instruments for minimally invasive surgery. [35]

<table>
<thead>
<tr>
<th>Joint Type</th>
<th>Merit</th>
<th>Preventing Axial Split</th>
<th>Preventing Transverse Split</th>
<th>Preventing Slippage</th>
<th>Torsional Stiffness</th>
<th>Space Efficiency (Size vs. DOF)</th>
<th>Providing Inner Lumen</th>
<th>Overall Design Complexity</th>
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<tr>
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<td>Friction-Planar</td>
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<td>-</td>
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<td>0</td>
<td>+</td>
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<td>+</td>
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<td></td>
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<td>Revolved</td>
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<td>+</td>
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<tr>
<td>Bending Flexure</td>
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<td>0</td>
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<td>6</td>
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From this qualitative evaluation, the authors suggest that bending flexure joints have the most desirable characteristics compared to the other joint types, earning 6 out of a possible 7 points for the spatial implementations. The function of bending flexure joints is based on the intentional compliance of a material. Typically, the compliant material has superelastic properties, such as nitinol, enabling it to undergo significant deformation and use its elastic nature to return back to its unstressed position. In this way, the compliant region which makes up the joint acts similar to a spring where continuous force is required to hold the joint in an actuated position.

The specific performance advantages of the bending flexure joint from the qualitative comparison include preventing axial and transverse splitting, torsional stiffness, providing an inner lumen as well as a low joint complexity. Considering the ultimate goal of achieving a 3-DoF wrist with an active end-effector, having an open lumen will enable the use of an off the shelf end-effector that can be actuated with a wire which passes through the tube’s lumen. Alternatively, an open lumen could provide the possibility of integrating suction into the instrument in place of an end-effector. Likely the most important advantage of this joint type is the low complexity as they can be manufactured from a single piece of material. From a survey of continuum robots used for medical applications, Burgner et al. state that continuum joints can be constructed at smaller scales than those with discrete links due to the simplicity of their structures. [36] Figure 6 is used to illustrate this concept.
Other joint types of note from the review paper include perpendicular rolling belted joints as used in the 8-mm EndoWrist. This joint type was structurally capable however lost marks for not providing an inner lumen and for overall design complexity. The 8-mm EndoWrist is made up of 14 components to achieve 2-DoF articulation (pitch & yaw). This high level of complexity is what limits the same design to be used at smaller scales. This is made evident with the 5-mm EndoWrist which employs a different joint type, perpendicular rolling friction, made up of about 5 components. Due to the improved scalability that bending flexure joints have as well as the desirable performance characteristics defined by Jelínek et al., bending flexure joints will be pursued for creating the instrument’s wrist joint.

2.3 Bending Flexure Joints

2.3.1 Notched nitinol tube mechanisms

The most common form of bending flexure joint is a notched nitinol tube joint in which a section of a nitinol tube is cut away to allow for directional compliance in the tube. The joint can be actuated by applying tension to a cable fixed to the tube distally and in line with the cut. Tensioning the cable causes the joint to bend in the direction of the cut. So long as the flexing material remains within its elastic strain limit (6-10% for nitinol), releasing the cable tension allows the joint to return to its original, straight position. These types of joints have been
implemented for miniature dexterous medical instruments, including fiber-optic endoscopic cameras, articulated lasers, suction and irrigation probes, as well as wristed forceps, scissors and drills. [37]–[50] Various cutting patterns and shapes have been proposed to achieve directional compliance in the tube. The most basic of these designs involves cutting a square notch past the midline of the tube. [38], [43]–[45] To avoid buckling, a series of small notches are used to achieve the desired range of motion. An example of this type of joint can be seen in Figure 7. This type of square notch joint has been made from a tube with an outer diameter as small as 0.46 mm. [37] Therefore notched nitinol tube joints are a good candidate to achieve articulation of a wrist at the 2 mm scale.

![Notched nitinol tube with square asymmetric cuts](image)

**Figure 7:** Notched nitinol tube with square asymmetric cuts. The joint is actuated by tensioning a cable that is fixed to the tube distal to the cuts and routed inside the tube.

Some existing notched-tube topologies are depicted in Figure 8. The primary classification for these topologies is asymmetric and symmetric notches. This describes whether there is a line of symmetry down the tube. Also, asymmetric notches typically involve cuts that cross over the midline of the tube whereas symmetric notches do not. Combining these individual notch shapes in different ways can allow different degrees of freedom. More specifically, cuts along a single plane can achieve planar, 1-DoF bending while cuts in multiple planes can achieve 2-DoF bending.
2.3.2 Superelastic Nitinol

Nitinol is a nickel-titanium alloy with unique superelastic properties along with relatively high stiffness. Nitinol can achieve approximately an order of magnitude more elastic strain than metals such as titanium and stainless steel and is an order of magnitude stiffer than plastics such as PTFE and polyurethane. It achieves superelasticity by storing mechanical energy in a solid-solid phase change instead of in dislocations as is the case in most metals. The stress-strain behaviour of nitinol compared against stainless steel is included in Figure 9. The most notable difference is the elastic strain limit.
Figure 9: Stress-strain properties of superelastic nitinol (black) compared against stainless steel (grey). The dashed vertical lines represent the respective elastic strain limit. [51]

2.4 Defining a Notch Topology

Selecting a notch topology is dependent on the desired number of degrees of freedom, and the characteristics of the different notch shapes and patterns. These factors are discussed in this section and a topology is selected to meet the desired capabilities of the instrument’s wrist.

2.4.1 1-DoF vs. 2-DoF

Upon reviewing the existing notch topologies, the joints can be grouped into either 1-DoF bending or 2-DoF bending. Different notch topologies offer different degrees of freedom and thus different wrist configurations. Ultimately, three degrees of freedom are required to create a wrist. A 1-DoF bending notch topology that bends in a single direction or a single plane (such as from Figure 7) could be integrated into a roll-pitch-roll (RPR) wrist configuration where the compliant bending would provide pitch. A notch topology which has two bending degrees of freedom, allowing it to bend in any direction (such as the symmetric notch topology in Figure 8), could be integrated into a roll-pitch-yaw (RPY) wrist configuration where the tube’s bending would provide both pitch & yaw. A RPR wrist would roll the compliant bending joint from its base as well as require independent roll distal to the compliant bending joint whereas the RPY
configuration would only require rolling the entire joint at the base. RPR wrists have a
singularity in the middle of the wrist’s workspace while RPY designs do not. [52] The RPR
design may allow for more compact bending as the only notches are contributing to bending in a
single direction, or within the plane. However, achieving roll at the end of a sharp bend is very
challenging which is not required with RPY. Because of the limitations of RPR, a RPY wrist is
more desirable, and therefore a 2-DoF notch topology is pursued. This requires making cuts in
multiple planes around the tube.

2.4.2 Asymmetric vs. Symmetric

Comparing an asymmetric notch with a symmetric notch, asymmetric notches bend in a single
direction while symmetric notches can bend in both directions in plane. Symmetric notches have
antagonistic cables, making it possible to stiffen the joint by pre-tensioning the actuation cables.
However, since the joints bend in both directions, fatigue is expected to onset faster compared to
an asymmetric notch with the same strain limits. Asymmetric notches require lower actuation
forces compared to symmetric notches due to the longer moment arm.

Asymmetric notches with a square profile have the important advantage of simple
manufacturing. These square notches can be cut using a basic tabletop CNC which costs under
$3000. [53] Other more complex topologies require wire EDM cutting machines or laser cutters
which are more expensive and not as readily available. Cutting square symmetric notches on a
tabletop mill is feasible however much more challenging due to the high sensitivity of the
thickness of the remaining compliant section. As a result, the square symmetric notches are much
more likely to break during or soon after the manufacturing process.

Upon analyzing the various notched tube cutting topologies, it was realized that square
asymmetric notches have not been used to achieve 2-DoF bending. Such a joint design would
conceivably allow for an RPY wrist configuration as well as be simpler to manufacture, require
lower actuation forces and potentially last longer than existing 2-DoF notch designs. For these
reasons, this research will aim to develop a 2-DoF bending notch topology with square
asymmetric notches. Such a design would be the first to be presented in literature to the best of
the author’s knowledge.
2.5 Defining a Topology using Square Asymmetric Notches for 2-DoF Bending

2.5.1 Notch Topology

In order to achieve 2-DoF bending using square asymmetric notches, cuts must be made in multiple planes. This is an important difference compared to 1-DoF bending square asymmetric notch joints which have all of the cuts aligned. Other 2-DoF bending designs, often involving symmetric notches, have cuts that are perpendicular or rotated 90 degrees. This section will aim to define the cutting planes and actuation cable placement which will lead to an easily controllable joint design. One of the key factors in making the joint easily controllable for a 2-DoF bending is minimizing coupling, or crosstalk. This occurs when the actuation cable responsible for achieving bending in one direction affects bending in a different direction. When this occurs, it is often difficult to predict and therefore cannot be modelled leading to poor control.

In an effort to simplify the control of the joint, it is preferable to have a single cable responsible for bending the joint in a single direction. Applying this to an existing 2-DoF topology such as the symmetric topology from Figure 8, this would involve having four cables, each aligned with a cut side for actuation. A cross section illustrating this concept is included in Figure 10. Since the moment arm between the actuation cable and the flexing material’s neutral axis is what causes the notch to bend, a strategy to avoid coupling would be to maximize the moment arm for the cable responsible for actuating the notch and minimize the moment arm for cables used for bending in other directions. In Figure 10, it can be seen that by positioning the cables in line with each cut side, it falls along the neutral bending plane (represented by the dashed line) of the perpendicular notches. With this topology and cable alignment, coupling is avoided.
Figure 10: 2-DoF symmetric notch topology illustrating how coupling is avoided. Left: 2-DoF symmetric notch topology. Right: Cross section of the joint highlighting the location of the actuation cables with respect to the neutral bending planes. The desirable moment arm from the actuation cable to the neutral bending plane is labelled. The undesirable moment arm is zero since the actuation cable is in line with the neutral bending plane of the notches in the other plane.

