COMPACT MODULAR TELEOPERATED LAPAROENDOSCOPIC SINGLE-SITE ROBOTIC SURGICAL SYSTEM: DESIGN, DEVELOPMENT, AND PRELIMINARY VALIDATION

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ABSTRACT

Minimally invasive surgery (MIS) has increasingly supplanted traditional open surgery as the preferred technique for a wide variety of common medical procedures due to vast reductions in patient scarring, trauma, and recovery time. Traditional MIS is performed by passing multiple instruments and an endoscope through several keyhole incisions in the patient body. The emerging MIS technique of single-port laparoscopy seeks to further reduce visible patient scarring by reducing the number of required operative incisions from three to one. The primary limitation in performing single-port laparoscopy is the physical burden imposed on the surgical team by passing multiple instruments and an endoscope through a single incision in close physical proximity. The spatial and dexterous challenges associated with single-port laparoscopy make the procedure an ideal candidate for robotic assistance.

To date a variety of teleoperated surgical robotic systems have been developed to improve a surgeon’s ability to perform demanding single-port procedures. However larger systems are bulky, expensive, and afford limited angular motion while smaller designs suffer complications arising from limited translation, speed, and force generation. The research presented in this thesis seeks to develop and validate a simple, compact, low cost single site teleoperated laparoendoscopic surgical robotic system. A successful design would potentially further shrink the gap in rates of positive patient outcomes between groups of surgeons by providing more surgeons better access to the benefits of robotically assisted surgical procedures.

The system presented in this thesis builds upon previous work done at the University of Hawai‘i at Mānoa and includes independently operated instrument and endoscope manipulators with a shared base structure as well as compact, articulated instruments designed to overcome single incision geometry complications. Results indicate the system has successfully met the goals associated with minimizing physical size, improving modularity, and increasing the compactness and simplicity of the system.
The use of 3D printed components and structures offers exciting new opportunities to reduce cost, simplify hardware design, and provides an effective pathway towards accessible, cost-effective robotic surgical systems. Although additional control design work is required to achieve full parity with both the previous University of Hawai‘i multi-port system and existing commercial systems the performance of the presented system is sufficient to successfully complete standard Society of American Gastrointestinal and Endoscopic Surgeons Fundamentals of Laparoscopic Surgery (SAGES FLS) peg transfer tasks.

Future work includes developing simulation environments to explore new control strategies that may improve the responsiveness of the system, the intuitiveness of the control, and potentially reintroduce degrees of freedom (DOF’s) compromised through the physical constraints of single-port minimally invasive instrument geometry. Meeting these design challenges will allow full validation of system performance and pave the way towards the next stages of pre-clinical development.
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1. INTRODUCTION

The progression of advancement in the field of surgical robotics has aimed to fulfill a twofold need in the medical community. One breed of robotic surgical system is designed to facilitate new medical procedures previously impossible or impractical to execute with existing technology. The other primary class of surgical robotics systems is developed specifically to reduce long term costs, standardize improvements in patient outcomes, and reduce surgeon fatigue. These goals are accomplished by providing technology to equalize the performance among surgeons with varying skill level. The initial breed of robotic technology that affords surgeons pathways to executing novel procedures is always of acute interest. A new four-degree-of-freedom (DOF), dexterous surgical implement under development by F. Khan et al. [1] offers surgeons new tools to perform pediatric neurosurgical procedures previously impossible due to the motion constraints of existing technology. Similarly, Rucker and Webster [2] report a new neurosurgical robot capable of operating within the confines of an MRI imaging device. The system is designed to specifically treat epileptic seizure foci in the hippocampus through thermal ablation. This new minimally invasive alternative could avoid the lengthy recovery and potential morbidity associated with traditional open brain surgery. Thereby providing the 0.5 to 1.0% of the global population affected by epilepsy the long term benefits of surgical treatment and cure at much reduced risk. Advancements in surgical technology are not only constrained to neurological treatment. A. Mahoney et al present a new system capable of manipulating free floating instrument capsules within the human body using an external array of magnetic fields [3]. This technology could potentially allow external control and navigation of remote, non-tethered, surgical instruments to gastrointestinal sites within the body currently inaccessible without conventional open surgical methods. Magnetic levitation and control represents a dramatic change in the methodology of minimally invasive surgical (MIS) techniques that stands to make gastrointestinal screening procedures safer, faster, and more comprehensive. Another limitation of current minimally invasive surgical techniques is the lack of adequate operative vision. Traditional laparoscopic cameras are typically long, rigid tubes that cannot be manipulated to adequately view the operative site during
certain procedures. The work done by A. Jiang et al. [4] describes a new type of laparoscopic design, the variable stiffness camera. The system is based upon the phenomenon of granular jamming - a principle whereby a collection of small particles act as a fluid under normal circumstances but compact into a rigid, solid structure under the application of an internal/external pressure differential. This new technology would allow visual access to angles, orientations, and locations previously inaccessible with traditional laparoscopes, and dramatically expand the suite of procedures performed with minimally invasive techniques.

Although the aforementioned technology and similar systems advance technical boundaries, they can be constrained from widespread use by the typically specialized nature of the medical procedures in which they are incorporated. Beyond this narrowed scope of specialized equipment design there exists the clear need in the medical community for technology to equalize the rates of positive outcomes among surgeons of varying skill levels. Teneholtz et al. report a distinct discrepancy in surgical outcomes of mitral valve repair between experienced cardiac surgeons and medical students in training [5]. This gap continues to persist among groups of practicing surgeons as a function of experience and ability. As a result of this gap less experienced surgeons often elect to perform safer, less challenging procedures at the expense of long term patient health. The work of Teneholtz et al. to develop a surgical simulator for the repair of mitral valves in the human heart specifically addresses this skills gap by creating new surgical tools to enhance the surgeon’s capability and allow more cardiac surgeons to pursue operative plans that generate the highest quality patient outcomes. A review of patient outcomes from robotically assisted bariatric surgical procedures by Kockerling et al. [6] shows reductions in anastomotic leak rates, bleeding rates, and mortality rates compared to traditional, manual laparoscopic surgery. Furthermore, reductions in the learning curve associated with the challenging Roux-en-Y (RYGB) gastric bypass procedure can be realized with robotic assistance. Here too more patients reap the treatment and cure benefits of technically challenging procedures that may now be performed safely by a larger number of surgeons. The need to standardize high quality patient outcomes is also not limited to Western healthcare systems as evidenced by the report of O. Al-Alao et al. documenting the growth of robot assisted surgery in Qatar [7].
The development of new surgical technology to close the gap in operative skill between groups of surgeons is a broad field with primary applications in demanding manual procedures. N. Dillon et al. [8] and B. Bell et al. [9] report competing systems designed to automate portions of mastoidectomy. This procedure is a preliminary operation required for a number of surgeries such as: cochlear implantation, acoustic neuroma tumor removal, and general mastoid infections. Bell et al. work specifically towards robotically assisted cochlear implantation. In mastoidectomy, a portion of the skull is shaved, removed, or drilled through to provide access to the underlying anatomical structures. There is a high risk of operative damage to any of the surrounding tissue, such as the facial nerve, that can lead to complications as severe as permanent partial-facial paralysis. Application of technology to mitigate this risk increases the number of patients who may benefit from the treatment. Pursuing similar goals, A. Bajo et al present a new system to perform trans-nasal minimally invasive surgery of the throat [10]. This is preferred over open surgery as it preserves the integrity of the larynx and other critical anatomical structures in the region. The development of a trans-nasal system eliminates the need for a laryngoscope and the accompanying anesthesia necessitated by current systems dependent upon trans-oral access. The result is a safer, less invasive operation more readily performed by a larger cadre of surgeons. Robotic assistance can also be applied to instrument imaging and guidance as demonstrated by P. Loschak et al [11] via a new system for robotic steering of cardiac ultrasound imaging catheters. Many cardiac arrhythmias can be effectively treated by radiofrequency catheter ablation. However traditional systems are severely limited by the use of x-ray fluoroscopy as the primary imaging methodology. X-ray imaging cannot effectively distinguish soft tissue structures and also exposes patients and surgical staff to ionizing radiation. For these reasons, intracardiac echocardiography (ICE) catheters are a newer, safer technology routinely used during ablation procedures for their fine-scale soft tissue visualization capability. Unfortunately, manual use of ICE catheters requires specialized training and maintaining proper imaging plain alignment is a significant challenge. The development of assistive robotic technology for this application reduces the surgical training load and improves the safety, speed, and robustness of the ablation procedure. Consistent with the previously discussed systems, the use of robotic ICE catheter steering
reduces the risk and complexity of the ablation procedure allowing a greater number of patients access to the benefits of treatment.

The research presented in this thesis falls into the class of assistive surgical robotic systems developed to reduce long term costs, standardize improvements in patient outcomes, and reduce surgeon fatigue. The primary goal of the research is to further shrink the gap in rates of positive patient outcomes between groups of surgeons by providing more surgeons better access to the benefits of teleoperated laparoendoscopic surgical robotic systems. This is accomplished by developing and validating a teleoperated laparoendoscopic surgical robotic system that is smaller, portable, and a dramatically less expensive system than conventionally available commercial systems. Adoption of this technology into the broader medical community would make robotic assisted surgical procedures both more practical and economically viable in a number of currently underserved regions. Since robotically assisted procedures have been shown to improve rates of positive patient outcomes compared to traditional manual procedures [6, 12], technology leading to greater adoption of robotic assisted surgery can be expected to close the outcome gap for groups of patients served by surgeons of varying skill.

The robotic system presented in this thesis is designed specifically to facilitate single-port access (SPA) laparoendoscopic minimally invasive surgery. Single-port access surgery [13] aims to reduce the invasiveness and amount of visible scarring from traditional minimally invasive laparoscopic surgery by reducing the number of operative incisions. This is accomplished by passing two individual instruments and an endoscope through a single, common incision as opposed to the traditional method of individual incisions for each surgical implement. A primary complication introduced by single-site techniques is the loss of instrument triangulation within the operative field. Since all instruments pass through a common incision there is difficulty recreating the instrument spacing and orientation found at the operative site in traditional multi-port MIS. This geometry is critical for providing the surgeon with adequate dexterity and ranges of motion to effectively accomplish typical surgical tasks at the operative site [14]. Fortunately, this limitation can be practically resolved by performing the procedure with angled or articulated instruments [15]. These instruments are developed to provide
functionality similar to existing, standard laparoscopic instruments. Although these modified instruments are effective in reintroducing the required instrument motion within the operative field, they also impose a formidable physical burden on the surgeon and surgical team [14, 16]. Attempting to manually manipulate two, slender instruments confined in close physical proximity while another member of the surgical team must manually position an endoscope occupying the same space creates a cumbersome and physically limited operative environment. For surgeons utilizing the increasingly popular and generalized SPA technique [17, 18], addressing the specific challenge of accurately manipulating two instruments and an endoscope passed through a common incision point continues to make SPA an ideal candidate for teleoperated robotic automation and the primary focus of this research. The improved dexterity, accuracy, and positional control of assistive robotic systems can effectively address the manual difficulties associated with re-triangulated instruments and reduced ranges of motion.

Although a number of single-site robotic systems have been developed to address the limitations of manual SPA surgery, there are functional challenges associated with each of the prominent, existing design approaches. Larger systems equipped for single port operation such as the Intuitive Surgical da Vinci [19] and Titan [20] systems are bulky, expensive, and afford limited angular motion. Smaller designs such as the miniature system from Wortman et al. [21], the Araknes system [22], and the internal manipulator system of Won-Ho et al. [23] suffer complications arising from limited translation, speed, and force generation. By addressing these functional deficiencies, the simple, compact, modular teleoperated surgical system presented in this thesis provides advantages in portability, cost, and ease of use compared to existing systems. The stated advantages make the presented system a more viable assistive robotic option for a broader segment of the global medical community thereby potentially increasing the number of surgeons operating with robotic assistance and improving the rates of positive patient outcomes.