Making the same comparison for an asymmetric notch design positioned 90° apart, shown in Figure 11, an important difference is noted. Aligning the cables with each cut side does not position them along the neutral axis of the perpendicular cuts. As a result, an undesirable moment arm exists between each actuation cable and the notches in the other planes. This undesirable moment arm is illustrated with the dimension in Figure 11 showing the distance from the cable to the neutral axis of one of the perpendicular cuts. This topology is undesirable and will likely lead to coupling.
**Figure 11:** Asymmetric notch topology with 90° spacing. The cross-section illustrates that while the desirable moment arm is increased, this topology results in a significant undesirable moment arm. This is expected to lead to coupling.

In an attempt to reduce the undesirable moment arm seen in the 90° case, a 120° offset is proposed (Figure 12). While the moment arm is reduced, there is still risk of coupling. To address this, the location of the cables will be discussed.

**Figure 12:** Cross-section of asymmetric notch topology with 120° spacing. This new spacing reduces the undesirable moment arm of the 90° spacing case without reducing the desirable moment arm although coupling is still likely.
2.5.2 Cable placement and guides

Existing 2-DoF bending notched tube solutions have most commonly routed the cables within the wall of the tube. This requires more advanced machining abilities such as wire EDM cutting. For the 1-DoF square asymmetric notches example, which were machined using a tabletop CNC, the design allowed for routing the cable on the inside of the tube as there was only one actuation cable. Neither of these approaches can be readily transferred to this topology. Therefore, a new cable placement is proposed. From Figure 12, it can be seen that the further toward the outside of the tube the actuation cable is positioned, the longer the desired moment arm and the shorter the undesired moment arm. Thus, the cables are positioned on the outside of the tube, as seen in Figure 13. This change also increases the desired moment arm, as shown in the figure, making the desirable moment arm drastically larger than the very small undesirable moment arm. The increased desired moment arm also reduces the maximum cable tension allowing for smaller cable to be used for actuation, which is important for miniaturizing the instrument.

Figure 13: Asymmetric notches spaced 120° apart with cables on the outside of the tube. Routing the cables on the outside of the tube increases the desirable moment arm significantly while also reducing the undesirable moment arm. This design is expected to have minimal coupling as a result.
Positioning the cables on the outside of the tube requires an additional measure to ensure that they remain alongside the tube and aligned properly. To achieve this, small rings are used which loop around the cable and a section of the tube to constrain the cable’s position. These rings are made from steel wire and are wound to create what looks like two wraps of a spring.

2.5.3 Final Joint Design

Lastly, assuming that more than three notches will be required to achieve the maximum bending angle, the joints must either be nested in a spiralling pattern or staggered with a series of joints in the same direction. The approach chosen is to nest the notches as this allows for the entire tube to bend about a common region as opposed to a series of staggered joints which may bend in a non-intuitive way. This leads to the final notch topology and wrist design, shown in Figure 14; a series of asymmetric cuts spaced 120° apart, helically patterned around the tube.

Figure 14: Final notch topology and wrist joint design. The top image shows the cutting pattern while the bottom image shows an assembled version which includes the three actuation cables as well as the rings for cable guides.

With this design, there are three primary bending directions toward each of the three cables. Bending in between these primary directions can be done by pulling on two cables simultaneously. In this way, the notches associated with those two cables will bend while the third set of notches should not be affected. Therefore, at most two of the three cables will be tensioned to bend in any direction. When the tension on the cables is removed, the joint should always return back to the straight position. The kinematics for this new type of joint are discussed in Chapter 3.
The topology of the joint has been developed to avoid coupling based on the orientation of the square asymmetric notches and the placement of the cables. Aside from these design features, certain dimensions of this joint topology can either reduce or increase coupling. Chapter 4 discusses the selection of these dimensions of the tube and notch topology as well as explores how well this design avoids coupling along with the affect of varying joint parameters.
3.1 Chapter Summary

This chapter proposes a kinematic model for the new wrist design. An existing kinematic model for 1-DoF bending square notch joints is discussed and used and modified for the 2-DoF bending case. Four modifications were made to the existing model in order to apply it to the 2-DoF bending case.

3.2 Square Notch Geometric Parameters

Previous work by York et al. derived a kinematic model for a 1-DoF wrist composed of a series of aligned square asymmetric notches actuated by a single cable. [54] Parameter definitions from this existing model used to define the geometry of a square notch is followed for the kinematic model proposed here.

Considering a single square notch in a tube, the parameters used to define the geometry are as follows: inner and outer radii of the tube, $r_i$ & $r_o$, the height of the cut, $h$, and cut depth, $g$. For multiple cuts along the tube, the distance between the cuts is denoted as $c$. An important dimension which is used in the kinematics is the distance from the centre of the tube to the neutral bending plane, $\bar{y}$. This can be calculated using $r_i$, $r_o$ and $g$ and is described in [54]. These parameters are illustrated in Figure 15.
Figure 15: Square asymmetric notch joint geometric parameters.

### 3.3 Existing One-DoF Kinematic Model

The existing kinematic model maps a cable displacement, $\Delta l$, to parameters defining the shape of the notch then maps those shape parameters to task space. The model assumes constant curvature bending of the notch. This assumption is more accurate with smaller $h$ values. The parameters which define the shape of the notch are the bending curvature of a single notch, $\kappa$, and its arc-length at the tube’s midline, $s$. The angle of the bend can be solved as $\theta = s \kappa$. Based on the
geometry of the notch, the following equation is derived which maps the arc parameters to a cable displacement.

\[
\Delta l = h - 2\left(\frac{1}{\kappa} - r_i\right)\sin\left(\frac{\kappa h}{2(1 + \bar{y}k)}\right)
\]  

(1)

This equation must be inverted in order to map the cable displacement to the arc parameters. To invert the equation, a small angle assumption is made.

\[
\kappa \approx \frac{\Delta l}{h(r_i + \bar{y}) - \Delta ly} \quad s = \frac{h}{1 + \bar{y}k}
\]  

(2)

Lastly, these arc parameters can be used to define a transformation of the position and orientation across the notch in task space.

\[
T_{j+1}^j = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \cos(\kappa s) & -\sin(\kappa s) & 0 \\
0 & \sin(\kappa s) & \cos(\kappa s) & \frac{\cos(\kappa s) - 1}{\kappa} \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  

(3)

The total transformation of the multiple notch joint can be determined by multiplying that matrix with a matrix defining the offset distance, \( c \), for \( n \) notches.

\[
T_{wrist} = \prod_{j=1}^{n} T_{j+1}^j T_c
\]  

(4)

Where \( T_c \) is a transformation defining a linear translation along the \( z \)-axis of distance \( c \). The total cable displacement is therefore \( \Delta l_{total} = n\Delta l \). This model provides the basis for the kinematic model which will define the bending of the new 2-DoF bending joint design.

### 3.4 Kinematic Model Extended for Multi-DoF Bending Joint

The key differences between the single-DoF model and a multi-DoF model for a notched tube joint is the cuts within different planes as well as the use of multiple cables for actuation. Figure 16 shows a tube segment with three notches in three separate planes. The top two notches are undergoing bending due to two of the three red actuation cables. An important assumption made for the proposed kinematic model is that each cable will only influence the bending of the aligned notches. From Chapter 2, the joint was designed to reduce coupling and therefore it is
expected that this assumption is valid. Chapter 4 will verify this assumption using finite element methods.

![Figure 16: Multi-DoF Square Notch Joint Segment](image)

To extend the kinematics to three notches arranged in different bending planes, four modifications have been made. First, the transformation $T_c$ must account for a rotation of 120° about the z-axis as well as an offset of $c$, the width between each notch. Therefore $T_c$ becomes:

$$
T_c = \begin{bmatrix}
\cos(120°) & -\sin(120°) & 0 & 0 \\
\sin(120°) & \cos(120°) & 0 & 0 \\
0 & 0 & 1 & c \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

(5)

Second, each transformation across the notch is a function of one of three cable displacements. The transformation of a 3 notch segment such as the one in Figure 16 would be as follows:

$$
T_{3\text{notch}} = T_1 T_c T_2 T_c T_3 T_c, \quad \text{where } T_i = T_{\text{notch}}(\Delta l_i)
$$

(6)
Here, each cable has a respective cable displacement $\Delta l_i$ as well as series of notches it aligns with. To calculate the mechanism’s overall transformation, accounting for all of the notches on the wrist, the transformation becomes:

$$T_{\text{wrist}} = \prod_{i=1}^{n} T_{\text{3 notch}}$$

(7)

where $n$ is the number of cuts in each direction. The total number of cuts would then be $3n$. In addition to this modification, to avoid dividing by zero when a notch is straight or unbent from Equation 3, the curvature $\kappa$ is assigned a very small value ($\varepsilon = 1^{-5}$) for the transformation across the notch. Similar to the existing model, this model assumes that an overall cable displacement, $n\Delta l$, contributes equally to the closing of all aligned notches.

The third modification accounts for the change in position of the actuation cables when solving for the curvature of the notch. The value $d$ from Figure 16 represents the distance between the tube’s midline to the actuation cables. However, when actuated, the cable tends to deviate away from the outer wall of the tube due to the design of the cable guides. To account for this, a correction $\varepsilon_{\text{corr}}$ is necessary to increase $d$ to better represent the joint behaviour. The solution for the curvature is therefore:

$$\kappa \approx \frac{\Delta l}{h(d + \varepsilon_{\text{corr}} + \bar{y}) - \Delta l y}$$

(8)

The fourth modification considers the nature of asymmetric notches, specifically the fact that the midline of the tube, $s$, shortens as the tube bends. This is due to the neutral bending plane’s position near the outer edge of the tube. Because of the neutral bending plane’s position, the cable path lengths which are not contributing to the closing of the notch will also shorten. Therefore, some extra cable displacement is required in order to achieve the intended cable displacement. In other words, true cable displacement, $\Delta l_{\text{true}}$, will be based on the cable displacement found based on the kinematics, $\Delta l_{\text{kin}}$, plus some additional displacement, $\Delta l_{\text{add}}$, to remove slack caused by a shortening path length. The additional cable displacement is necessary for all actuated cables when more than one cable is actuated. The effect of this can be seen in Figure 16 where the cable path lengths on the right side of the middle notch are shorter than the length that they would be if the notch was not actuated, $h$. 

The calculation of $\Delta l_{true}$ is performed as follows: first, the desired midline arc lengths $s$ and curvatures, $\kappa$, are determined for the three cut directions. Next, the path length of each cable across each of the notches which it is not influencing is solved based on the geometry of the notch and the position of the cable. Figure 17 shows a cross section of a notch and the location of the three cables. The constant distance from the midline of the tube to the cable, $d$, is used to determine the path length.

Figure 17: Dimension $d$ is a constant distance measuring from the midline of the tube to the cable

$$s_{cbl} = s(1 + \kappa d \sin(30^\circ)) \quad (9)$$

$$\text{slack} = h - s_{cbl}$$

Where $\text{slack}$ defines the length of slack introduced in the cable across the notch. To calculate $\Delta l_{add}$ accounting for all instances where slack is introduced, it is the shape of the other notches that must be considered for a given cable. The cables and their aligned notch parameters are assigned a subscript 1-3.

$$s_{cbl\ not\ 1} = s_1(1 + \kappa_1 d \sin(30^\circ))$$

$$s_{cbl\ not\ 2} = s_2(1 + \kappa_2 d \sin(30^\circ)) \quad (10)$$

$$s_{cbl\ not\ 3} = s_3(1 + \kappa_3 d \sin(30^\circ))$$
\[ \Delta l_{\text{add}1} = n(2h - s_{\text{cbl not } 2} - s_{\text{cbl not } 3}) \]
\[ \Delta l_{\text{add}2} = n(2h - s_{\text{cbl not } 1} - s_{\text{cbl not } 3}) \]
\[ \Delta l_{\text{add}3} = n(2h - s_{\text{cbl not } 1} - s_{\text{cbl not } 2}) \]

Lastly, the total cable displacement can be calculated as the sum of the displacement from the kinematics and the additional cable displacement.

\[ \Delta l_{\text{total}} = \Delta l_{\text{kin}} + \Delta l_{\text{add}} \]

Without this adjustment, the cables could be shortened with the expectation that it would deflect the joint but only slack would be removed.

As mentioned in Chapter 2, bending the wrist in any direction can be achieved by actuating at most two of the three cables. The previous discussion on extra cable displacement required to avoid slack in the cable may suggest that actuating all three cables simultaneously is required. However, the benefit seen from removing slack in an unactuated cable is likely negligible and therefore the concept of only needing to actuate two cables at any given time still holds.

### 3.5 Forward Kinematics of Manipulator

To complete the forward kinematics, the PSM’s first three degrees of freedom must be included as a transformation matrix. The transformation from the base frame located at the remote centre of motion to the first notch of the wrist is as follows:

\[
T_{PSM} = \begin{bmatrix}
\cos(\theta_1)\sin(\theta_2) & -\sin(\theta_1) & -\cos(\theta_1)\cos(\theta_2) & -d_3\cos(\theta_1)\cos(\theta_2) \\
\sin(\theta_1)\sin(\theta_2) & \cos(\theta_1) & -\cos(\theta_2)\sin(\theta_1) & -d_3\cos(\theta_2)\sin(\theta_1) \\
\cos(\theta_2) & 0 & \sin(\theta_1) & d_3\sin(\theta_2) \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

Using Figure 5 from Chapter 1 as a guide, \( \theta_1 \) and \( \theta_2 \) represent the two revolute joints while \( d_3 \) defines the distance from the remote centre of motion to the first notch of the wrist. Based on the design of the trocar and a requirement of the da Vinci Research Kit’s software, the instrument’s end-effector will always be well past the remote centre of motion, making \( d_3 \) always positive.

The wrist kinematics is the bending kinematics combined with a degree of freedom to roll the entire tube at its base.
\[ T_{\text{wrist}} = T_{\text{roll}}T_{\text{bending}} \]  

\[
T_{\text{wrist}} = \begin{bmatrix}
\cos(\theta4) & -\sin(\theta4) & 0 & 0 \\
\sin(\theta4) & \cos(\theta4) & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix} \prod_{n} T_{\text{3notch}}
\]

The full forward kinematics of the manipulator is then:

\[ T_{FK} = T_{PSM}T_{\text{wrist}} \]
Chapter 4
Parameter Selection and Manufacturing of the Wrist

4 Parameter Selection and Manufacturing of the Wrist

4.1 Chapter Summary

This chapter discusses the selection of parameters which define the geometry and dimensions of the wrist joint. One of the joint parameters, $c$, has influence over whether actuation of the joint is decoupled. The joint is tested for coupling through an finite element analysis of a modelled version of the joint. The parameter $c$ is varied to determine its effect on coupling. Following the parameter selection, the manufacturing and assembly of the wrist is described.

4.2 Finite Element Modelling for Parameter Selection

The finite element modelling (FEM) package ANSYS 16.2 (ANSYS Inc., USA) is used to model the joint and predict which parameter values will be most desirable. The FEM software will inform the selection of the following parameters: the notch cut depth, $g$, the offset distance, $c$, as well as the actuation cable diameter. The software is also used to provide a verification of the previous assumptions made in Chapters 2 & 3 that the angle of each notch is only influenced by the aligned actuation cable or in other words that coupling is negligible. The material parameters used for nitinol are based on those provided by Liu et al. based on material from the supplier NDC, the same supplier for the tubes used for this research. [50] The material properties are included in Table 4.

<table>
<thead>
<tr>
<th>Table 4: ANSYS Properties for Nitinol taken from [50]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus of the Austenite phase ($E$)</td>
</tr>
<tr>
<td>Poisson’s Ratio ($\nu$)</td>
</tr>
<tr>
<td>Material response ratio between tension and compression ($\alpha$)</td>
</tr>
<tr>
<td>Maximum residual strain ($\varepsilon l$)</td>
</tr>
<tr>
<td>Starting stress value for the forward phase transformation ($\sigma SAS$)</td>
</tr>
<tr>
<td>Final stress value for the forward phase transformation ($\sigma FAS$)</td>
</tr>
<tr>
<td>Starting stress value for the reverse phase transformation ($\sigma SSA$)</td>
</tr>
<tr>
<td>Final stress value for the reverse phase transformation ($\sigma FSA$)</td>
</tr>
</tbody>
</table>

To recreate the true bending behaviour of the joint, a cable is modelled and fixed to the joint and can be displaced to cause the joint to bend, as shown in Figure 18. To simulate the attachment
between the joint and the actuation cable, a spot weld contact was used, and a frictional contact was specified with a coefficient of friction of 0.3 between the outer wall of the tube and the cable. A rigid constraint was implemented to fix the joint’s base. The joint was actuated by applying a displacement to the bottom face of the cable. The model mesh consists of elements of type Solid186, and the mesh size of 0.1 mm.

![Figure 18: ANSYS Joint Loading. The model on the left is used for defining the cut depth. The model on the right is used to define the offset distance and detect coupling.](image)

4.3 Parameter Selection

This section discusses how the parameters which define the dimensions of the joint are selected to ultimately manufacture the joint. Refer to Figure 15 from Chapter 3 for the parameter definitions.

4.3.1 Tube Size, OD & ID

The most important constraint that has been selected for this new instrument and what will define the tube size is achieving a 2 mm shaft diameter. The outer diameter of the tube can be determined if the actuation cable and steel wire diameters are defined. Given that the moment arm for the actuation cable and steel wire diameters are defined. Given that the moment arm for the actuation cables are maximized and therefore the tensions required are minimized, the smallest available actuation cable of 0.15 mm (0.006”) is selected initially for determining the tube’s outer diameter. The steel wire selected for the rings is the same as the actuation cable at 0.15 mm diameter. This adds a total thickness of 0.6 mm to the outer diameter of the tube.
Therefore, to achieve a 2 mm shaft diameter, a 1.4 mm outer diameter is desired. Based on the tube sizes readily available, a 1.37 mm outer diameter tube is selected with an inner diameter of 0.94 mm.

4.3.2 Notch depth, g

The most important factor for selecting the notch depth is the strain at maximum closure of the notch. These joints must remain within the elastic strain limit in order to return to their original unstressed position. The manufacturer of the procured nitinol tube, NDC, provides an elastic strain limit of 6%. Swaney et al. report that the recoverable strain for nitinol is typically quoted for 8-10% so the value provided by NDC may be conservative. [37] In order to increase joint stiffness while remain within the elastic strain limit of the nitinol, the joint is designed to reach 6% strain at full closure of the notch.

FEM is used to determine a notch depth that results in 6% strain at full closure. A single notch is modelled and varying notch depths are applied. The values for g are expressed as a percentage of the outer diameter. The height of the notch, h, and the offsets, c, for this test are selected to be 50% and 25% of the tube’s outer diameter. These parameters are expected to have minimal affect on the strain of the joint. Notch depth, g, is varied from 80%-90% of the outer diameter and the total equivalent strain is recorded when the notch is fully closed. Five samples were used at 2.5% intervals. Images and a plot of the results are included in Figure 19 and Figure 20.