This research builds upon previous work completed at the University of Hawai‘i at Mānoa by redesigning the previous UH multi-port laparoscopic surgical robotic system [24] into a more compact single port system. The preliminary design concept as
described by Berkelman and Okamoto [25] modifies a 180mm X 330mm ViKY XL endoscope manipulator base from EndoControl SA to use as a shared, two DOF base structure. Two independent, four DOF, serial manipulator arms are incorporated into the base along with the pre-existing, single, one DOF endoscope manipulator. The four DOF manipulator arms operate a pair of interchangeable, two DOF, mechanized instruments. The instruments are modular and rapidly interchangeable minimizing the need to introduce different surgical tool tips via additional incisions. Each instrument – manipulator arm pair is teleoperated via a Geomagic/Sensable Phantom Omni [26] master control modified with an additional end effector control interface. Instrument end-effector motions are also coupled to non-zoom endoscope positioning motions for ease of use and intuitive operator control. The assembled robot can be autoclaved for simple setup and tear-down by removing both instruments. Full description of overall system size, ranges of motion, and force generation are described in [25]. Control of the system is achieved via blended position and velocity control to provide smooth trajectory motion and fine scale positional resolution. System commands are executed via parallel PC and motor controller enclosure pairs. There is one computer – controller box set for each instrument – manipulator arm pair. Parallel systems allow greater operating redundancy and improved communications speed and reliability.

The research methods discussed in this thesis include the areas of robotic system development necessary to create a fully operable, stand-alone, robotic surgical system. These methods specifically include mechanical design, electronics hardware design, and control software design. The mechanical design of the system envelops a number of interconnected, modular subsystems acting in concert to perform desired surgical tasks with a level of accuracy and dexterity comparable to existing and previous robotic systems [24, 27]. Subsystem development consists of: the technical design and construction of the physical robot platform, the independently controlled four DOF manipulator arms, mechanized, articulated, and triangulated instruments, and an operator controlled end effector interface. When considering mechanical design specifically, special consideration has been given to incorporating 3D printed components to further reduce the cost and complexity of the overall robotic system. All components except rack and pinion gearing were produced using a Dimension uPrint 3D printer using a
standard, commercially available ABS P-430 material. DFA/DFM design concepts were utilized to replace traditional multi-piece joints and structures with unitary, compliant features. 3D printing construction parameters were selected to best balance part density with structural rigidity in order to reduce manufacturing times. Spatial printing orientations were optimized to maintain acceptable tolerances for precision fit features as well as to align print material layering perpendicular to applied forces and torques. Additional finishing processes were used where necessary to achieve tolerances beyond the capability of the Dimension uPrint system.

Actuation of the mechanical robot structures is achieved via motor control hardware and software. Hardware design and development includes incorporation of Geomagic/Sensible Phantom Omni master controllers, additional analog end effector control, and actuator motor controller configuration and operation. The software developed to control the system is based on position and velocity hybrid control. Positional inputs from the master controllers are translated into a series of proportional velocity commands for each joint actuation motor. An inverse kinematic model is used to generate target positional commands. This model accounts for manipulator link joint positions, orientation of the instrument shafts as they pass through the common incision, the fixed bend in the instrument shafts to achieve end-effector triangulation, and articulated end effector orientation and position. Target positions generated by the model are translated to velocity motor commands based upon the error between present and commanded position. Proportional gain is used to increase system response to control inputs. Each manipulator – instrument pair, accompanying hardware, and software have been split into parallel systems operating concurrently to alleviate communication latency complications arising from the number of actuator motors simultaneously controlled during operation. Increasing the individual motor controller communications frequency through parallel control processing provides improved control precision and response.

A number of evaluations have been performed to analyze, investigate, and demonstrate the capability of the surgical robotic system presented in this thesis. These evaluations fall into two primary categories: investigating functional performance of the system and investigating teleoperated performance in standard laparoscopic surgical
training tasks selected from the Society of American Gastrointestinal and Endoscopic Surgeons Fundamentals of Laparoscopic Surgery (SAGES FLS). Functional performance has been specifically evaluated via analysis of the estimated operational volume of the system and instruments as well as the accuracy and repeatability of end-effector positional control. Operational volume has been estimated through approximate geometric representations of robot and manipulator space when swept through all reachable poses. Accuracy and repeatability of control have been quantified via optical tracking of the end-effector tool tip during simple shape tracing exercises. Standard FLS peg transfer trails described in [28] have been used to investigate and evaluate teleoperated performance of the system. The data collected through this diverse testing protocol is compared with performance data from previous systems developed at the University of Hawai‘i at Mānoa as well as existing, commercial surgical systems such as the DaVinci [24, 27] to quantify the viability of the novel system presented in this thesis.

Analysis of system operating volumes has shown that the mechanical design of the single-port system presented meets the goals of developing a compact, portable teleoperated laparoendoscopic surgical robotic platform. Modularity of the system has also been improved in addition to further miniaturization. The incorporation of quick disconnect, stand-alone instrument assemblies along with a novel interchangeable tool-tip provision yields a flexible mechanical platform capable of efficiently supporting a diverse array of operative tools. Cost reduction goals have been achieved through the utilization of inexpensive, easy to produce 3D printed ABS components. The use of plastics allows for reductions in raw material and manufacturing costs as well as substantial reductions in complexity, fasteners, and maintenance costs. Although the preliminary hardware goals have been accomplished additional control design work is required to achieve full functional parity with the previous UH multi-port system and existing commercial systems. While a number of control strategies have presently been explored there exist additional approaches that may improve the responsiveness of the system, the intuitiveness of the control, and potentially reintroduce DOF’s compromised through the physical constraints of single-port minimally invasive instrument geometry. Meeting these design challenges will allow validation of system performance and pave the way towards the next stages of pre-clinical development.
2. METHODS

2.1 MECHANICAL DESIGN

The mechanical design of the teleoperated laparoendoscopic surgical robot can be separated into four discrete parts: the base assembly comprising the substructure of the robot, the independent manipulator arms that travel along the base assembly and position the instruments, the articulated, mechanized, and angled instruments themselves, and the end effector master control interface. The mechanical design elements act to translate motor motions driven by software commands into instrument end effector motions to accomplish operative tasks.

2.1.1 ROBOT BASE ASSEMBLY

The foundational platform upon which the physical laparoendoscopic surgical robot has been built is the base assembly. This base is constructed by modifying a commercially available ViKY XL teleoperated endoscope positioner from EndoControl SA. Specifications for the ViKY XL are discussed in previous University of Hawai‘i at Mānoa work describing the preliminary system design [29]. The base functionality of the ViKY XL includes a lower ring with an integrated mounting provision for securing the positioner robot to the operating table and patient. The ring itself is comprised of two members: a lower ring frame with a laser welded internal ring gear and an upper ring secured to its lower counterpart with beveled rollers. The inclination base structure is secured to a distal point on the upper ring and includes another integrated internal gear profile as well as a composite bushing to allow for remote motion about an imaginary axis of rotation beneath the entire robot assembly in the vertical direction. The inclination rack is secured to the inclination base structure via a pinion gear laser welded to an enclosed drivetrain. The inclination rack consists of this pinion gear enclosure, a shaped guide follower secured to the composite bushing that traces motion about the
remote center, and a simple vertical upright. The rear of the upright is populated with a metric rack gear profile and includes a small press fit lock pin at the extremity. The endoscope positioner link is mated directly to the vertical upright by another pinion gear assembly and machined collar. The endoscope shaft itself is secured via light spring clamp to an endoscope positioning arm which is fastened directly to the machined collar traveling along the rack gear profile on the single vertical upright. The system has three total degrees of freedom: rotation of the upper base ring against the lower, tilting of the inclination structure about the remote axis of motion, and vertical translation of the endoscope positioner arm along the vertical upright. An annotated image of the ViKY XL endoscope positioner is shown in Figure 1. The ViKY XL system is controlled by an accompanying voice and pedal command console provided by EndoControl. This external control system is redundant for the purposes of this thesis research and has not been incorporated.

Figure 1. Annotated image of the ViKY XL endoscope positioner showing components and joint actuators.

A functional teleoperated laparoendoscopic surgical system requires at a minimum two separate instruments and an endoscope to be independently positioned and manipulated by the operator. A number of modifications are required in order to use a simple endoscope manipulator for this purpose. These modifications include: development of a parallel vertical upright with integrated rack gear that passively tracks
the motion of the existing motor driven vertical upright in order to actuate an additional manipulator link and a satisfactory, integrated sub-frame for structural support. An additional simulated incision trocar has also been incorporated for the purpose of evaluating system performance in a controlled environment.

In developing a parallel vertical upright to passively track the motion of the existing upright on the ViKY XL the primary requirement was to align the axis of rotation for the new upright with the remote axis of rotation of the existing upright. This was accomplished using SolidWorks 3D CAD models. Beginning with the underlying ViKY XL model an adaptor component (See Figure 2) was designed to fasten to the upper rotating ring of the ViKY XL via 6-32 stainless steel, cap head, machine screws. The component also includes a relief to utilize existing ViKY XL features as locating mechanisms to ensure proper tangential alignment of the adaptor to the upper rotation ring. The adaptor protrudes from the top planar surface of the upper ring and then bends downward at a 90 degree angle in the vertical direction until it intersects the remote axis of rotation of the existing vertical upright. A threaded boss is placed on this axis to secure the joint of the parallel upright. A riser component (See Figure 2) is designed using a clearance hole for a $\frac{5}{16} - 18$ stainless steel, cap head, shoulder bolt. The shoulder bolt secures to the adaptor and the riser rotates about the shoulder portion of the fastener. The profile of the riser extends back up in the vertical direction from the axis of rotation following the projected geometry of the existing vertical upright while discarding the additional features associated with the motor drive assembly. The riser terminates in the same horizontal plane as the motorized assembly on the existing vertical upright, at the same vertical distance above the upper ring surface, and at the same inclination orientation. The distal end of the riser flares into a cubic shape with an internal relief for the parallel vertical rack gear assembly. A 6-32 threaded hole provides a means to secure the rack gear assembly to the distal riser boss via recessed set screw.

The final member of the parallel vertical upright is the rack gear assembly shown in Figure 3. This assembly is designed as a section of 0.500 module, stainless steel rack gear with a 20 degree pressure angle encased in a housing. The housing enclosure is designed to modify the cross sectional profile of the stainless steel rack gear to match the
unique cross sectional profile of the existing ViKY XL rack gear. While initially designed as a two part total assembly including a housing enclosure and rack gear, the housing enclosure itself was split into three separate segments due to limitations in the maximum component geometry produced by the Dimension uPrint 3D printer utilized for fabrication. The housing enclosure segments are secured to the underlying rack gear section via a series of 3 mm diameter recessed spring pins.

![Figure 2](image)

**Figure 2.** Parallel vertical upright assembly showing all individual components, fastener locations, and axis of upright rotation.

To allow the parallel vertical upright to passively track the existing, motorized ViKY XL upright, the two structures are tied together via a modular sub-frame assembly. This assembly consists of three primary components: A top channel brace, a triangulated lower trocar support frame, and a rear x-member frame. The top channel brace is designed to support the weight of the parallel upright, manipulator arm assembly, and instrument assembly with minimum deflection in a plane both orthogonal to the vertical upright and with a vertical gravity force projection. This is achieved with an I-beam structure oriented perpendicular to the applied parallel upright load. This structure is linearly offset from the distal end of the parallel and existing vertical uprights to provide adequate clearance for the endoscope camera assembly motions. This is realized with a
pair of solid boss structures extending from the upper I-beam surface. These structures are further detailed to include open, downward facing cavities to mate with the distal ends of both uprights. The cavity shapes are matched to the cross-sectional projection of the upright structure with a light interference tolerance of approximately 0.015”. The tolerance is set on the loose side to accommodate minor dimensional errors in some off axis structures resulting from the 3D printing process. The top channel brace is secured to both uprights with 6-32 stainless steel, serrated cup point, set screws. The channel brace must also eliminate lateral motion of the second parallel upright in addition to minimizing deflection under load at shallow inclination angles. Lateral stiffness is generated by augmenting the basic beam structure with a pair of offset, parallel triangulating features. These features comprise the upper and lower surface of the top channel brace and extend beyond the dimensions of the I-beam shape. The triangulated shapes increase the strength of the brace in lateral compression and tension without reducing the required endoscope camera assembly clearance. The employment of 3D printing as a prototyping method allows the construction of such integrated, complicated geometry at minimal cost. Figure 4 illustrates the critical geometric structures of the top channel brace.

Figure 3. Rack gear assembly showing components, spring pin fastening locations, and illustrating the widened gear profile to match the unique ViKY XL vertical upright rack gear profile.
Figure 4. Top channel brace component with critical geometric structures annotated.