![Figure 19: FEM Results for notch depth at 90% (left) and notch depth at 80% (right). Note the difference in location of the maximum strain.](image-url)
The notch depth associated with 6% strain is 85% (1.16 mm). This is the value that is selected which has a resulting neutral bending axis location, $\bar{y}$, of 0.56 mm.

4.3.3 Notch height, $h$, and number of notches in each plane, $n$

The parameters $h$ and $n$ are selected based primarily on the maximum bending angle of the joint. The notch height defines the maximum bending angle for a single notch and the number of notches $n$ multiplies the maximum bending angle of a single notch by some integer value. Based on existing instruments, the wrist should articulate to 80° in every direction. Achieving this requirement should be met both at and between the primary bending directions. From the kinematics, the maximum bending angle in between the primary bending directions is approximately 15% less than along the primary bending directions. As a result, the maximum bending angle along the primary bending directions should be greater than 80°. A maximum bending angle of 90° along the primary bending directions is selected with the smallest maximum bending angle considering all directions being 77°. This is considered adequately close to 80°.

With a maximum bending angle of 90° along the primary bending direction, $n$ must be selected which will in turn define $h$. As $n$ must be an integer, the bending angle of a single notch is
restricted to either 90°, 45°, 30°, 22.5°, 18° etc. The larger the maximum bending angle of a single notch, the larger the required $h$ value. This relationship is defined from York et al. [38]

$$\theta_{max} = \frac{h}{r_o + \bar{y}}$$

(16)

Selecting a large $h$ may lead to buckling during actuation and an unpredictable bending shape. The existing kinematic model assumes that the notches undergo constant curvature in bending, as well as applies a small angle approximation to solve, which is more accurate for smaller notch heights. Selecting a height that is very small requires more notches to achieve the maximum joint bending angle resulting in more length of the joint designated for solid tube offsets, $c$, which do not contribute to the bending of the joint, reducing the joint’s compactness. In an effort to achieve the most compact joint possible while still maintaining good predictability in the joint’s bending behaviour, a maximum bending angle of 30° for a single notch is selected. This has an associated notch height of 0.65 mm. To reduce time taken for manufacturing, the notch height will be selected based on the closest end mill size available. A 0.026” end mill is selected, creating a notch height of 0.66 mm. The number of notches within each bending plane is therefore three to achieve 90° maximum bending along the primary bending planes. Three notches in each direction results in nine notches total to make up the wrist joint.

4.3.4 Offset, $c$

The width between cuts, known as the offset $c$, is length along the joint which is not contributing to the bending but is necessary as multiple notches are required to achieve large (>40°) bending angles. Initially this distance was minimized as much as possible so long as the joint could be machined successfully. However, this highlighted an initially unforeseen constraint that must be included when selecting an offset width. When the offset width is very small, there is risk that the offset width can become as or more compliant than the intended compliant section of the joint. This significantly affects coupling between the different actuation directions. This is a unique consideration for 2-DoF bending notched tube joints and does not affect existing 1-DoF square asymmetric notch joints. Therefore, the offset width must be selected to be substantially thicker than the compliant section of the notch. The affect of coupling due to varying the offset width will be explored through finite element analysis techniques in the following section. From this analysis, an offset width is selected.
4.4 Determining Offset Width and Coupling using Finite Element Analyses

4.4.1 FEA Study

An existing assumption regarding the design of the wrist joint is that coupling is negligible. Specifically, that each actuation cable will only influence the notches it is aligned with. However, depending on the parameter selection, this may not be true. To ensure that the bending occurs at the intended location, the offset distance, $c$, between notches must be sufficiently large. An offset distance that is too small may result in the material between notches being more compliant than the intended bending section of the joint, changing the bending behaviour. However, increasing the offset distance will increase the overall length of the joint, making it less compact. It is expected that the thickness of $c$ must be at least as large as the remaining material of the notch. Defining how much larger is tested using a finite element analysis in ANSYS. A three notch tube segment is modelled based on the parameters defined in this chapter. The offset distance, $c$, is varied from 100% (0.22 mm) to 200% (0.43 mm) of the intended bending section’s width (OD-g) at 20% increments. The modelled joint segment is actuated by a cable aligned with the middle notch such that it fully closes which corresponds with a bending angle of 30°. The angle of each notch is measured to determine the presence of coupling. Images and a plot of the results are included in Figure 21 and Figure 22.
Figure 21: Bending behaviour for two joint sections with varying offset lengths, with colour representing strain. The joint on the left has an offset length of $(OD-g)$ while the joint on the right has an offset length of $2(OD-g)$.

Figure 22: Offset length vs. angle of unactuated notches when an adjacent notch is actuated to fully close $(30^\circ)$. The plot demonstrates that as the offset length increases, the coupling is reduced.
The smallest offset length which provided less than 2° of coupling is 1.65 times (OD-g) or 0.34 mm. This value provides a compromise between good decoupling of the joint while still achieving a compact joint.

4.4.2 Cable size selection revisited

From the FEA tests, the actuation cable tension required to close a single notch with the selected parameters was 1.7 N. Multiplying this result by three to close three aligned notches is still well below the rated minimum breaking force of 23 N for the initially selected cable diameter of 0.15 mm, supplied by Carl Stahl Sava Industries, Inc., USA. Therefore, this cable size is selected for actuating the joint.

4.4.3 Parameter selection summary

Table 5 summarizes the parameter selection for the wrist joint.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube outer diameter, OD</td>
<td>1.37 mm</td>
</tr>
<tr>
<td>Tube inner diameter, ID</td>
<td>0.94 mm</td>
</tr>
<tr>
<td>Notch depth, g</td>
<td>1.16 mm</td>
</tr>
<tr>
<td>Notch height, h</td>
<td>0.66 mm</td>
</tr>
<tr>
<td>Number of notches in each plane, n</td>
<td>3</td>
</tr>
<tr>
<td>Offset, c</td>
<td>0.34 mm</td>
</tr>
<tr>
<td>Total joint length</td>
<td>8.66 mm</td>
</tr>
<tr>
<td>Actuation cable diameter</td>
<td>0.15 mm</td>
</tr>
</tbody>
</table>

4.5 Machining and Assembling the Wrist

All machining and assembly of the wrist joint and instrument shaft is done within the lab at CIGITI with basic manufacturing equipment; a dremel, a tabletop mill, a soldering station as well as a microscope. The tabletop mill used is a Minitech Mini-Mill (Minitech Machinery, USA) with a standard two-flute end-mill, 0.026” diameter. The following steps describe the process for machining the wrist joint as well as assembling it with the actuation cables, the cable guides, the instrument shaft and an end-effector. Images of the milling setup are included in Figure 23 and Figure 24. Figure 25 displays an assembled wrist with an end-effector.
4.5.1 Machining the Wrist

1. Cut nitinol tube down to size
2. Clamp tube with brass collet and then clamp brass collet into mill’s fourth axis
3. Position supporting base beneath the tube and clamp free end of tube to the supporting base
4. Mill the notches under manual control and with the aid of a microscope, using the fourth axis for rotating the tube between cuts
5. Mark the locations for the solder points at the distal end of the notches using the end mill

Figure 23: Tube clamp setup on the mill. A brass collet is used as an interface between the fourth axis clamp and the tube. A custom clamp is used to fix the other end of the tube. An air hose provides cooling.

Figure 24: View of cut tube through microscope.
4.5.2 Assembly with Actuation Cables, Cable Guides, Instrument Shaft & End-effector

1. With aid of microscope, add solder beads to distal end of cuts at markers
2. Position cable on tube and constrain with steel wire rings
3. Tin cable (add solder to cable)
4. Solder the tinned section of cable to the solder bead on the tube
5. Repeat steps 2-4 for all three sides
6. Slide nitinol tube into a steel tube extension with three slots for the actuation cables
7. Solder nitinol tube to steel tube
8. Pass actuation cables of end-effector down lumen of tube
9. Solder base of end-effector to the distal end of the nitinol tube

Figure 25: Assembled wrist with end-effector, Canadian dime for size reference.
5.1 Chapter Summary

This chapter discusses a base mechanism for controlling the instrument’s wrist. The base mechanism acts as an interface between the actuation disks of the PSM to achieve the desired control of the wrist. This is a unique challenge based on the wrist design since three cables achieve only two degrees of freedom. A “wiper” mechanism is proposed which can achieve the desired control of the wrist. This mechanism is highly unique for actuating a cable which is necessary given the unique requirements for controlling the wrist. The mapping of actuator space to cable displacement is included.

5.2 Base Design Requirements

The function of the base mechanism is to convert the rotations of the four actuation disks into the four degrees of freedom seen at the instrument’s tip; roll, bending the joint in any direction (2 DoF) and actuation of the end-effector. The four actuation disks are limited to +/- 170° range of motion. Rolling the entire shaft can be achieved using the same approach as existing instruments in which one actuation disk directly drives the rotation of the instrument shaft via cables, with some ratio to ensure the instrument can roll beyond 360 degrees. Actuating the end-effector should also have its own actuation disk in order to drive it independently, similar to the 5-mm EndoWrist. The remaining two actuation disks are thus responsible for articulating the wrist (pitch-yaw bending). As described previously, three cables are used to actuate the bending of the wrist. The challenge here is designing a mechanism which can actuate the three cables using two actuation disks.