The proximal end of the sub-frame in relation to the patient is comprised of a triangulated lower trocar support frame [See Figure 5]. This frame consists of two components: left and right upright adaptors. These two components are functional mirror images of each other although the individual geometries have been designed to interface with the two different base upright assemblies. Each adaptor consists of a simple square collar mated with the external surfaces at the base of the rack gear portion of each upright. The collar is secured to the underlying structure with a 6-32 stainless steel, serrated cup point, set screw. A tapered T-beam feature protrudes away from the collar towards the “incision point”. The incision point is defined as the point in which both instruments and the endoscope triangulate and share a common point in space. The T-beam terminates at a radius of roughly 25 mm around the incision point. The terminus of the beam is designed as a downward face boss incorporating a 6.35 mm diameter pin hole to provide free rotation about the inclination axis for the trocar mock up.

An x-frame connecting the top channel brace with the triangulated lower trocar support frame comprises the final component of the sub-frame [See Figure 5]. The x-frame itself is comprised of three discrete components: upper brace tubes, lower brace tubes, and a center connector. Each of the tubes consists of a 12.70 mm diameter center section with 6.35 mm tubular connectors extending from each end. One connector
extends axially from the main center section and the other connector extends away at a 45\degree angle. The x-frame is built with a pair of upper brace tubes and a pair of lower brace tubes. Each tube is solidly constructed with no center void. Manufacturing a walled tubed structure with the specific multi-axis geometry required is practically prohibitive with a 3D printer. 3D printers construct a component as a series of 2D image layers stacked in the vertical direction. As such the axis of construction cannot be rotated during the build. This results in multi-axis tubular structures that do not maintain proper concentricity throughout the part, non-ideal alignment of the print layering in relation to component loading, and excessive consumption of support material during the build. Additionally, the brace tubes are primarily loaded in compression once installed in the x-frame. This minimizes the relevance of the reduced torsional stiffness of solid tubular structures compared to the more ideal walled tubular structure. Each of the axis brace tube connectors is press fit into the center connector using line on line tolerances. Although line on line can be a tight press fit for traditionally manufactured components the orientation sensitivity of manufacturing tolerances in 3D printed components makes this tolerance paradigm functionally appropriate in this application. The off axis connector extensions for all four brace tubes are rotated to align in a parallel plane. These connectors are mated to receivers designed into the top surfaces of the triangulated lower trocar support frame components and the lower surface of the top channel brace. An exploded view of the assembled sub-frame can be seen in Figure 5. The assembled sub-frame installed onto the modified ViKY XL base can be seen in Figure 6.

For the purposes of evaluating the performance of the surgical robot some method of simulating a trocar inserted through the patient’s abdominal wall is required. The simulated trocar incision must allow freedom of motion for both instruments and the endoscope as they pivot about the common point of triangulation and it must align with the axis of rotation for the ViKY XL base ring and inclination assemblies. A proper simulated incision point meets these criteria and provides a fixed point about which the joints of the ViKY XL base rotate. This ensures a simpler, consistent kinematic model of the robot independent of the higher level positioning commands executed by the ViKY XL actuators. These requirements were met by designing a small, 25 mm radius ring structure constructed from three, layered components. The upper and lower rings are
manufactured via 3D printing and include offset flanges. When oriented properly, these sets of flanges mate and form a single pin shape. There is one pin on two opposite sides of the ring along its diameter. These pins interface with the triangulated lower trocar support frame to fix the position of the trocar while still allowing motion around the axis of rotation for the inclination assembly. The trocar is also positioned in the center of the ViKY XL ring to rotate about that additional axis as well. A line on line interference fit is utilized for the “trocar” pin joints to provide some rotational stability of the joint through friction. The center piece of the trocar is a 25 mm radius disc of 0.125” standard silicone rubber. The rubber disc is held between the two outer rings with six 6-32 stainless steel, cap head, screws distributed evenly about the circumference. The center of the disk is perforated with clearance holes for both instrument shafts and the endoscope shaft. With lubrication, the rubber provides the necessary compliance to allow the instruments to pivot about each other in order to achieve the necessary ranges of motion at the distal end effectors. Figure 6 includes the simulated trocar installed in the complete sub-frame assembly.

**Figure 6.** Exploded view of x-frame assembly with all components annotated.
2.1.2 INDEPENDENT MANIPULATOR ARMS

Each of the two parallel uprights extending in the vertical direction at a controlled incline from the ViKY XL base ring support an independent serial link manipulator. The manipulator arm is comprised of several key components, the base link and pinion drive assembly, a middle link and inner joint assembly, an outer link and outer joint assembly, a distal universal joint assembly, and an integrated instrument attachment and rotation assembly. Although the left and right manipulator arms are directional mirror images of each other, as many components as possible have been designed to be non-directional and universal to either the left or right side of the robot. The initial interface of the
manipulator arm and the vertical upright on the ViKY XL base is achieved with the base link. In addition to traversing the vertical parallel uprights the base link also forms the support structure for the more distal manipulator links and assemblies. The base link has three predominant features shown in Figure 7: The rear motor mount, internal upright sleeve, and lower, outer joint boss. The rear motor mount aligns the motor perpendicular to the rack gear tooth profile on the rear side of the vertical uprights. This alignment allows a single spur gear mounted on the drive motor planetary gear head output to be utilized for mechanized motion of the manipulator arm along the vertical upright rack gear. The motor mount features recessed, countersunk mounting screw provisions to minimize the mounting profile and shrink the overall size of the component. The cylindrical tapered external ribs on the outward side of the mount both align the motor during assembly and adequately stiffen the geometry for off axis 3D printing. When installed the base link drive motor transmits torque to the rack gear profile of the vertical uprights via a single 0.500 module 40 tooth stainless steel spur gear with integral mounting hub. The ID of the gear bore is oversized from the OD of the drive motor shaft by 1 mm. This allows the use of a 3D printed bushing to mate the gear to the drive motor shaft. The bushing features a rear boss that properly spaces the gear from the face of the drive motor to ensure accurate tooth alignment with the vertical upright gear profile. The inner cross sectional geometry of the bushing matches the non-cylindrical cross sectional geometry of the motor drive shaft. This positively secures the angular orientation of the spur gear in relation to the drive shaft. A 2 mm stainless steel, cone tip, set screw secures the bushing and gear assembly to the motor shaft in the axial direction. The use of 3D printed components as a motor drive shaft interface medium allows the use of component geometry to fix the relative angular positions of the components in lieu of a traditional temporary set screw or permanent adhesive or welding procedure. This is critical because the traditional removable set screw does not perform well with robotic manipulators and permanent fastening methods are not desirable for prototyping. The dynamic, highly variable joint velocities and rapidly changing direction of link motion act to loosen a set screw over time and introduce hysteresis into the joint. The geometries achievable via 3D printing satisfy both the temporary fastening requirements of prototyping and the robust torque transmission found in permanent fastening methods.
The internal upright sleeve structure comprising the middle section of the base link has the same cross sectional profile as the vertical upright itself with additional tolerancing to minimize friction during motion. The parts are produced with a line on line tolerance between the inner surface of the sleeve and the external dimensions of the upright racks. After production the inner sleeve surfaces are post-finished by hand to ensure an appropriate balance between dimensional play of the interface and surface friction during motions. This is accomplished via sanding with at least 400 grit sand paper or delicate hand file. There is also a narrow, 3 mm opening in the rear wall of the upright sleeve that exposes the underlying vertical upright rack gear teeth allowing gear mesh with the base link drive motor and spur gear. The rounded boss features above and below the gear opening are designed to support the rear part loading resulting from instrument manipulation about the fulcrum of the vertical upright itself. This reduces the friction wear from gear tooth contact on the more delicate part structures surrounding the drive component interface. The lower, outer joint boss protrudes from the side of the upright sleeve opposite the motor mount. The simple rectangular boss contains 6-32 threaded holes along two, perpendicular axes used to fasten the joint retaining cap of the middle link. The lower, angular structure supports the weight of the middle link and the
integrated 6.35 mm diameter joint pin fixes the rotational axis of the joint between the base link and the middle link. Figure 16 shows the fully assembled manipulator link.

The middle link is secured to and rotated about the base link via a joint assembly. The joint assembly uses a cap-like component along with the drive motor shaft itself to form the rotational joint between the two links. The joint cap is a light structure that secures the drive motor to the base link [See Figure 8]. It has basic geometry that fastens to the large, rectangular front boss on the base link with three 6-32 stainless steel, cap head, machine screws. Two screws fasten in the horizontal direction and one screw fastens in the vertical direction to draw the cap tight and eliminate vertical hysteresis in the joint. The top surface of the cap contains a thin, 1.5 mm lip comprising the top circumference of the component. The lip stiffens the component against the vertical loading resulting from a distal projection of the motor shaft and joint axis beyond the proximal anchor points. The underside of the cap contains recessed, counter-sunk drive motor mounting fastener provisions to reduce the component profile. There is also another joint pin integrated in to the underside of the cap. Unlike the lower joint pin located on the base link, the upper joint pin has a clearance hole to allow the drive motor shaft to pass through. To assemble the joint the drive motor is secured to the joint cap, the inner link is pressed onto the lower joint pin, and the joint cap/motor assembly is pressed onto the inner link from above and then fastened to the base link to secure the entire joint assembly. The proximal end of the middle link that mates with the inner joint assembly has upper and lower reliefs to match the joint pins and a clearance hole for the drive motor shaft. The cross sectional geometry of the clearance hole matches the non-circular cross sectional geometry of the motor shaft. Thus the middle link is secured to the drive motor shaft via light press fit and torque is transmitted through the non-circular matching geometric interface between the two components. There is also an additional 6-32 stainless steel, serrated cup point, set screw used to secure the motor drive shaft inside the middle link once installed. The middle link itself is primarily a solid square beam link with a 12.640 mm X 12.700 mm cross section and measuring 88.900 mm from inner joint axis to outer joint axis. Link dimensions have been determined based on previous design analysis [25] investigating the relationship between link geometry and the reachable volumes of end-effector motion at the operative site. The middle link structure
does not follow a direct linear path from inner joint axis to outer joint axis. The middle link features a 166.5 degree bend approximately half way down the length of the link. This bend is oriented away from the incision site and is a mirror image feature between the left hand and right hand manipulator arms. The bend serves as an offset relief to expand the rotation range of the outer link as it rotates about its joint axis. A traditional straight link without an offset would only allow approximately +/- 90 degrees of outer link rotation. This constrained range of joint motion would severely limit the end-effector reachable volume at the operative sight. By incorporating an offset geometry the range of joint motion for the outer link is expanded to + 90 and – 166.5 degrees. The final primary feature of the middle link is an angled, offset lower lip extended from the distal end of the link. This lip realigns the inner and outer joint axis in a plane parallel to the vertical base uprights and contains an integrated 6.35 mm joint pin to form the foundational structure of the outer link joint. Figure 9 shows the top view of an inner link model with all critical features annotated.

**Figure 8.** Exploded view of the inner joint assembly with all components labeled.
The outer link is secured to and rotated about the middle link via the same joint structure that exists between the middle link and base link. The distal geometry of the outer joint cap incorporating the joint pins and motor mount is identical to the equivalent geometry on the inner joint cap. However the proximal geometry of the outer link cap differs from the inner link cap due to the unique shape of the middle link. The outer link cap does not include any surface that can be secured to the inner side of the middle link in order to maximize the range of motion of the joint. In order to create lateral stability in the joint cap an outer flange protrudes downward from the outer edge of the joint cap in relation to the incision site. The flange is of an angle shape to stabilize the cap in two dimensions and mates against the angled underlying surfaces of the middle link. Two 6-32 stainless steel, cap head, screws secure the joint cap to the middle link from the top surface. Fastening along the axis parallel to the joint axis tensions the joint and removes any excess hysteresis emanating from 3D printer production tolerance limitations.

**Figure 10** shows an exploded view of the outer joint. The outer link [See Figure 10] assembles into the outer joint identically to the middle link in the inner joint. The outer link connects the outer joint to the universal joint at the distal end of the manipulator arm. The link originates as a square beam that drafts into a solid tube structure at the distal face. The distal face includes a ¼-20 tapped hole to receive the stainless steel, cap head, shoulder bolt used for the first degree of rotational freedom in the universal joint. The 88.590 mm outer link length was derived from motion analyses in [29]. **Figure 11** shows the outer link with critical dimensions noted.
A passive universal joint provides a two degree of freedom connection between the outer manipulator link and the instrument attachment and rotation assembly. The universal joint consists of a rotating fork [See Figure 12] secured to the outer link via ¼-20 stainless steel, cap head, shoulder bolt. The rotating fork assembles to the lower base of the instrument attachment and rotation assembly via two press pins. The pins are 3D printed with a line on line interference fit to both the instrument attachment and rotation assembly and the rotating fork. The length of the stanchions on the lower base and the fingers on the rotating fork are dimensioned to achieve +26 to –45 degrees of...
rotation about the press pins and a full 360 degrees of rotation about the shoulder bolt. The lower base is aligned vertically when at 0 degrees and rotation is measured in the clockwise direction. Figure 12 shows an exploded view of the universal joint assembly.

![Figure 12. Exploded view of manipulator arm universal joint with components and joint axis annotated.](image)

The final component of the manipulator arm is the instrument attachment and rotation assembly. This assembly is made up of several key components: the lower base, mounting cup, drive gear assembly, and retaining ring. The lower base is comprised of a ring-shaped top surface that transitions downward into a fork stanchion structure. The forks are ribbed for additional stiffness and have 6.350 mm holes at the tips to receive the universal joint press pins. Nested into the outer fork structure in relation to the incision site are the instrument rotation drive motor and accompanying motor mounting provisions. The motor mount includes a recessed cup on the underside of the lower mount ring to align and seat the motor. The ribbed fork structure wraps around the motor diameter. A circular protrusion on the upper ring accommodates the motor mounting cup. An additional oblong recess on the top surface of the upper ring provides a countersunk location for the motor fasteners. Locating the heads of the motor fasteners below the top surface of the upper ring is critical to eliminating interference between the fasteners and the drive gear assembly that performs instrument rotations about the instrument shaft. Additionally, the upper ring of the base contains six, evenly distributed,
6-32 tapped mounting holes used to secure the drive gear assembly to the lower base via the retaining ring. **Figure 13** shows an annotated model of the lower base.

The mounting cup component [See **Figure 14**] is the direct interface with the instrument to secure it to the manipulator arm and is based off a traditional bicycle seat clamp. It is comprised of two main features. The first feature is the lower portion of the cup, a hollow cylinder with an enclosed lower surface. The solid lower face of the cup has a center clearance hole for the instrument shaft and four circularly distributed 6-32 tapped mounting holes used to fasten the mounting cup to the drive gear assembly. The upper portion of the cup features compliant geometry to secure the instrument. This portion is defined by two free-floating, arc shaped fingers that are anchored as the rear of the cup. The distal edges of the fingers are recurved to accommodate the fastening lever and threaded anchor of the integrated rail clamp. The fingers are shaped to leave an approximately 6 mm clearance between them when the clamp is open. As the clamp is tightened, the fingers compress, deforming the radius of the finger curvature and securing the object inside by compression. The instrument is secured rotationally inside the cup by an integrated, internal key at the base of the fingers. This key mates with a slot in the interface boss of the instrument as the instrument is inserted into the mounting cup. The use of the keyed rail clamp allows simple, quick installation and removal of the instrument during use. This modular design feature affords the operator access to multiple end-effector types in the operative field without lengthy procedural delays or additional incisions to introduce the instruments.

The drive gear assembly consists of two meshed, 3D printed spur gears used to rotate the instrument about its shaft axis upon the introduction of torque from the drive motor. Simple spur gears allow both forward and reverse rotations. The tooth profile for the gears has been made sufficiently large to allow the gears to be produced by 3D printing on the Dimension uPrint machine. Layering, orientation, and other printing parameters were optimized to produce components with adequate tooth shear strength. The drive motor pinion gear is designed to press onto the motor shaft. It is secured axially via a non-circular internal surface geometry to mate directly to the non-circular cross section geometry of the motor shaft. An upper boss on the pinion gear that extends
beyond the tooth profile vertically provides additional contact surface with the motor shaft and serves as an alignment dowel for the retaining right during assembly. The main gear includes a center clearance hole for the instrument shaft and a mounting fastener hole pattern matched to the lower surface of the mounting cup. 6-32 stainless steel, cap head, screws are used to secure the main gear to the underside of the mounting cup. The main gear also features one additional critical structure: a stepped, 32 mm diameter circular boss extending from the underside of the main gear. The boss fits inside of the large opening of the lower base top ring structure and axially secures the main gear to the lower base. The interface of the gear and lower base creates a bearing structure by which the drive motor rotates the instrument. **Figure 15** shows the gear structures among an exploded view of the instrument attachment and rotation assembly.

![Figure 15](image)

**Figure 15.** Gear structures among an exploded view of the instrument attachment and rotation assembly.

There is no angular directional requirement for mounting the main gear. The drive motor is installed from the underside of the lower base and secured with M1.6 fasteners from the top surface of the base. The drive motor pinion gear is pressed onto the motor shaft after aligning the component geometry. The mounting cup, main gear, and retaining ring assembly is then installed onto the lower base, drive motor, pinion gear assembly using the aforementioned 6-32 hardware. The retaining ring fasteners are tightened in stages, in a star shaped pattern to evenly clamp the main gear to the lower base.
base. This allows fastener torque to directly control the functional tolerance of the assembled rotational bearing. Fastener torque is adjusted by hand until satisfactory bearing tolerances are achieved. Undersized tap holes integrated into the 3D printed, ABS lower base create a tight thread profile for the stainless steel fasteners. This creates a self-locking thread similar to traditional nylon locking fasteners that prevent fasteners from coming loose even when installed with very light torque. Dimensions for individual components of the instrument attachment and rotation assembly were generated to minimize the profile of the overall constructed assembly.

![Figure 14](image1.png)

**Figure 14.** Annotated CAD model of instrument attachment and rotation mounting cup showing key structures.

![Figure 15](image2.png)

**Figure 15.** Exploded view of instrument attachment and rotation assembly with components labeled.
Figure 16. CAD model of fully assembled manipulator arm. Left arm shown.

Figure 17. Assembled, 3D printed manipulator arm assembly installed onto parallel vertical upright. Left arm shown.
Figure 18. Complete robot platform shown. ViKY XL base is modified with additional parallel upright and sub-frame. Both left and right manipulator arms are installed onto respective uprights. Right manipulator arm (at left) has mock instrument installed for optical tracking.
2.1.3 ARTICULATED, ANGLED, AND MECHANIZED INSTRUMENTS

Full utilization of the surgical robot is realized by simultaneously operating two independent instruments during surgical tasks. In order to function appropriately through a single, common incision point, each of the instruments must feature an angled shaft to reestablish the required instrument spacing within the operative field. To achieve the dexterity necessary to complete complex surgical tasks each instrument includes a distal, articulated, mechanized wrist structure that provides bending of +/- 90 degrees away from the instrument shaft axis in two perpendicular directions simultaneously. Additionally, each instrument must include a mechanized assembly to actuate the instrument end-effector based on teleoperation master controller inputs. The two instruments developed for use with the system presented in this thesis are identical in function, geometry, and assembly. To fully describe the design the instruments can be considered as three integrated sub-systems: the instrument housing and motor pack, the end-effector actuation linkage, and the wrist actuation linkage. Instrument designs are built upon previous work in [28].

The instrument housing and motor pack is made up of several key elements: the instrument shaft, the base housing, the motor plate, and drive motors. The instrument shaft is manufactured from 6 mm diameter stainless steel tubing with a 0.500 mm wall thickness. Each shaft is approximately 280 mm in length and includes a 45 degree bend at one end. The bend is made around a 16 mm radius and terminates at the end of the shaft. The shaft is then inserted into the base housing [See Figure 19] via an axially centered through-hole in the lower boss. The parts mate with a line on line tolerance for a light press fit and the end of the shaft is aligned with the upper surface plane of the lower boss structure. The shaft is secured to the base housing via a single 6-32 stainless steel, serrated cup point set screw fastened through the lower boss on the housing. The 12.500 mm diameter lower shaft mating boss expands into the 29.875 mm manipulator arm mounting cup mating boss when traversing the component from bottom to top. The mounting cup boss includes a full depth keyway to rotationally secure the instrument inside the mating cup of the manipulator arm. Above the mounting cup boss the base
housing expands in a single step to the full 55.750 mm outer diameter of the mechanized assembly portion of the instrument. The upper surface of the lower boss structure includes three evenly distributed, 25 mm diameter, 3.175 mm deep recesses. These recesses, or cups, are distributed around the instrument shaft through-hole on the center axis of the instrument assembly and are used to positively locate the bottom segments of the instrument drive motors to prevent angular deflection under applied torque loads. Three triangular risers extend vertically from the top surfaces between pairs of motor recess cups. The back wall curvature of each riser is matched to the common 55.750 mm overall instrument outer diameter. The top surface of each riser includes a 12.700 mm deep tapped 6-32 hole used to fasten the motor plate to the base housing.

![CAD Model of Instrument Base Housing](image)

**Figure 19.** Annotated CAD model of the instrument base housing showing all key features.

The motor plate, mounted to the top of the base housing, includes a number of key structures that facilitate mechanized motion of the instrument wrist and end-effector components. The bottom boss of the component is a 55.750 mm disc with a thickness of 3.175 mm. The disc includes mounting provisions for the three instrument drive motors, guide tube spacing bosses for the wrist actuation cables, central, axial guide tube boss for the end-effector actuator cable, vertical alignment forks for the end-effector linear actuator link, and riser rails to mount the wrist actuator gear box plate. **Figure 20** shows a CAD model of the motor plate with critical features annotated. The motor mounting
provisions include a main clearance hole for the drive motor shaft and front shaft bearing assembly as well as three holes for M1.6 mounting fasteners. The tapered, countersunk fastener clearance holes are distributed in a circular pattern concentric to the drive shaft axis of rotation. The drive motors themselves have been selected based upon previous work at University of Hawaiʻi at Mānoa [25]. All actuation cables passing through the instrument shaft to the end-effector and wrist assemblies are enclosed in 1/16” OD, 0.016” wall thickness, high-pressure polyetheretherketone (PEEK) tubing. Passing actuation wires through guide tubes reduces friction during actuation displacements, prevents binding of wires, and allows the actuation wires to transmit force in compression as well as tension. The guide tubes for the wrist actuation wires are positively located as they pass through the motor plate by two mirrored guide tube spacing bosses. The spacing bosses align the guide tubes as they exit the instrument shaft and properly orient them towards the wrist actuation gear box mechanisms. Each boss receives two individual wire guide tubes. The end-effector actuation wire also passes through a central guide tube. The boss for this guide tube is concentric to the outer diameter of the motor plate main disc and aligns the end-effector cable with the cable pull linear actuator. The vertical guide forks for the end-effector linear actuator link are located directly adjacent to the guide tube boss. The forks extend from the upper surface of the main disc approximately 23 mm and create a track for the actuator link to translate along when motor torque is applied. Three distinct riser rails comprise the final motor plate structure. The rails are equally distributed around the outer circumference of the motor plate main disc and oriented outboard from each drive motor along lines connecting the motor plate center point to each drive motor axis of rotation. The T-shaped upper rail structures form a mounting platform for the wrist actuation gear box plate. The two plates are fastened with four 6-32 stainless steel, cap head screws. Fastener provisions for securing the motor plate to the base housing are located in between pairs of riser rails along the outer perimeter of the motor plate main disc.
The first mechanized motion of the instrument is end-effector manipulation via the actuation mechanism. There are two main components of the end-effector system: the interchangeable end-effector tip assemblies and the modified drive motor and linear actuation link assembly. A standard 20mm long curved, serrated stainless steel, two jaw grasper has been developed and used as the primary end-effector tool tip. The end-effector tip is constructed by disassembling an existing manual minimally invasive surgical (MIS) instrument and removing the tool tip and mechanical actuation linkage. The isolated tool tip and mechanical linkage is reconstructed and a 380 mm long segment of 0.013” diameter Nitinol wire is bonded to the tool tip mechanical linkage with polyurethane glue. The tool tip is then permanently bonded into a stepped 12.700 mm long 3D printed bushing. The resulting interchangeable mechanized instrument end-effector assembly is modular, compact, and operates via wire actuation as opposed to the direct mechanical bar linkage used in manual MIS instruments. Both mechanized instruments have been equipped with grasper tool tips for validation of the robotic surgical system. However using the above assembly method any commercially available 5 mm (shaft diameter) manual MIS instrument end-effector can be adapted for quick interchange use with the mechanized instruments presented in this thesis. To install a tool tip into the instrument the actuation wire is fed through a clearance hole in the center
of the wrist assembly and through the PEEK guide tube until the tool tip contacts the wrist assembly. The 3D printed end effector bushing is then pressed by hand into the receiving cup of the wrist assembly. Miniature rib features within the wrist cup rotationally stabilize the tool tip during operation while permitting manual angular realignment of the end-effector in relation to the instrument shaft if necessary. **Figure 21** shows a standard grasper tool tip removed from the instrument with key features labeled.