In exploring possible design solutions, one possible direction was to use a similar approach to the 5-mm EndoWrist base. Controlling the pitch-yaw articulation involves using a gimbal/Stewart platform style mechanism in which many cables which drive the wrist are fixed to a flat surface which can pivot about its centre. Since three points are required to define a plane, one point of the Stewart platform is fixed with the other two points, driven by the two actuators, controlling the angle of the plane. This mechanism works well when the midline of the continuum wrist
maintains its length and all of the actuation cables can remain a fixed distance away from one central pivot point. However, this does not apply for the new miniature wrist design proposed here. From the kinematics of the wrist design described in Chapter 4, the shortening of the midline requires that an extra cable displacement is required in the case of two cable bending. As a result, the actuation cables cannot be assumed to remain a fixed distance away from one central pivot point. Instead, a new mechanism which provides significant freedom over the control of the actuation cables is required.

To develop a new base mechanism to control the bending of the wrist, it has been assumed that to bend the wrist to any reachable orientation, at most two cables are needed for actuation while the third cable maintains its length. This assumption is based on the kinematics of the wrist joint. The position which requires the longest length of cable is the straight position. All other positions would shorten each cable by some amount. By maintaining the length of the third cable, a small amount of slack may be introduced but this is not expected to affect the behaviour of the joint.

5.3 The Wiper Mechanism

A mechanism has been proposed to control the wrist, shown in Figure 26 and Figure 27. With this design, the two actuators can pull on any two of the three cables by any amount (within its limits). This is achieved by a unique approach to increase the cable path length at the instrument’s base and thereby shortening the path length at the wrist given that the total cable path length remains constant. The approach involves “pushing” on the cable to deviate from its shortest possible path length at the base. Both actuators can push or displace one of two cable paths adjacent to it, by actuating to the left or to the right. With three actuation cables total, one of the cables can be actuated by both actuators while the other two can be actuated by just one of the actuators. This allows for any two of the three cables to be displaced by any amount at any given time.

The method of “pushing” the cables to displace them and elongate their paths at the base is achieved by changing the angle of a rigid link which pivots about one end. The movements of the rigid links resemble windshield wipers on a car which motivates their name, “wipers”. The angle of each wiper (θ) corresponds with a resulting cable displacement or shortening, (Δl).
Every reachable orientation of the wrist has a unique cable displacement which can then be mapped to a desired angle for each wiper.

Figure 26: Instrument Base with Wiper Mechanism

Figure 27: Wiper Mechanism with left wiper actuating the blue cable.
Figure 28 illustrates how every bending angle can be achieved with the two wipers. The coloured lines define each of the three cutting planes and their colours match the coloured cables of Figure 27. Actuating each of the three cables individually will bend in the direction of each of the coloured lines. Figure 27 would have a resulting articulation in the direction of the blue line of Figure 28 as the blue cable is the only cable being actuated. The green cable is routed such that it can be actuated by either wiper. Bending in between the three different cutting planes is achieved by angling the wipers in the directions shown in the figure.

![Figure 28: Wiper angles required to bend in every direction.](image)

5.3.1 Actuator Singularity

This method of actuation has an important drawback. Crossing the green bending plane from Figure 28 results in an instantaneous shift of the wipers. This occurs because one of the actuation cables can be controlled by either of the actuators and crossing this cutting plane requires a transition between which wiper is actuating the shared cable. As the bending direction crosses that boundary, the wiper that is currently actuating the shared cable must be freed to actuate a different cable.

Addressing this problem to avoid a jump seen at the wrist could involve assigning that bending direction along the cutting plane to take up a small angle, such as 5 degrees, rather than be infinitely thin, as shown in Figure 28. As the desired bending direction crosses through this section, a smooth transition could take place between the wipers. When the desired bending direction is within this crossover section, the commanded bending direction would be along the
bending plane. As a result, this solution would reduce the accuracy of the desired bending direction when within this transition region although only by a small and controllable amount. Ultimately, this trade off is reasonable in order to avoid an unintentional jump in the wrist’s bend angle.

5.4 Wiper Mechanism Kinematics

The kinematics of the wiper is a mapping of the angle of the wiper to a resulting cable displacement. Solving for the wiper angle with a known cable displacement can occur after the desired cable displacement is determined. To simplify the problem, the cable is considered to be a straight line between three points, A, B, & C as shown in Figure 29. The figure depicts the simplified version of the cable path to solve the kinematics as well as the realistic cable path as it travels around the pulleys. The blue lines represent the actuation cable. The dimensions of the wiper mechanism (in millimetres) are also included.
Coordinate points are assigned to A & C with the pivot point of the wiper as the reference, O. The base structure is designed such that points A, B & C are collinear when the wiper angle is zero. Points A and C are fixed and their coordinates are based on the dimensions of the structure. The position of point B can be solved with a known length of the wiper measuring from the pivot point, L=15 mm, a known wiper width, w=6 mm, and the angle of the wiper, $\theta$.

$$B = (L \sin \theta + \frac{w}{2} \cos \theta, L \cos \theta - \frac{w}{2} \sin \theta)$$

The length of the cable is then simply the length of AB + BC. The cable displacement is therefore

$$\Delta l = (AB + BC) - AC$$
A plot of the wiper angle vs. cable displacement is shown in Figure 30. The blue line represents the algebraic solution described here. The red points represent the true geometric result based on the above diagram which includes the curved paths for the post at point A, the pulley on the wiper at point B, as well as the pulley at point C. The data was retrieved from a SolidWorks Sketch. The average error between the results from 0 to 45 degrees is 0.067mm. This error is low enough to use the simplified algebraic approach described here despite not accounting for the arcs.

Figure 30: Wiper Angle vs. Cable Displacement mapping.

The final step to control the cables with the wiper mechanism is to determine which direction the wipers must pivot. Since two of the three cables can only be controlled with a specific wiper pivoting in a certain direction, if either of those cables requires actuation, the associated wiper has a known direction. The shared cable is checked last and will be controlled by whichever wiper is not being used. In the unique case that only the shared cable is being actuated, this would fall under the singularity handling condition and both wipers should actuate it equally, half the total cable displacement each.

5.5 Components of the Base Assembly

The base is composed of either existing components from the recycled instrument (main chassis, capstans, pulleys, actuation disks), 3D printed components (structural additions, wipers, new
actuation disks) and items purchased off the shelf (screws, pulleys, wire guide for end-effector). The tabletop 3D printers used were the Form 2 (Formlabs Inc., USA) and the LulzBot TAZ 5 (Aleph Objects, Inc., USA). The capstans are used as cable tensioners for the three actuation cables. An off the shelf brass collet is integrated with the existing roll mechanism to allow for a means to firmly clamp the steel tube.
Chapter 6
Wrist Joint Characterization & Model Accuracy Results

6 Wrist Joint Characterization & Model Accuracy Results

6.1 Chapter Summary

A series of experiments were conducted to characterize the wrist joint as well as determine the accuracy of the proposed kinematic model for the wrist. Characterization experiments included cable displacement & tension vs. bending angle & radius, cable tension vs. force output and end-effector wire tension vs. tip deflection. Accuracy testing of the wrist’s bending involved driving the actuation cables using the dVRK and comparing the predicted position and orientation with the measured position and orientation.

6.2 Characterization of Wrist Joint

Three experiments were performed for characterization of the joint using the specified parameters from Chapter 4. First, the wrist is actuated through its range of motion while measuring the actuation cable’s tension and displacement as well as the bending angle and radius of the wrist. The second experiment involves measuring the force generation abilities of the wrist at different bending angles. The third experiment, measures the undesirable deflection of the tip of the wrist in the presence of a wire tension for actuating an end-effector.

6.2.1 Characterization 1: Cable displacement and tension vs. bending angle and radius

This experiment measures the relationship between the inputs of the notched-tube joint, cable displacement and cable tension, and the outputs of the joint, bending angle and bending radius. Figure 31 shows the experimental setup. The wrist joint is positioned below a pair of cameras to record the shape of the wrist. The cameras used are Flea3 1.3 MP cameras (Point Grey, Vancouver Canada) which are arranged in a stereo-configuration and calibrated using the MATLAB® Camera Calibration Toolbox. To induce bending, a 460P Series linear stage (Newport Corporation, Irvine, California, United States) translates an attached FSH00095 JR S-Beam Load Cell (FUTEK, USA) which is connected to one of the actuation cables. The data collection process involves translating the linear stage by 0.5 mm increments and recording the
cable tension values and the wrist shape at each increment. The wrist was actuated from straight to approximately 80°, maintaining the 0.5 mm increments, then back to straight. The joint is clamped such that the bending could easily be seen from the cameras. The stereo-configuration allows for measuring changes in depth in the event that the joint did not bend perfectly in plane with the camera. Two bending cases are evaluated, single cable actuation which involves bending along one of the primary bending planes and double cable actuation which involves actuating the joint with two cables and bending directly in between primary bending planes. For double cable actuation, in order to ensure that the tension on both cables is equal, a single cable is used which loops around a pulley connected to the load cell. The two free ends of the cable are both fixed to the joint and aligned with their separate set of notches. The tension recorded by the sensor for the double cable actuation case is what is recorded and represents double the tension of each cable. All tests are repeated five times. The resulting plots of the collected data are shown in Figure 32 and Figure 33 along with the standard error. The minimum bend radius achieved with single and double cable actuation is 5.27 mm and 4.95 mm, respectively.

Figure 31: Experimental setup for measuring cable displacement and tension while recording images of the wrist shape.
Figure 32: Cable tension vs. bending angle for single and double cable actuation.