![Figure 21](image)

**Figure 21.** Removable bi-jaw grasper end-effector shown with components labeled.

At the rear of the instrument the end-effector drive motor is coupled to a linearly actuating link to transmit translational motion via wire to achieve end-effector opening and closing motions. The drive motor is modified by bonding a 12.700 mm long segment of threaded rod to the motor shaft via coupling nut and polyurethane glue to create a power screw transmission assembly. The 3D printed linear actuation link [See **Figure 22**] includes upper and lower hexagonal recesses in the rear lobe of the component to accept standard hex nuts. A nut is bonded into each recess using polyurethane glue and the link is threaded onto the power screw segment of the drive motor shaft. The narrow inner section of the link is positioned between the two vertical guide forks on the motor plate. During actuation the forks prohibit the link from rotating with the drive motor shaft resulting in a directional vertical translational motion along the length of the fork. Direction of translation is dependent on the direction of motor rotation. The front lobe of the link contains a rectangular through feature intersected by a perpendicular 6-32 tapped hole. The threaded hole extends from the outer surface of the front lobe through the
rectangular relief and into the inner section of the link. During operation the end-effector actuation wire is passed through the rectangular through-hole and secured to the link via a 6-32 stainless steel, cap head screw threaded into the inner portion of the link. As the drive motor translates the link the vertical motion is transmitted to the mechanical linkage in the tool tip itself to generate the desired end-effector opening and closing motions.

![Diagram](image)

**Figure 22.** End-effector actuation mechanism shown with components labeled. End-effector actuation linkage is shown in the closed position.

The second major mechanized motion is the articulated wrist actuation. This is achieved via two separate rotational degrees of freedom about a pair of orthogonal joint axes. The wrist mechanisms can be separated into two individual assemblies: the articulating wrist spine assembly and the identical pair of mechanized drive wheel assemblies. The articulating wrist spine assembly is located as the distal end of the instrument shaft just outboard of the 45 degree shaft bend. It consists of several components: wrist cup, spine discs, spine spheres, and wrist base. The overall spine assembly is a modified version of the initial design reported in previous work from
The basic structure is as in [24]. The wrist base is a stepped component made from Delrin. The lower boss forms an interference press fit with the ID of the instrument shaft to secure the wrist assembly to the end of the instrument. The upper, larger diameter boss seats against the outer diameter of the instrument shaft to positively locate the wrist assembly axially [See Figure 23]. The friction press fit of the lower boss secures the wrist assembly rotationally as well. The center portion of the upper boss is recessed to mate with the first spine sphere, a 0.100” diameter Delrin plastic ball. The two inner spine discs and two remaining spine spheres are stacked in an alternating pattern on top of the first sphere and wrist base to construct the actual wrist spine structure [See Figure 23]. The wrist cup is the final component incorporated into the assembly. The underside of the bottom surface of the cup is recessed to mate with the upper spine sphere as shown in Figure 23. Multiple strands of 0.013” Nitinol wire are used to secure the entire wrist spine assembly through wire tension. There are two distinct sets of Nitinol wire used. The primary set of control wires consists of four wires evenly distributed around the outer circumferences of the spine discs, wrist cup, and wrist base. Four 0.015” diameter clearance holes are drilled through all stacked components in the wrist spine assembly and the control wires are passed through from the wrist base to the wrist cup. An additional set of four offset 0.020” diameter retaining holes are drilled into the base of the wrist cup. The control wires are pulled through the clearance holes in the bottom of the cup and the ends of the wires are crimped in a downward facing ‘J’ shape. The control wires are tensioned from the underside of the wrist base to secure the wrist spine assembly and eliminate all slack from each stacked disc/sphere pair. This is accomplished by pulling the open segment of the crimped wire end into the retaining holes [See Figure 24]. An additional set of four 0.013” Nitinol retaining wires are used to retain the spine spheres within the wrist structure and provide torsional stiffness during bending. These wires are installed in the same manner as the control wires but terminate immediately upon exiting the proximal end of the wrist base. The eight wires (two pairs of control and four retaining) are distributed around the outer circumference of the spine disc, wrist cup, and wrist base and form a cage to locate and retain the individual wrist spine components during actuation of the effective joint.
Figure 23. Detailed view of articulated instrument wrist assembly with components labeled.

Figure 24. View looking into the wrist cup. Crimped control and retaining wires are shown secured via through and retaining holes.

The mechanized drive wheel assemblies used to actuate the wrist spine joint with 2 DOF are located at the proximal end of the instrument outboard of the drive motor pack. Each of the two identical assemblies is comprised of a drive shaft, 90 degree
gearbox, drive wheel, and a pair of wire tensioning screws. The assemblies are mounted to the instrument via the gearbox plate. The drive shaft is used to transmit torque from the wrist actuator drive motors, located in the instrument housing and motor pack, through the motor plate to the input shaft of the 90 degree gearbox. The 3D printed drive shafts use a tight line on line tolerance for an interference press fit with the 3 mm diameter gear box input shaft. The lower diameter of the drive shaft flares to 12.500 mm to incorporate an M2 stainless steel, cone point set screw. The lower set screw is used to secure the drive shaft to the drive motor output shaft [See Figure 25]. The 30:1 ratio, 90 degree Rhino Drive gear box installs into a matched port on the gear box plate [See Figure 25]. The rear of the port features a clearance hole for the rear segment of the gear box output shaft as well as fastening provisions to secure the gear box to the gear box plate with a pair of 6-32, stainless steel, cap head screws. The input and output shafts of the OEM gear box are modified for use with the mating components in the instrument assembly. The lower portion of the input shaft is cut back to a length of no more than 5 mm. This allows an adequate mating surface for the drive shaft without the negative impact to concentricity of the 3D printed shaft that occurs when pressing a longer input shaft segment into the inner diameter of the drive shaft. Additionally the front portion of the output shaft is cut back to a length of no more than 5 mm to mate with the 3D printed drive wheel. Reducing the output shaft length is necessary to ensure proper alignment of the drive wheel and the wrist control cable guide tubes extending from the motor plate. The cut output shaft is also slotted in the middle. A 9 mm X 4 mm X 0.030” rectangular 6061 aluminum key is secured in the slot using polyurethane glue [See Figure 26]. The drive wheel itself includes a number of critical features designed to perform the mechanical actuation of the wrist spine joint including the rear hub, the wire guide, and reliefs for the tension screw threaded inserts. The rear hub of the drive wheel is a 13 mm diameter cylinder that is 4 mm thick. The rear face of the hub includes a keyed relief to mate with the keyed output shaft of the 90 degree gear box. The top and bottom surfaces of the hub include M2 tapped holes. An M2 stainless steel, cup point set screw is used to secure the hub to the gear box output shaft. The wire guide is the prominent frontal feature on the drive wheel. The wire guide is a 210 degree arc swept along a 7.5 mm radius that starts and terminates just above the horizontal mid-plane of the component.
A 1 mm deep channel along the outer circumference of the arc constitutes the walled portion of the guide and keeps the control wires aligned on the wheel as it rotates. The reliefs for the tension screw threaded inserts are cut into the left and right upper surfaces of the guide arc. The reliefs are designed to accommodate a standard, stainless steel M1.6 hex nut via light press fit. A 1.6 mm through hole extends from the center of the hex nut relief through the side walls of the guide arc feature. Figure 27 shows the drive wheels with all critical geometry annotated. The wire tensioning screws are manufactured from standard M1.6 X 12.250 mm stainless steel, cheese head screws. A 4 mm X 4 mm oval shaped 6061 aluminum cable guide includes an M1.6 through hole on one end and a 0.015” wire through hole on the other. The cable guide is retained under the head of the tension screw with an M1.6 stainless steel, jam nut secured in place with polyurethane glue. This allows the cable guide to maintain a fixed angular orientation while the tension screw is adjusted. Figure 28 shows the tension screws installed on the drive wheel.

![Figure 27](image.png)

**Figure 27.** Drive wheels with all critical geometry annotated.

![Figure 28](image.png)

**Figure 28.** Tension screws installed on the drive wheel.

---

Figure 25. Assembled wrist actuator drive wheel assemblies installed onto instrument base and motor plate. All critical components are labeled.
Each drive wheel assembly actuates the wrist joint assembly along one of the two joint axes. Simultaneous actuation about both wrist joint axes is possible. During assembly each tension screw is adjusted to pretension each control wire with the wrist and drive wheel assemblies in a neutral position. The wrist is extended axially away
from the instrument shaft and the drive wheels are oriented with the 2 mm set screw facing in the vertical direction. To actuate the joint the drive wheels are rotated with the gear box output shaft upon application of drive motor torque to the gear box input shaft via the 3D printed drive shaft. The rotation of the drive wheel generates an angular displacement of the wrist spine via the control cables. A drive wheel rotation of roughly 90 degrees in the clockwise and counter clockwise directions translates to an approximate wrist assembly bend of +/- 90 degrees. Figure 28 shows the deformation of the wrist joint resulting from rotation of the drive wheel assembly.

![Figure 28. Actuation of single wrist joint axis by rotation of control wire drive wheel shown. Wrist structure can rotate +/- 90 degrees about each of the two orthogonal joint axes.](image)
2.1.4 END EFFECTOR MASTER CONTROL INTERFACE

The specialized end-effector master controller interface (EEMCI) acts to provide the teleoperator with a simulated pair of instrument end-effectors to generate control inputs to the robotic surgical system. The EEMCI attaches to the pen stylus of a standard Geomagic/Sensable Phantom Omni [26] haptic controller. The attachment method allows the operator to utilize all 6 DOF of the Geomagic/Sensable Phantom Omni to generate control commands while the EEMCI introduces a seventh DOF to directly control end-effector actuation position. The EEMCI assembly consists of two components: the base link and the actuated finger-tip link. The base link includes several key features. The Geomagic/Sensable Phantom Omni attachment rings extend upward from the rear segment of the base link. The attachment rings are made of two concentric circles of varying diameter positioned along a common center axis. The different ring diameters allow the base link to securely mate with the tapered Geomagic/Sensable Phantom Omni control stylus. The mating tolerance is set for a line on line fit and the compliance of the 3D printed base link ring features is utilized to generate a light press fit with the stylus. The attachment ring method allows the EEMCI to be securely retained to the stylus during operation yet removable for servicing or adjustments. The inner surface of the attachment ring base transitions into a 9.500 mm
thick forked structure. This forked structure includes matching top and bottom 3.750 mm diameter bosses that form the actuated finger-tip link joint pinion. On the outer surface of the attachment ring base the thumb retainer arm extends approximately 66 mm via a 0.125” solid square tube with a single, thin wall reinforcing rib. A 2 mm X 21.750 mm potentiometer retaining channel is also molded into the inner surface of the square tube. The tube terminates at the distal end by flaring into a 0.80” diameter ring. **Figure 30** shows an annotated CAD model of the base link.

**Figure 30.** Annotated CAD model of end-effector master controller (EEMCI) interface base link with all critical features labeled.

The actuated finger-tip link mirrors the overall shape and geometry of the base link with a few key exceptions: the potentiometer mounting rail and cover and the joint clip and stop. The joint clip itself is a c-shaped structure generated from an arc swept 270 degrees. The clip is set with a 0.250 mm mating tolerance to the joint pinion on the base link. The finger-tip link simply snaps onto the base link for assembly and freely rotates around the joint axis. The joint stop is a rectangular structure incorporated into the outer diameter of the joint clip shape [See **Figure 31**]. The stop extends beyond the radius of the clip and prevents hyperextension of the joint by contacting the outer surface of the base link joint fork. The rest of the main link structure is comprised of a 0.125” solid square beam extending approximately 45 mm away from the joint clip that terminates in
another 0.80” diameter ring. The potentiometer mounting rail is located along the beam toward the distal ring. The mounting rail is a separate, solid, rectangular beam extending orthogonally from the main beam approximately 28 mm. The rail includes two 1.250 mm tap holes for fastening the linear control potentiometer to the link. An additional mounting rail is mirrored about the primary rail [See Figure 31] to universalize the EEMCI assembly for left and right master controllers. The mounting rail cover protrudes orthogonally from the top surface of the main beam above both under slung rails. The cover both protects the control potentiometer during operation and functions in conjunction with the mounting rails to form a fork structure that maintains proper alignment between the finger-tip link and the base link during joint actuation.