Figure 33: Cable displacement vs. bending angle for single and double cable actuation.
6.2.2 Characterization 2: Cable tension vs. force output

With a similar experimental setup used in the previous experiment, the second characterization experiment involves varying the cable tension to apply a force at the tip of the instrument. Instead of recording the shape of the wrist with cameras, a force sensor is positioned at the tip to measure the force output of the wrist. To measure the forces seen at the tip, the tip of the wrist is positioned within a small hole (1.59 mm diameter, 2 mm depth) in a plate which is fixed to a Multi-Axis Gamma Force/Torque Sensor (ATI Industrial Automation, USA). The instrument has a tip offset of 10.5 mm which measures from the last notch to the end of the tube to represent the length of an off the shelf end-effector. The tension on the actuation cable(s) is varied and the force measurements are recorded. The tension is varied from the starting position and increased by 0.5 N until buckling of the wrist is noticeable and then reduced to 0 N and then back to the start position’s tension, if start position was not 0. Five different positions are evaluated, (-90, -45, 0, 45, 90) where positions -90, -45 and 0 involved single cable actuation and positions 0, 45 and 90 involved double cable actuation. A support block was included to minimize deflections of the steel tube when pushing on the sensor. Only lateral forces (not plunging) were measured. Figure 34 shows the experimental setup. Figure 35 and Figure 36 shows a plot of the results. Table 6 summarizes the force range for each configuration. For the non-zero positions, forces are measured in two separate directions since the joint’s cables are tensioned further and then released to zero followed by retensioning to the starting tension. During the release to zero tension, the joint is trying to straighten and therefore is pushing on the sensor in the opposite direction as when the cable is tensioned.
Figure 34: Experimental setup for cable tension vs. force output. Image on the right depicts the -90° configuration. The positive and negative signs represent the directions for both angle and force.

Figure 35: Single Cable Actuation: Cable Tension vs. Force Applied at Tip
The third characterization experiment involves measuring the change in the wrist’s position when tension is applied to a wire passed down the lumen of the tube to actuate an end-effector. This tip deflection represents an undesirable coupling between actuation of an end-effector and the instrument’s tip position. Due to the design of the wrist joint, high wire tensions can result in compressing the joint. The experimental setup is the same as the first characterization experiment except that the actuation cable is replaced with two 0.2 mm diameter steel wires, the same wire used to control a pair of off-the-shelf biopsy forceps. The wire is restricted from being pulled past the end of the tube to simulate applying a clasping force between the jaws. The wire’s tension is increased in increments of 0.2 N up to 2 N. The test is repeated five times at each of

\[ \text{Table 6: Force output data summary} \]

<table>
<thead>
<tr>
<th>Angle</th>
<th>Force Range (N)</th>
</tr>
</thead>
</table>
| Single Cable  
-90° | [-0.26, 0.36] |
| -45° | [-0.37, 0.25] |
| 0° | [-0.29, 0] |
| Double Cable  
0° | [0, 0.15] |
| 45° | [-0.25, 0.45] |
| 90° | [-0.27, 0.38] |

6.2.3 Characterization 3: End-effector cable tension vs. tip deflection

The third characterization experiment involves measuring the change in the wrist’s position when tension is applied to a wire passed down the lumen of the tube to actuate an end-effector. This tip deflection represents an undesirable coupling between actuation of an end-effector and the instrument’s tip position. Due to the design of the wrist joint, high wire tensions can result in compressing the joint. The experimental setup is the same as the first characterization experiment except that the actuation cable is replaced with two 0.2 mm diameter steel wires, the same wire used to control a pair of off-the-shelf biopsy forceps. The wire is restricted from being pulled past the end of the tube to simulate applying a clasping force between the jaws. The wire’s tension is increased in increments of 0.2 N up to 2 N. The test is repeated five times at each of
the three different joint bending angles, $0^\circ$, $45^\circ$ & $90^\circ$. Figure 37 shows a plot of the results along with standard error.

![Figure 37: End-effector wire tension vs. Tip Deflection](image)

6.3 Kinematic Model Accuracy for Wrist Joint

In Chapter 3, a kinematic model was proposed which predicts how the wrist will bend based on the displacements of the actuation cables. To measure the accuracy of the model, the wrist was actuated to many points throughout the workspace in a random order. The predicted position and orientation was compared with the measured position and orientation to determine the error.

To perform the experiment, the wrist joint was attached to a shaft which was secured to a da Vinci tool base. The tool was mounted on to a Patient-Side Manipulator which allowed for controlling the tool through software. The three actuation cables were controlled by separate actuators. The wrist was positioned above an Aurora (NDI Medical, Canada) electromagnetic tracker with a sensor secured within a distal section of the tube. Only the three actuators which controlled the three cables were used for this test, the other four degrees of freedom were held constant.

The method used to determine a global reference for the wrist involved actuating the wrist to bend in each of the three primary bending planes as well as outline the boundary of the
workspace. The positions were recorded and the values were transformed to align with the
kinematics positions based on a least squares estimation using Horn’s quaternion-based
algorithm. The result is the transformation matrix which shifts the arbitrary sensor location to the
location near the origin based on the kinematics. This calibration process was also used to inform
the actuation cable’s zero position as well as the location of the sensor within the tube.

The bending workspace of the wrist was discretized by first discretizing the range of a single
actuation cable’s displacement and then combining multiple cables with that same discretization.
The resulting tip position and orientation was solved for each input to create a discretized
workspace with 135 total positions. The order of the target positions was generated randomly.

To avoid actuating three cables at a time which would not be possible with normal operation, the
accuracy tests were split into three parts. For each of the three parts, one of the cables was not
actuated. As a result, two thirds of the workspace was tested at a time for a total of three times
and therefore each target point was visited twice.

Table 7 lists the error values for the accuracy testing. Figure 38 displays the experimental setup
alongside the calibration trajectory. Figure 39 displays a comparison of predicted positions in red
vs. measured positions in blue and its error.

Table 7: Accuracy results comparing the measured tip positions and orientations with the
proposed kinematic model for the wrist joint

<table>
<thead>
<tr>
<th></th>
<th>Position Error</th>
<th>Orientation Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.64 mm</td>
<td>(7.2°, 5.7°, 8.1°)</td>
</tr>
<tr>
<td>95th Percentile</td>
<td>1.36 mm</td>
<td>(14.8°,12.8°, 17.6°)</td>
</tr>
</tbody>
</table>
Figure 38: Experimental Setup and Calibration Trajectory

Figure 39: Comparison of Desired (red) and Measured (blue) Positions for Accuracy Test
Chapter 7
Teleoperation of the Miniature Instrument on the da Vinci Research Kit

7 Teleoperation of the Miniature Instrument on the da Vinci Research Kit

7.1 Chapter Summary

This chapter outlines a teleoperation experiment of the instrument in a mock clinical scenario. Two instruments along with an endoscope were passed through ports into a bell pepper. Using scissors and forceps, a section of the pepper was dissected. The experiment demonstrated that the instruments are capable of performing basic operations.

7.2 Teleoperation Setup within a Bell Pepper

To evaluate the capability of the miniature instrument in a surgical capacity, a mock clinical scenario was setup using a bell pepper. A bell pepper offers a natural cavity within its centre as well as a fleshy material which can be manipulated and dissected. Additionally, the seeds are a unique item that can be handled and extracted. In general, the use of a bell pepper offers many similarities to the internal cavities of the human body and is a very affordable option for initial medical device testing. Bell peppers have been used for neuroendoscopic training however have not been used for surgical robotics testing in the past, to the author’s knowledge.

For this experiment, two instruments were assembled, one with biopsy forceps as the end-effector and the other with scissors. Three ports were made on the pepper, one for each instrument and the third port for an endoscope, seen in Figure 40. The instruments were teleoperated using the master manipulators by the author.
Figure 40: Experimental Setup for Teleoperation Task within Bell Pepper

Once the instruments and endoscope were positioned inside the pepper, the task was to dissect the flesh and seeds from the top of the pepper. This involved both instruments working in coordination, the forceps for grabbing the seeds and flesh and the scissors to cut away the surrounding wall. Occasionally, a pick and place of the seeds was performed to experiment with the dexterity and accuracy of the instrument control.

7.3 Qualitative Results

Figure 41 includes images of the teleoperation task from the view of the endoscope. The teleoperation task was performed for 23 minutes. A video of the procedure was recorded. Figure 42 shows an image of existing instruments within the same cavity for comparison.

The instruments fit very easily into the relatively constrained volume and had adequate space to work in coordination. The small diameter allowed for the instruments to work in very close proximity. This was evident in the cases where the forceps could grab the 4 mm diameter seed while the scissors cut away the flesh at the base of the seed. The instruments were very capable of grabbing a part of the pepper’s flesh and cutting through it. The wrist’s ability to articulate
fully within the confined space was possible although the offset from the primary location of bending which is toward the base of the wrist to the tip of the end-effectors appeared large within the small volume. Coupling between the end-effector actuation and the change in the tip position was insignificant and for the most part unnoticeable.