![Figure 31. Annotated CAD model of end-effector master controller interface finger-tip actuated link with key components labeled.](image)

To use the EEMCI and generate system control inputs the operator’s thumb is inserted into the base link ring and the index finger is inserted into the finger-tip link ring in order to spatially manipulate the EEMCI and Geomagic/Sensible Phantom Omni stylus. The thumb and index finger actuate the EEMCI joint to generate end-effector tool position commands. Figure 32 shows the EEMCI with potentiometer installed in both open and closed command positions.
Figure 32. Composite image of the end-effector master controller interface in use. Both open and closed joint configurations are shown.

2.2 ELECTRICAL HARDWARE DESIGN

The electrical hardware designed for the laparoendoscopic teleoperated surgical robot consists of several key components: the master controllers, PCs, motor controller boxes, and drive motors. The electrical hardware collects inputs from the operator and feeds them into the control software discussed in Section 2.3. The motor commands generated by the control software are then executed via motor controllers to achieve end-effector motions in the operative field. The methods for designing and fabricating the electrical hardware are organized into three sections overall system hardware architecture, motor controller configuration, and end-effector analog reference input circuit design.

2.2.1 HARDWARE ARCHITECTURE

The electrical hardware for the surgical robot is split into two, independent, parallel systems to best control the independent manipulator arm-instrument pairs. The user operates the system by spatially manipulating each of the Geomagic/ Sensable Phantom Omni master controllers in continuous time [See Figure 33].
Figure 33. Complete parallel electrical hardware schematic showing control hardware for left and right sides of the surgical robot.
Each Geomagic/Sensable Phantom Omni includes multiple encoders to capture Cartesian and rotational stylus positions in discrete time. Encoder data for stylus position and rotation are captured as a pair of arrays and used as the input for the control algorithm. Each Geomagic/Sensable Phantom Omni is outfitted with an end-effector control interface as discussed in Section 2.1.4 to capture an additional control input for end-effector/tool tip position. Each master controller is connected to the control PC via FireWire cable for communications speed. The C code control algorithm uses the master controller input to generate the array of motor commands required for the robot instrument end-effectors to match the current position and orientation of the master controller stylus. The control PC communicates with each of the seven distinct manipulator arm-instrument pair drive motors via standard RS232 communication. A Perle I/O8+ PCI Serial Card provides the required number of serial communication ports. The single controller used with the end-effector drive motor is also wired to an EEMCI. Each set of Faulhaber motor controllers include six MCBL 3006S units and one MCBL 2805 unit. The controller sets are housed in two parallel enclosures each with a 24V power supply [See Figure 34]. Each controller is connected directly to a drive motor with an approximately six foot length of shielded 24AWG 10 conductor cable through a bulkhead connector. Figure 33 illustrates the individual components and their position within the overall system hardware architecture.

2.2.2 MOTOR CONTROLLER CONFIGURATION

Each set of seven drive motor controllers and their shared 24V DC power supply are installed into a single enclosure box [See Figure 34]. Each controller is connected to power and ground, connected to an RS232 communication cable via null modem adaptor, and the controller output cables are run to bulkhead connectors in the rear wall of the enclosure. Two bulkhead connectors are used to allow quick disassembly of the physical robot from the motor controller enclosures. Connectors are populated according to drive motor functionality. One connector contains all output cables for the manipulator arm drive motors and the second connector contains the output cables for the mechanized
instrument drive motors. The control parameters of each controller are optimized for compatibility with the mechanical systems of the surgical robot. Table 1 summarizes the parameter variables used for each of the six MCBL 3006S controllers. Configuration of the single MCBL 2805 controller is discussed in the next section. Factory values are used for parameters not included in the configuration table. Motor part numbers have been selected based on previous University of Hawai‘i at Mānoa work [24, 29].

![Motor controller box with lid removed and all components labeled](image1)

**Figure 34.** Motor controller box shown with lid removed and all components labeled.

![Instrument motor pack and manipulator arm linkage with all drive motors numbered by joint](image2)

**Figure 35.** Instrument motor pack and manipulator arm linkage with all drive motors numbered by joint.
Table 1. Complete list of controller configuration parameters listed by actuation joint.

<table>
<thead>
<tr>
<th>Joint Number</th>
<th>Motor P/N</th>
<th>Baud Rate</th>
<th>Motor Type</th>
<th>Continuous Current Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2036U024B K1155</td>
<td>115k</td>
<td>4</td>
<td>1000 mA</td>
</tr>
<tr>
<td>1</td>
<td>2036U024B K1155</td>
<td>115k</td>
<td>4</td>
<td>1000 mA</td>
</tr>
<tr>
<td>2</td>
<td>2036U024B K1155</td>
<td>115k</td>
<td>4</td>
<td>1000 mA</td>
</tr>
<tr>
<td>3</td>
<td>1628T024B K1155</td>
<td>115k</td>
<td>2</td>
<td>600 mA</td>
</tr>
<tr>
<td>4</td>
<td>2444S024B K1155</td>
<td>115k</td>
<td>5</td>
<td>1750 mA</td>
</tr>
<tr>
<td>5</td>
<td>2444S024B K1155</td>
<td>115k</td>
<td>5</td>
<td>1750 mA</td>
</tr>
</tbody>
</table>

2.2.3 END-EFFECTOR ANALOG REFERENCE INPUT CIRCUIT DESIGN

The position of the instrument end-effector is controlled in discrete time by an analog reference input provided directly to the end-effector drive motor controller. The high level functions of the controller are still managed via RS232 communication with the control PC. A simple circuit incorporating a linear potentiometer mounted to the EEMCI [See Figure 36] applies a scalar voltage to the motor controller based on EEMCI orientation. This allows drive motor motions to precisely track EEMCI motions when operating the MCBL 2805 controller in analog position control mode. Table 2 includes all the additional parameter configurations to calibrate accurate positional control of the end-effector based on user inputs [See Figure 37].

Figure 36. Simple schematic of analog circuit used to generate reference input signal for positional control of instrument end-effector.
Table 2. Complete list of controller configuration parameters for instrument end-effector.

<table>
<thead>
<tr>
<th>Joint Number</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor P/N</td>
<td>2444S024B K1155</td>
</tr>
<tr>
<td>Baud Rate</td>
<td>19K</td>
</tr>
<tr>
<td>Motor Type</td>
<td>5</td>
</tr>
<tr>
<td>Continuous Current Limit</td>
<td>250 mA</td>
</tr>
<tr>
<td>Acceleration Limit</td>
<td>30,000</td>
</tr>
<tr>
<td>Position Limit</td>
<td>9,000</td>
</tr>
<tr>
<td>Operating Mode</td>
<td>APCMOD</td>
</tr>
</tbody>
</table>

Figure 37. EEMCI motions coupled directly to end effector motions through analog reference input to MCBL 2805 motor controller.
2.3 KINEMATIC CONTROL

Control of the surgical robot is accomplished using both forward and inverse surgical robot system kinematics developed by the advisor and author. Kinematic models are used to generate target end-effector positions based on master controller inputs. A proportional gain multiplied by the error between current and desired position creates discrete time motor velocity commands used to achieve desired end-effector motions and trajectories. Absolute end-effector motions are realized via coupled joint motions. This is due to the kinematic complexity of a serial link arm manipulating an end effector through a pivot point along a bent shaft being swept through a 360 degree arc. Forward kinematics are used to determine start position of the end-effector tip, inverse kinematics are used to determine tip goal positions based on master controller inputs, and positional error is used to generate required joint velocity commands. Mechanized instrument wrist bending motions are controlled with a separate error based velocity control algorithm operating in parallel to the manipulator control. The following discussion of control algorithms focuses on the right side of the system. Control of the left half is accomplished by taking a mirror image of these kinematic models.

2.3.1 FORWARD KINEMATIC MODEL

The forward kinematic model of the system is used to calculate the starting end-effector tip position used as the base reference in the position control algorithm for the manipulator arm. To calculate the forward kinematics the origin of the base coordinate frame is placed at the incision site and aligned as shown in Figure 38 and as discussed in [25]. Figure 38 also shows the startup configuration of the right side of the system and includes starting joint angles in radians and variable labels for offsets and link lengths. Initial conditions are given as:
Figure 38. Annotated images of surgical robot system in startup configuration. Base frame origin is at the incision point with Z direction along endoscope axis.

The position \((x, y, z)\) of the joint axis intersection of the manipulator arm universal joint, or gimbal, is calculated using the following equations for a two link serial link manipulator as described in [29].

\[
\theta_{1init} = \frac{\pi}{4} \quad (2.1)
\]
\[
\theta_{2init} = \frac{3\pi}{4} \quad (2.2)
\]
\[
\theta_{3init} = 0 \quad (2.3)
\]
\[
d_0 = 150 \text{ mm} \quad (2.4)
\]

\[
G_x = X_o + L_1 \cos(\theta_1) + L_2 \cos(\theta_1 + \theta_2) \quad (2.5)
\]
\[
G_y = Y_o + L_1 \sin(\theta_1) + L_2 \sin(\theta_1 + \theta_2) \quad (2.6)
\]
\[
G_z = d_0 \quad (2.7)
\]
Next the length of instrument shaft between the gimbal and incision point, $R_G$, and the length of the instrument shaft protruding below the incision point, $R_E$, are determined. $L_R$ is the total length of the instrument shaft from the center of gimbal motion to the end-effector tip projection onto the instrument shaft axis.

\[
R_G = \sqrt{G_x^2 + G_y^2 + G_z^2} \tag{2.8}
\]

\[
R_E = L_R - R_G \tag{2.9}
\]

The position of the end-effector tip projection onto the instrument shaft axis in base frame coordinates is calculated as:

\[
\mathbf{R} = -\frac{R_E}{R_G} \mathbf{G} \tag{2.10}
\]

The perpendicular offset vector between the instrument shaft axis and the end-effector tip must be calculated in order to determine the position of the end-effector tip in base frame coordinates. This offset vector accounts for the 45 degree shaft bend in the angled instrument(s). The vector can be calculated by taking the cross product of the $\mathbf{R}$ unit vector and the base frame $\mathbf{Y}$ unit vector multiplied by the magnitude of the offset between the instrument shaft and end-effector tip, $OFF$ [See Equation 2.11]. This cross product is possible because the initial configuration of the system orients the offset vector along the $x$-axis of the base frame. **Figure 39** shows the measurements corresponding to the instrument shaft variables referenced above.

![Figure 39. Mechanized instrument shown with shaft dimensions used in kinematic calculations annotated.](image-url)
Thus the initial position of the end-effector tip at system startup expressed in base frame coordinates can be described as:

\[ P_{\text{tip}} = R + R_{\text{OFFSET}} \]  \hspace{1cm} (2.12)

### 2.3.2 INVERSE KINEMATIC MODEL

A hybrid of position and velocity control has been utilized for the surgical robot presented in this thesis. Position control allows accurate motions with minimal control drift and velocity control algorithms generate smooth motor motion commands to minimize overshoot and control lag. Thus the hybrid architecture employed creates a control structure that maintains positional accuracy in relation to master controller inputs while performing controlled, intuitive motions during operation. To execute this algorithm an array of target joint positions must be generated to match the end-effector tip position and orientation with the master controller input at each time step. The inverse kinematic model used to generate these target joint positions is discussed below.

The control loop first determines the target end-effector tip position and orientation in base frame coordinates as follows:

\[ P_{\text{TIPGOAL}} = P_{\text{TIP}} + \Delta_{\text{Master}} \]  \hspace{1cm} (2.13)

Next the position of the projection of the end-effector tip onto the instrument shaft axis must be determined before rotation of the shaft (\( \theta_3 = 0 \)). The magnitude of the distance from the incision point to the projection on the instrument shaft and the distance from the incision point to \( P_{\text{TIPGOAL}} \) are calculated. These values are used to determine the projection point in base frame coordinates by determining the intersection of two circles. One circle is centered at the incision point with a radius equal to the magnitude of the distance between the incision and the projection point and the second circle is centered at \( P_{\text{TIPGOAL}} \) with a radius \( OFF \). The geometry is shown in Figure 40.
Sides of the triangle shown in Figure 40 are described as:

\[ R_{\text{TIPGOAL}} = \sqrt{P_{\text{TIPGOALX}}^2 + P_{\text{TIPGOALY}}^2 + P_{\text{TIPGOALZ}}^2} \]  \hspace{1cm} (2.14)

\[ R_{\text{RODEND0}} = \sqrt{R_{\text{TIPGOAL}}^2 + \text{OFF}^2} \]  \hspace{1cm} (2.15)

Since the vector from the incision to the projected point of the end-effector tip onto the instrument shaft axis (\(P_{P0}\)) is first determined before any shaft rotation \(P_{P0y}\) is equal to \(P_{\text{TIPGOALy}}\). Therefore \(P_{P0x}\) and \(P_{P0z}\) are defined by circle intersection as calculated below. See Figure 41 for an illustration of the geometry.

\[ R_{\text{TIPGOAL}} = a + b \]  \hspace{1cm} (2.16)

\[ a = \frac{R_{\text{RODEND0}}^2 - \text{OFF}^2 + R_{\text{TIPGOAL}}^2}{2 \cdot R_{\text{TIPGOAL}}} \]  \hspace{1cm} (2.17)

\[ h = \sqrt{R_{\text{RODEND0}}^2 - a^2} \]  \hspace{1cm} (2.18)

\[ P_{2x} = a \cdot \frac{P_{\text{TIPGOALX}}}{R_{\text{TIPGOAL}}} \]  \hspace{1cm} (2.19)
\[ P_{2z} = a \times \frac{P_{\text{TIPGOALz}}}{R_{\text{TIPGOAL}}} \]  \hspace{1cm} (2.20)

\[ P_{P0x} = P_{2x} + h \times \frac{P_{\text{TIPGOALz}}}{R_{\text{TIPGOAL}}} \]  \hspace{1cm} (2.21)

\[ P_{P0z} = P_{2z} - h \times \frac{P_{\text{TIPGOALx}}}{R_{\text{TIPGOAL}}} \]  \hspace{1cm} (2.22)

Figure 41. Circle intersection diagram used to determine PP0x and PP0z. All points and line segments referenced in Equations 2.16 – 2.22 are annotated.

Next the vector from the incision point to \( P_{p0} (R_{PP0}) \) can be rotated by \( \theta_3 \) about the unit vector from the incision point to \( P_{\text{TIPGOAL}} (R_{\text{TIPU}}) \) using the following Rodrigues formula rotation calculations [30]:

\[ R_{\text{TIPU}} = -\frac{P_{\text{TIP}}}{R_{\text{TIPGOAL}}} \]  \hspace{1cm} (2.23)
The target manipulator gimbal position \((G)\) can be calculated from \(R_{PP0}\) using the following equation set as discussed in [26]:

\[
R_{PP0} = R_{PP0 \cdot R_{TIP0}}(\theta_3) \cdot R_{PP0}
\]  

(2.25)

The target gimbal position is then used to determine the target joint positions \((\theta_1, \theta_2, \text{ and } d)\) needed to place the end-effector tip in the position and orientation commanded by the master controller in the given time step. The equations used to calculate joint positions are shown below and partially derived in [26].

\[
R_{RODEND} = \sqrt{R_{PP0x}^2 + R_{PP0y}^2 + R_{PP0z}^2}
\]  

(2.26)

\[
R_G = L_R - R_{RODEND}
\]  

(2.27)

\[
\mathbf{G} = -\frac{R_G}{R_{RODEND}} \cdot \mathbf{R}_{PP0}
\]  

(2.28)

The target gimbal position is then used to determine the target joint positions \((\theta_1, \theta_2, \text{ and } d)\) needed to place the end-effector tip in the position and orientation commanded by the master controller in the given time step. The equations used to calculate joint positions are shown below and partially derived in [26].

\[
d_{GOAL} = G_z
\]  

(2.29)

\[
\theta_{1GOAL} = \text{atan2} (G_y - Y_0, G_x - X_0) - \arccos \left( \frac{(G_y - Y_0)^2 + (G_x - X_0)^2 + L_1^2 - L_2^2}{2L_1 \sqrt{(G_y - Y_0)^2 + (G_x - X_0)^2}} \right)
\]  

(2.30)
The kinematic model used to control the wrist bending motions is the same hybrid style algorithm utilized to control the manipulator arms. The primary function of the position control portion of the wrist model is to read changes in the position of the master controller gimbal and changes in the master controller stylus rotation and map those inputs to wrist motions coupled to the orientation and position of the instrument shaft and end-effector. This allows for wrist bending directions to remain aligned with the instrument shaft as viewed by the user during operation. The following equations are used to generate the desired wrist joint positions:

$$\theta_{2GOAL} = \pi - \arccos \left[ \frac{L_1^2 + L_2^2 - (Y - Y_0)^2 - (X - X_0)^2}{2L_1L_2} \right]$$  \hspace{1cm} (2.31)$$

$$\theta_{3GOAL} = \Delta_{Master} \theta_3$$  \hspace{1cm} (2.32)$$

**2.3.4 PROPORTIONAL VELOCITY CONTROL**

The array of instrument and manipulator goal joint positions generated by the kinematic models are used along with the current joint position values to generate motor velocity commands. These commands are calculated based on the error between the target and current positions at each time step. Each goal joint position is bounded by individual upper and lower joint limits based on the specific geometries of each joint.
Commanded positions beyond the limits are capped at the limit bound to prevent damage to the surgical robot arising from attempts to satisfy commanded motions not physically supported by the system. The filtered joint positions are used to determine motor velocity commands in lieu of the absolute kinematic goal positions. All velocities are formulated using a simple error based proportional gain except for instrument shaft rotation ($\theta_3$). The velocity command for this joint is modified to compensate for additional effective shaft rotations introduced by coupled motions of the manipulator links during operation. All joint limits and equations used for generating velocity commands are shown below:

**Joint Limits:**

\[
110 \text{ mm} < d < 270 \text{ mm} \quad (2.37)
\]

\[
0 < \theta_1 < \pi \quad (2.38)
\]

\[
0 < \theta_2 < \frac{11\pi}{12} \quad (2.39)
\]

\[
0 < \theta_3 < 10\pi \quad (2.40)
\]

\[
-\frac{5\pi}{4} < \theta_4 < \frac{5\pi}{4} \quad (2.41)
\]

\[
-\frac{5\pi}{4} < \theta_5 < \frac{5\pi}{4} \quad (2.42)
\]

**Velocity Command Equations:**

\[
V_d = (d_{GOAL} - d) \cdot K_{Pd} \quad (2.43)
\]

\[
V_1 = (\theta_{1GOAL} - \theta_1) \cdot K_{Pl} \quad (2.44)
\]

\[
V_2 = (\theta_{2GOAL} - \theta_2) \cdot K_{Pl} \quad (2.45)
\]
\[ V_3 = \left[ \theta_{3\text{GOAL}} - \theta_3 - \left( \theta_{1\text{GOAL}} - \frac{\pi}{4} \right) - \left( \theta_{2\text{GOAL}} - \frac{3\pi}{4} \right) \right] * K_{P3} \quad (2.46) \]

\[ V_4 = ( \theta_{4\text{GOAL}} - \theta_4 ) * K_{PW} \quad (2.47) \]

\[ V_5 = ( \theta_{5\text{GOAL}} - \theta_5 ) * K_{PW} \quad (2.48) \]
3. RESULTS

Several key criteria have been used to assess the viability of the novel, teleoperated, single-site robotic surgical system presented in this thesis. Initial evaluations focus on the physical size of the robot during operation as a key metric to quantify the success of developing a compact, portable, single-site robotic surgical platform. A subset of this dimension based analysis reviews the size of the instruments designed in conjunction with the primary robot platform. The volume of the instrument machine pack is of particular interest due to the importance of minimizing the occurrence of instrument-instrument collisions during operation. Performance of the control design is also considered as a key metric for evaluating the accuracy and repeatability of the system during teleoperation. Optical tracking has been used to measure end-effector tool tip position during shape tracing exercises. This data gives an indication of the positional accuracy of the system in base frame coordinates and illustrates the level of drift inherent in the control strategies investigated. The final evaluation criteria quantify the competence of the system in performing ‘useful’ surgical tasks. A standard peg transfer exercise as described by the Society of American Gastrointestinal and Endoscopic Surgeons Fundamentals of Laparoscopic Surgery (SAGES FLS) has been used as a benchmark ‘useful’ surgical task for the purposes of evaluating the practical viability of the robotic system in an operating environment.

Results data has been collected from the teleoperated robotic surgical system presented in this thesis as well as from the previous UH teleoperated surgical robot [24], from the DaVinci surgical robot manufactured by Intuitive Surgical, Inc., and the University of Washington RAVEN system [31]. Analyzing data across multiple robotic platforms allows functional comparisons between current and past UH surgical robots, commercial benchmarks (DaVinci), and equivalent experimental research platforms. Such a broad assessment fully contextualizes the upside potential of the presented system while also fully quantifying the remaining performance gap that must be closed in the pursuit of developing a disruptive, commercially viable robotic surgical system.
3.1 OPERATING VOLUME ASSESSMENT

Operating volume has been identified as the target metric for quantifying the extent to which the overall surgical robot presented has been miniaturized relative to previous UH systems [24], surgical robots in active medical practice, and other research systems [31]. For the purposes of this thesis operating volume is described as the total volume of space occupied by any and all components, structures, frames, bases, manipulators, etc. as the robot is moved through all valid, reachable poses. Complete computational calculation of the operating volume as done in [29] has proven impractical in the current analysis. This is due to the inclusion of the additional degrees of freedom required to fully represent each system as well as constraints in developing accurate physical models of the commercially available system considered. In lieu of numeric analysis each system has been decomposed into respective core operating geometry dictated by the physical robotic platforms and manipulator kinematics. Geometric decompositions and representations of each system can be seen in Figure 42. The total volume of each geometric model has been calculated using SolidWorks and annotated on the diagrams in Figure 42.

Figure 43 illustrates the comparison in operating volume between all systems investigated. As can be seen in figure the previous multi-port UH system and the present single-port UH system are each roughly an order of magnitude smaller than the current commercial bench mark system, the DaVinci. Furthermore the present UH system is another 53% smaller than the previous multi-port robot and 81% smaller than the RAVEN in addition to reducing the number of operative incisions from three to one. A similar geometric analysis of the mechanized instruments developed for the present and previous UH systems shows similar results. This analysis focuses specifically on the machine pack of the different instrument designs and represents each as a simple cylinder. The size of the machine pack is critically important in the design of the present single-port system due to its influence on the frequency of instrument-instrument collisions during teleoperation. Figure 44 shows a direct comparison between the two instrument designs and Table 3 lists the machine pack volume calculations.
Figure 42. Current UH robotic surgical system, previous UH robotic surgical system, and Intuitive DaVinci robotic surgical systems shown decomposed into simple geometric representations based on measured platform shape and manipulator ranges of motion. Representations are annotated with shape volumes in cubic meters.
Figure 43. Bar chart illustrating the differences in the volume of geometric representations among the robotic surgical systems assessed. RAVEN data from [31].

Figure 44. Instrument machine pack size comparison between the previous system design and the current system design.
As can be seen in Table 3 the instruments designed and developed for the single-port system are approximately 30% smaller in volume than the previous iteration. In addition to a substantial reduction in machine pack volume the single-port instruments also feature improved serviceability and adjustability. Instrument volume for the DaVinci system has not been explicitly calculated but can be assumed to be scaled proportionately to the overall operating volume values formulated above.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Diameter (cm)</th>
<th>Height (cm)</th>
<th>Volume (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Previous UH</td>
<td>5.7</td>
<td>15.6</td>
<td>399.1</td>
</tr>
<tr>
<td>Current UH</td>
<td>5.7</td>
<td>10.8</td>
<td>276.9</td>
</tr>
</tbody>
</table>

Table 3. Instrument machine pack volume calculations.

3.2 PERFORMANCE OF CONTROL DESIGN

The performance of the control algorithms developed for the robotic surgical system presented in this thesis can be measured as a function of the accuracy and repeatability of the instrument end-effector tip control. Absolute positional accuracy is not critically important in the development of teleoperated surgical robotics because the operator functions as part of the closed loop control system and is capable of making minor adjustments to correct for any errors in absolute end-effector tip position during use. Tip errors undetectable to a typical operator under normal endoscope magnification fall within the acceptable error threshold adopted by systems presently utilized in operating rooms. This range is loosely one to two millimeters. Although a wider absolute accuracy error threshold is acceptable there still remains a firm requirement for repeatability of control. Repeatability, commonly expressed as control drift, is the measure of the ability of the system to return the end-effector tip to the same, previously occupied position in space when the master controller is returned to the same previous point in controller space. In teleoperated robotic surgical systems control drift must be minimized to prevent the end-effector from gradually moving outside of the master
controller control range during operation. To evaluate the control performance of the system presented an optical tracking system has been used to measure the accuracy and repeatability. A Northern Digital Polaris Vicra optical tracker was utilized along with a matching constellation of reflective spheres installed on the end of the instrument machine pack as shown in Figure 45.