Figure 41: Screenshots from endoscopic view of the teleoperation task. The diameter of the seeds are approximately 4 mm for size reference. The top left image shows the biopsy forceps on the right instrument grasp a piece of flesh while the scissors on the left instrument cut through the middle of the flesh. The top right image demonstrates the wrist’s ability to reach around a structure and into a small cavity. The bottom left image shows a pick and place of one of the seeds. The bottom right image shows the instruments working in very close proximity.
Figure 42: Existing EndoWrist Instruments within the same cavity for size comparison.
Chapter 8
Discussion

8 Discussion

8.1 Research Approach and the da Vinci Platform

Upon researching the limitations associated with performing robotic surgery for new applications with smaller operating volumes, the existing instrument sizes were reported as the main barrier. It is important to note that although the da Vinci is by far the most prominent and widespread robotic surgical system in use today, its current design is not appropriate for use in all surgical applications. Specifically, the system is developed similar to laparoscopy which involves multiple ports for access to the same surgical site. However, other applications require a single entry port in which multiple instruments must be passed through parallel channels. Therefore, this particular implementation of a miniature instrument will not enable the application of the da Vinci to all surgical applications. Rather, the primary contribution of this research, the design and kinematics of a 2 mm 3-DoF wrist should be considered when in need of significant dexterity at a very small scale. Implementing the wrist as a da Vinci instrument has multiple advantages primarily through the use of the da Vinci Research Kit but also because of the increased likelihood that this research may be implemented clinically by creating a device that is compatible with a widespread robotic surgical system. Alternative implementations of this wrist could include incorporating it at the distal end of a concentric tube robotic system similar to [37] as well as integrating it with a manual, hand-held instrument. This research has attempted to further expand the potential of robotic surgery by discovering what is possible regarding dexterity and articulation at the 2 mm scale. Very few 3-DoF wrists with an active end-effector have been built and teleoperated at this scale which motivated this constraint. This size constraint also has allowed for the possibility of using this wrist joint for operating in one of the most confined surgical applications, endoscopic neurosurgery. Figure 43 shows how the wrist fits within the lateral ventricle of a brain model.
As mentioned, a key vehicle for this research is the da Vinci Research Kit. Developing custom instruments for this system has greatly accelerated the transition from concept to implementation. Rather than developing a new mechatronics actuation system along with the software and teleoperation components, creating an instrument for the dVRK is almost exclusively a mechanical design problem. This places the focus on the size, dexterity, and stiffness of the instrument’s wrist design, improving performance as well as leading to a faster design cycle. Also, introducing new technologies as an add-on to a commercially available robotic platform may accelerate their transfer to wider clinical use.

8.2 Joint Selection and Design

The primary factors which led to the selection of notched nitinol tubes for the joint type include the qualitative performance review of the various joint types used for minimally invasive surgery as well as the resources readily available within the research facility. These are reviewed to discuss potential bias regarding joint selection.

The review paper by Jelínek et al. scored bending flexure joints the highest based on their performance criteria. However this result is likely biased toward factors such as simpler joint complexity and providing an inner lumen while not including factors such as repeatability and lifetime. Different joint types are likely to be superior at different sizes however this is not captured in the performance analysis. The result of the performance analysis might lead to the question why aren’t the existing da Vinci instruments bending flexure joint types if they are
considered to have superior performance? To answer this, bending flexure joints are typically less repeatable than discrete hinged joints and they are more likely to break due to fatigue.

Considering the application, robustness and reliability should be paramount for clinical use of the reviewed joints. The bias present in the performance review seems to favour joints that are easily scalable which is the primary advantage of bending flexure joints. This aligns with the focus of this research, developing smaller instruments, and therefore the review is still referenced as an insight into suitable joint types for this application. Robustness is not reviewed in this research as it has been studied by Peirs et al. and Swaney et al. from which they were both able to achieve over 8000 cycles of their notched-nitinol tube joints which suggests that if these instruments are considered disposable or limited use, as is the case with the current da Vinci instruments, this type of joint could be reliably used in a clinical setting. [37], [46]

The other factor influencing the joint selection is the resources available at the facility where this research was conducted. Through other research pursuits, nitinol tubing was readily available. Most other joint designs required machining very small and relatively complex parts. As the only readily available means of machining was a tabletop mill, achieving the required precision for a complex part would likely need to be outsourced. However, from prior attempts, the mill was deemed suitable for cutting very basic notches out of nitinol tubing. Being able to manufacture the joint in house was preferred due to the nature of these joints being susceptible to breaking and the cost of outsourcing the machining. Therefore, the resources readily available influenced the joint selection. The benefit of this approach is that the resulting instrument design can be built at a relatively low cost and with minimal lead time.

The research field of notched nitinol tubes appears to have room for significant advancement. The review of existing notched tube topologies from Chapter 2 have fairly basic cutting shapes. Related research at CIGITI has begun exploring unique cutting shapes beyond simple squares or triangles in an effort to improve joint performance. Early results suggest that these unique topologies can improve the joint’s stiffness and compactness. Based on these early results and because this type of research is new, the potential for significantly improved performance of these joints appears to be high. It is expected that the square notch topologies for the joint presented in this research can be replaced with a different asymmetric topology and almost all of the contributions made from this research would still be relevant. Regarding future notched tube joint topologies, it is predicted that future optimal multi-DoF notched tube joints that are 2 mm
or less in diameter will compose of asymmetric notches with a unique cutting shape that are positioned 120 degrees apart and actuated with cables on the outside of the tube. Each individual notch will be able to bend up to 80 degrees without the current limitations of doing this with square notches resulting in the shortest possible joint length along the tube making for both a stiff and compact joint. This prediction is based on the hypothesis that asymmetric notches scale better than symmetric notches because removing material from both sides of a small tube will result in very thin middle bending structure. Also, when fatigue is considered, the primary benefit of increased range of motion for symmetric notches is minimized. Lastly, as the topologies of the notches become more complex, having more room for cutting may be crucial.

An additional benefit to the notched tube joint design refers back to the studies applying the da Vinci to neurosurgery and otolaryngology in which the authors commented on a lack of suction and irrigation instruments. Existing EndoWrist instruments do not have an open lumen to easily enable an articulating suction instrument but this is now possible with a notched tube wrist design.

8.3 Validity of Kinematics Approach and Assumptions

The main assumptions associated with the previous kinematics model for in plane bending of square notch joints include constant curvature bending of the notch and small angle approximation. These assumptions were tested by York et al. and determined that the measured path of the tip position throughout the joint’s bending range showed reasonable agreement with the kinematics. The maximum bending angle of a single notch for their prototype was 28°. The maximum bending angle selected for this joint is 30° so the results are expected to be similar.

The assumptions introduced with the new kinematic model for multi-DoF bending include the cable path locations and zero coupling. Due to the design of the cable guides, the cable path is not fully constrained along the joint. As a result, when in tension the cables may deviate from their ideal position. This can be accounted for in the case of the small extra distance epsilon used for the location of the cable which is actuating the notch. For the other cables across the notch that are not contributing to its bending but are still in tension, they won’t take on the arc shape as depicted in the three segment joint diagram of Chapter 3. Instead it will likely take on a straight line. Since the notch is assumed to be a small angle, the difference between an arc shape and a straight line should be negligible. Whether that line is shifted is of greater concern. From
observation, the amount that the cable shifts is not enough to change which set of notches it is influencing. This is in part due to the joint’s design and the notch spacing of 120°.

8.4 Wiper Mechanism

The base of the instrument developed to be compatible with the da Vinci Research Kit consisted of a unique solution to achieve control of three cables using two actuators. This solution was developed as a result of the constraint of using the same base as existing instruments. Use of the wiper mechanism could be avoided with the addition of a fifth actuator for the base however this would introduce the possibility of actuating all three cables simultaneously which is undesirable and may break the joint. The wiper mechanism mechanically ensures that at most two cables are actuated at any given time and therefore in the case of a malfunction, the wrist is less likely to fracture.

The uniqueness of the wiper mechanism goes further when considering the kinematics of the wrist. Due to the shortening midline of the tube during bending, a significant amount of freedom to shorten any two of the three cables by any amount is required. This is provided with the wiper mechanism which could not be achieved with other approaches to control three or more independent cables from the base.

8.5 Experimental Results Interpretation

Four experiments were conducted to both characterize and measure the accuracy of the wrist joint. The first characterization experiment which measures the bending behaviour based on cable displacement and tension provides some insight in to how the two inputs differ. The y-axis of the plots is bending angle as controlling the joint’s position or angle is the most conventional use for a teleoperated robotic system. The advantage of controlling the joint based on cable tension is that it is expected to be more repeatable in the presence of unwanted cable slack.

Defining a zero position for the cable displacement is challenging due to the ambiguity regarding whether the joint is being actuated or slack is removed near the zero cable displacement position. The problem with controlling position or orientation of the wrist with cable tension is shown in the plot which demonstrates a significant difference in the loading direction vs. unloading. Therefore, controlling the joint’s position based on cable tension would likely need to account for whether the joint is loading or unloading which would significantly complicate the control.
The cable displacement plot however shows minimal difference between the loading and unloading directions. This supports the approach used to control the wrist based on cable displacements. There is a small difference between loading and unloading although this is within an acceptable range for orientation error.

Based on the minimum bending radius results, the compactness measurement can be defined for the instrument: 1 mm shaft radius + 5 mm bending radius + 6 mm offset to base of forceps = 12 mm. This result is an improvement on the compactness of both existing instrument designs and is smaller than all of the other <3 mm wrist designs mentioned from Chapter 1 except for the I-Flex.

The second characterization experiment aimed to determine the force output range of the joint in various configurations. The results suggest that throughout the joint’s range of motion, the joint can transmit at least 0.15 N laterally at the tip of the end-effector. Of the configurations measured, actuating the tip from a straight position in between two of the primary bending planes is the weakest direction while the maximum force of 0.45 N was reached at a 45° angle when two cables are contributing equally and pushing in the direction of the bend. Using neurosurgery as an example, the forces required for brain tissue manipulation range from 0.01 N to 0.5 N. [55], [56] Currently the instrument may be capable of performing certain neurosurgical procedures however future development should prioritize stiffness and force output. Further testing is required based on a specific clinical task.

From the plots, in the cases where a pretension was required to position the wrist at a nonzero angle, there is a discontinuity in the plot. The cause of this is based on the experimental setup and hysteresis in the joint bending. The process for measuring the forces at the nonzero angles involved first bending the joint into position followed by positioning the sensor such that the tube was within the hole in the plate but the sensor read a zero value. Then after going through the range in cable tension, the tension was increased back to the starting tension. Due to the difference in loading and unloading of the material, the values do not align. A variation on this experiment to avoid this discontinuity could have involved returning the cable tension back to its max tension. The experimental setup had an artificial zero force output along the hysteresis curve and it is expected that repeated sweeps of the cable tension would avoid the discontinuity. As the
The intent of this experiment is to provide a benchmark for the force output range for the wrist joint, this information is retrieved despite the discontinuity.

The third characterization experiment measured the affect of applying tension on two end-effector wires passed through the tube’s lumen. The configuration which showed the most coupling was in the straight configuration. All tip deflections were below 0.4 mm for wire tensions up to 2 N. Introducing the wire down the lumen increases the stiffness of the joint making the joint less likely to bend and buckle. A wire is used for end-effector actuation over a cable because the end-effector is designed to both push and pull on the wire to actuate the jaws. The first characterization experiment was conducted without the wire in the lumen of the tube so in the presence of the actuation wires the required cable tension is expected to increase.

The accuracy experiment compared the measured joint positions of the wrist with the proposed kinematic model. The resulting errors are within an acceptable range for initial development although require improvement through future design iterations. New measurement techniques may be necessary to evaluate the accuracy as the average position errors are approaching the resolution of the sensor at 0.48mm RMS. Although, the orientation resolution is very high at 0.3° RMS and given that the instrument is a wrist which attempts to achieve a range of orientations within a small volume the orientation result should be the focus. The 95th percentile errors for orientation are around 15° with the average error around 7°. While these results are likely adequate in a teleoperation setting, there is room for improvement. Preferably the 95th percentile error would be below 10° with an average error below 5°. Given that the results are close to this preferred accuracy, there is motivation to try to improve the performance of this design and model as opposed to pursuing a different design.

8.6 Limitations of Experiments

The main limitation associated with the first and third characterization experiments is the position measurement approach. Stereo cameras are calibrated to allow for the selection of points on the images to convert into a Cartesian position. Due to the limited resolution in the cameras, the primary source of error is in the selection of the same location on the tube between the two images as well as between each data point. As this is done by a human, defining the edge of the tube can be challenging as it can appear ambiguous once zoomed in. As a result, the standard
error bars for each data point are likely a result of the challenge of measuring at the 100 micron scale using this method and not due to variability in the repeated attempts.

One of the limitations of the second characterization experiment is due to the force sensors tendency to drift over time. As this experiment is intended to provide a general range for the maximum force the wrist can output, the effect of the drift was deemed sufficiently small. Additional effort was made to perform the tests rapidly and zero the sensor whenever possible.

The limitations of the accuracy experiment include manufacturing errors, sensing errors and the challenge of defining the actuator position associated with a cable displacement of zero. Despite our best efforts, variability between the cut depths of each notch is possible as well as a difference in the shape of the notch depending on the wear of the end mill. Differences in the size of the cable guide rings may also affect friction and the lateral movement of the cable. The rated error for the NDI Aurora’s 6DOF sensors is 0.48 mm RMS and 0.3° RMS. Given the size of the wrist’s workspace, the rated position error is significant. Lastly, the location of the actuator associated with a zero cable displacement without any slack is highly ambiguous. Due to friction in the cable, as slack is removed from the cable line it may also be applying a small force on the joint. Determining the zero position was done iteratively based on how the calibration data matched the model, specifically the maximum bending angles. The paper which introduced the kinematic model for square notches by York et al. did not address this challenge as they were only comparing if the tip position followed the modelled path as opposed to having a predicted position compared with a measured position as was the case for this experiment. [38]

The method to define a global reference for the wrist by applying a least squares error estimation to a set of calibration points was conducted for the following reasons. First, measuring the distance of the sensor with respect to the field generator or a reference within the required accuracy (<0.5 mm) using external measurement devices would be very challenging. Second, the experiment is intended to measure the new contribution to the model which involves bending in between the primary bending planes. As the single cable actuation kinematics have been proven previously by York et al., these paths were selected for calibration while the other points in between were left for testing. The boundary points were used to define the size of the dome and inform the location of the sensor within the tube.
8.7 Teleoperation Experiment

The wrist’s ability to articulate fully within the confined space was possible although the offset from the primary location of bending which is toward the base of the wrist to the tip of the end-effectors appeared large within the small volume. This could be improved by reducing the offset from the last notch of the wrist to the tip of the end-effector through a better assembly of the end-effectors and the tube as well as improving the wrist’s compactness. However, in one situation the instrument needed to reach around a structure and the curvature of the wrist aided in accessing a deep, tucked away section of the pepper. As different clinical applications have different instrument requirements, future modifications to modify the wrist’s compactness should be made with a specific clinical application in mind.

One potential drawback to the proposed wrist design which could be evaluated during the teleoperation task is the possibility of coupling between the end-effector actuation and the wrist. The presence of coupling, if any, was negligible and did not affect the ability to use the instruments. This suggests that the tensions required for actuation were likely below 2 N in order for the coupling to be insignificant. As this is still a potential concern, the tensions required for actuation of an end-effector should be minimized for future modifications.

There were multiple challenges that were faced during the teleoperation task which influenced the overall ability to perform the desired task. The endoscope was a single image (not stereo) and therefore the 3D surgeon display was not used. The presence of the 3D display provides the operator with depth perception but a stereo endoscope was not available at the time of the experiment. Another challenge was that the off-the-shelf biopsy forceps did not have any “teeth” which made grasping significantly more challenging. As the seeds were often slimy, attempts to grasp them often resulted in slipping off of them. A third challenge faced was the limited range of motion that was allowable due to the thick actuation cable used to control the scissors. This was not a problem for the biopsy forceps which have a much smaller actuation cable, suggesting that replacing the actuation cable for the scissors with something smaller should allow the wrist to articulate through its full range of motion.

The teleoperation task within a bell pepper demonstrated that the instruments are capable of operating in this mock clinical scenario. Tissue was successfully dissected without any significant limitations during operation. Upon review of what was achieved, this instrument
design appears to be well suited for performing surgical tasks within a small volume and development of the instruments should continue to test the instruments in a real clinical scenario.
Chapter 9
Conclusion

9 Conclusion

This research has demonstrated that constructing and accurately controlling a four-degree of freedom robotic instrument with a 2 mm shaft diameter and a 5 mm bending radius is feasible. The use of notched nitinol tubes greatly aids in the miniaturization of the instrument’s wrist joint while also offering compact articulation. Developing the device as a custom instrument on the da Vinci Research Kit accelerated design and testing significantly. The proposed kinematic model for the wrist joint offers reasonable agreement with the experimental results. When tested in a mock clinical scenario, the instruments had adequate room to articulate and work cooperatively within the small confines of a bell pepper. It is anticipated that based on these results, the miniature instrument developed for this research can perform tasks within a small volume that existing da Vinci instruments cannot perform due to its reduced size. Future development of this instrument has the potential to enable new surgical applications to benefit from robotic surgery.

9.1 Contributions Summary

The primary contributions of this research can be separated into three components: miniature wrist design & modelling, the wiper mechanism for actuating the wrist, and the integration with the da Vinci platform.

9.1.1 Wrist design and modelling

In order to achieve all of the desired criteria associated with developing a miniature robotic instrument, a new wrist joint is designed. This is the first joint which uses square asymmetric notches to achieve multi-DoF bending. The benefits of square asymmetric notches include a simple manufacturing process, low actuation forces and compact bending. The unique notch pattern involves positioning the notches such that they are offset by 120° which creates three primary bending directions. Almost all existing notched tube designs are restricted to planar bending or use 90° offsets. A unique cable guide approach is also implemented in order to route the cables external to the tube. Finally, a kinematic model is proposed for controlling the position and orientation of the wrist joint. The model builds off of an existing model for planar bending and extends it for multi-cable multi-DoF bending for square asymmetric notches. The most
important modification is the incorporation of an extra cable displacement to account for the shortening of the joint’s midline. The accuracy of the model is also evaluated and demonstrated reasonable agreement.

9.1.2 Wiper Mechanism

A unique solution to control three cables using two actuators is proposed. This solution involves pushing the cable to increase its path length. This mechanism is likely the first of its kind and achieves the strict requirements of the wrist actuation remarkably well, specifically the need to have significant freedom over the displacement of each cable to achieve the additional cable shortening. A basic kinematic model is presented which maps the angle of the wiper to a resulting cable displacement.

9.1.3 Instrument Development with da Vinci Platform Compatibility

This research is among the first instances of a custom instrument for the da Vinci Platform. This instrument is, to the author’s knowledge, the first 2 mm diameter 4-DoF wristed instrument to be used with the da Vinci Platform. It is also likely the first instance of performing a teleoperation task using two custom instruments in junction on the da Vinci Research Kit.
Chapter 10
Future Work

10 Future Work

The future work is organized as future design improvements and future testing.

10.1 Future Design Improvements

The direction with the most potential for improvement is the incorporation of new notch shapes beyond squares or triangles. Based on early results from other research within CIGITI, moving toward a more complex notch shape can potentially improve on almost all aspects of the joint’s performance including stiffness, compactness and repeatability. These improvements may provide notched-tube joints with a new capability that is unrivaled for joints at or below the 2 mm scale.

Another modification that would improve performance of the instrument include a new cable guide approach which constrains the cable along the entire length of the joint. This is challenging since it involves creating channels for the 0.15 mm cables without increasing the overall diameter. Similarly, a sheath around the entire joint is likely necessary for future clinical use to avoid artifacts blocking the notch closure.

10.2 Future Testing

The instrument requires further testing and refinement to achieve the ultimate goal of implementing it for clinical use. The first tests include testing the accuracy of the wiper mechanism incorporated with the wrist. Once this is considered adequate, teleoperation tasks can be performed to evaluate the efficiency of the instrument’s movements and its ability to perform the tasks. This could be conducted as a comparison with existing instruments to try to determine at what operating volume the new instrument outperforms the existing instruments, if at all. To transfer the technology to a clinical setting, joint parameter selection should be made based on the requirements of a specific clinical application. This would be followed by performing a specific procedure first within phantom models followed by animal testing before ultimately testing in humans.
References