The mechanized surgical instrument and mounted reflectors were calibrated as a distinct tool using the NDI software suite packaged with the tracker hardware. This calibration allows the real time calculation of end-effector tool tip position in a fixed coordinate frame as the instrument pivots about the incision point and rotates about the fixed shaft bend. Care was taken to place all tracking components in a manner to minimize reflection interference during the course of evaluations.
Simple shape tracing exercises were completed to evaluate control performance of the system compared to the performance of the previous UH work [24]. Optical tracking data taken during a teleoperated shape tracing exercise using the previous UH system is shown in Figure 46 below. The system performance illustrated in Figure 46 can be considered benchmark for evaluating the performance of the new robotic system presented in this thesis. Absolute positional errors constituting the sum error of user input, mechanical hysteresis, and control error remain small over the duration of the test and exhibited control drift from pass to pass is minor.

![Figure 46](image)

**Figure 46.** Positional data from square shape tracing exercise collected via optical tracking when operating the previous UH system.

Figure 47 shows data collected by performing a similar shape tracing exercise using the new robotic surgical system presented in this thesis. Although the shape traced varies from that in Figure 46 the methodology for conducting the test and processing the data is consistent. In this test the system was operated under simplified control architecture and under more controlled conditions. The additional controls were
introduced to isolate pure control performance from the additional variables that can compound the errors in optical tracking of the end-effector tool tip. A straight shaft instrument similar to the design used with the previous UH system was inserted through a specially modified trocar without a second instrument or endoscope. This was done to eliminate errors associated with calibrating the pivot tool setting required by angle shafted tools as well as eliminate unpredictable motions derived from multiple tools and an endoscope pivoting about each other through a single incision. Utilizing a straight shafted instrument for this test allowed the use of a more simple positional control algorithm than the design described in Section 2.3.2. The algorithm used allowed simple decoupling of motion in the vertical direction from X-Y motions providing a stable two dimensional operational plane on which to trace the projected shapes. Under these conditions the results achieved with the new single-port system are comparable to those garnered from previous work in Figure 46 when considering the additional vibration generated by the cantilevered mount arm used for tracking.

Figure 47. Positional data from square shape tracing exercise collected via optical tracking when operating the current UH system under controlled conditions.
After validating the performance of the presented system under narrow, controlled conditions the same test was performed with all constraints removed. A calibrated, bent shaft instrument and the requisite full control algorithm were used along with the standard trocar mock-up. Both the endoscope and instrument were passed through a single, common incision. The results are shown below in Figure 48:

![Graph showing positional data from square shape tracing exercise collected via optical tracking when operating the current UH system under no constraints.](image)

**Figure 48.** Positional data from square shape tracing exercise collected via optical tracking when operating the current UH system under no constraints.

As shown above the system seems to demonstrate large positional errors as well as drift when operated without the constraints used in Figure 47. In Figure 48 the initial shape trace is shown in dark blue continuing through the final trace shaded in light blue. In all repeated traces there is minimal choppiness to the individual line segments comprising the edges of the shape indicating low levels of mechanical hysteresis. However large positional errors can be seen in some corners as the instrument pivots about the endoscope shaft in the common incision. These uncontrolled movements
reflect the limitations of the mock-up trocar in providing the same motion control as actual single-port surgical trocars. The large changes in shape of the traced images as well as the drift along the Y axis partially result from the coupled motions in X-Y and Z, the use of an angled endoscope tip, and the end-effector home position required to avoid singularities generated by the highly coupled shaft rotation control algorithm. As shown in Figure 49 the shape to be traced must be located to the far right of the endoscope field of view in order to be completely traced by the end-effector.

![Figure 49. Endoscope view of end-effector home position and target shape before beginning exercise.](image)

The image distortion resulting from placing the target shape to the periphery of a 30° downward facing endoscope lens results in a projected screen image that does not correlate with the actual shape in base frame coordinates. This distortion grows as a function of manipulator Z-axis displacement. The coupled motion built into the control structure introduces additional error as the operator does not have independent control of Z motion to ensure a flat X-Y only shape trace during operation. Based upon the results in Figure 47 it can be concluded that the underlying mechanical structure, electrical hardware, and basic control approach of the robot are functional. However the combined limitations in the full, tip position control approach, viewing hardware, and simulated single-port trocar create conditions under which complete shape tracing validation tests are difficult to administer and analyze.
3.3 USEFUL SURGICAL TASK ASSESSMENT

A standard peg transfer exercise as described by the Society of American Gastrointestinal and Endoscopic Surgeons Fundamentals of Laparoscopic Surgery (SAGES FLS) has been selected to evaluate and compare the performance of the robotic surgical system presented in this thesis, the previous UH system [24], the Intuitive Surgical, Inc. DaVinci, and RAVEN [31]. The methodology of the peg transfer test is fully described in [28]. A training peg board consisting of twelve pegs and six rings was used to carry out the transfer trials. For each trial the operator moved each ring from one peg to the corresponding vacant peg. Figure 50 from [28] illustrates the motions required to perform a two-instrument peg transfer. In the test evaluating the previous UH system [28] the user moved all six rings from left to right and then back to the original positions from right to left. The total time in seconds required to make all twelve transfers was recorded in Table 4 along with average individual peg transfer times.

Figure 50. Composite images detailing the steps of a two instrument peg transfer.
Table 4. Total times for each peg transfer trial completed with the multiple users on the previous UH system from [28]. Average peg transfer times per trial shown.

<table>
<thead>
<tr>
<th>User</th>
<th>Trial</th>
<th>Total Time</th>
<th>Time per Peg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>151</td>
<td>12.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
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<td>10.7</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>378</td>
<td>31.5</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>285</td>
<td>23.8</td>
</tr>
<tr>
<td></td>
<td>6</td>
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<tr>
<td></td>
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<td>23.2</td>
</tr>
<tr>
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<td>13</td>
<td>397</td>
<td>33.1</td>
</tr>
<tr>
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<td>30.0</td>
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<td></td>
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<td>28.6</td>
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<tr>
<td>6</td>
<td>16</td>
<td>260</td>
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<tr>
<td></td>
<td>17</td>
<td>270</td>
<td>22.5</td>
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<tr>
<td></td>
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<td>237</td>
<td>19.8</td>
</tr>
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<td></td>
<td>24</td>
<td>275</td>
<td>22.9</td>
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<td>26</td>
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<td></td>
<td>27</td>
<td>264</td>
<td>22.0</td>
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<tr>
<td>10</td>
<td>28</td>
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<td>21.3</td>
</tr>
<tr>
<td>11</td>
<td>30</td>
<td>328</td>
<td>27.3</td>
</tr>
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<td></td>
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<td>25.3</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>256</td>
<td>21.3</td>
</tr>
</tbody>
</table>
An identical peg transfer test methodology was utilized when evaluating the performance of the DaVinci system. **Table 5** includes the total and individual peg transfer times achieved by the DaVinci.

**Table 5.** Total times for each peg transfer trial completed with the multiple users on the Intuitive DaVinci system. Average peg transfer times per trial shown.

<table>
<thead>
<tr>
<th>Number of Rings per Trial</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>132</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>User</th>
<th>Trial</th>
<th>Total Time</th>
<th>Time per Peg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>90</td>
<td>7.5</td>
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<tr>
<td></td>
<td>2</td>
<td>100</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>105</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>119</td>
<td>9.9</td>
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<tr>
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<td>5</td>
<td>111</td>
<td>9.3</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>109</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>95</td>
<td>7.9</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>107</td>
<td>8.9</td>
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<tr>
<td></td>
<td>9</td>
<td>99</td>
<td>8.3</td>
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<td></td>
<td>10</td>
<td>92</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>92</td>
<td>7.7</td>
</tr>
</tbody>
</table>

The peg transfer test methodology [28] was modified when evaluating the new UH single-site system presented in this thesis. The modification was made to account for functional challenges associated with the current control structure. These limitations made a standard, two-instrument transfer unreliable when executed on the single-site system. Therefore in lieu of the standard method a revised experiment comprised of single-instrument peg transfers was performed. Although the single-instrument transfers were not made between matched posts on the training peg board the distance traveled during transfers closely approximates those performed on the other systems evaluated above. The data collected from this evaluation provides an estimate of base line performance and an indication of results achievable in a fully functional, two-instrument peg transfer assessment of the new single-site system. **Figure 51** illustrates a single-instrument transfer and the resulting peg transfer times achieved on the single-site system are shown in **Table 6.**
Figure 51. Single-instrument peg transfers executed with the single-site system.

Table 6. Individual peg transfer times for each trial completed with a single user on the new single-site robotic surgical system.

<table>
<thead>
<tr>
<th>Number of Rings per Trial</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>User</th>
<th>Trial</th>
<th>Time per Peg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>17</td>
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<td></td>
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<td>6</td>
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<td>7</td>
<td>25</td>
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<tr>
<td></td>
<td>8</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>23</td>
</tr>
</tbody>
</table>
Figure 52 expresses peg transfer data from the DaVinci, RAVEN [31], and both UH systems as a series of box plots representing the individual peg transfer times achieved with each system. As shown in the figure there are a number of differences between the scale and distribution of peg transfer data among the different systems. These differences reflect not only absolute performance variation but also a number of uncontrolled variables present in the trials conducted between systems. The inclusion of additional variables provides valuable insight into a number of different factors that impact system performance. The magnitude of performance impact exhibited by these variables individually is indiscernible in the preliminary analysis presented. However the sum total effect provides import directions for future development and refinement of the single-port surgical robot. High level analysis shows that the performance of the new UH system when conducting only single-instrument peg transfers with reduced instrument DOF is on par with performance measured in two-instrument, full DOF trials on the previous UH system. Also the average peg transfer time for both UH systems and the
DaVinci are below the test failure time whereas the comparable RAVEN system average time exceeds the failure time. Of important note when comparing the two UH systems directly is the much smaller sample size in data gathered on the new system as well as the difference in experience level of the test subjects. Data collected on the new system was completed solely by an experienced user defined as an individual familiar with teleoperated robotic operation and one who is comfortable, confident, and capable while operating the system. In contrast the data from the previous system was collected partially by an experienced operator and principally by ten inexperienced volunteers [24].

**Figure 52** shows parity between the results from the untrained group operating the previous system and the data shown from the new system. However there exists a significant performance gap when comparing the results of experienced users. The minimum values for the previous UH plot represent the peg transfer times of an experienced user on that system and are shorter in time than the transfer times realized by an equivalent user on the new system.

When making comparisons between the performance of the two UH systems and the commercial bench mark system (Intuitive DaVinci) the differences in samples size and user experience must be properly considered. The data collected in the DaVinci system trials consists of a sample size equal to approximately half that of the previous UH system trials and was collected by one experienced user as well as one trained, practicing physician with over 100 robotically assisted surgical procedures logged. An analysis of the DaVinci system data shows very minimal variability in peg transfer times over all trials and a demonstrable performance advantage over both the current UH system as tested and the previous UH system when operated by an experienced user. It is important to note that the peg transfer times achieved with the DaVinci system by the experienced user (author) and the trained surgeon are roughly equivalent [See Table 5] suggesting that the clinical performance of the previous and current UH system can be reasonably extrapolated from the data gathered by experienced users in the SAGES FLS evaluations shown in **Figure 52**.
4. DISCUSSION

The primary goal of this research is to further shrink the gap in rates of positive patient outcomes between groups of surgeons by providing more surgeons better access to the benefits of teleoperated laparoendoscopic surgical robotic systems. This is accomplished by developing and validating a teleoperated laparoendoscopic surgical robotic system that is smaller, portable, and dramatically less expensive than conventionally available commercial systems. The level of success in reaching the stated goal has been measured using several criteria: an operating volume assessment to quantify the extent to which the single-port robotic surgical system presented has been miniaturized and modularized, assessing performance of the control algorithms developed for the single-port, and a useful surgical task assessment to determine the functional performance of the single-port system in simulated clinical tasks. Data has been compiled on the present system, the previous UH multi-port system, the Intuitive Surgical, Inc. DaVinci system, and University of Washington RAVEN system.

An analysis of operating volumes shows that the mechanical design of the single-port system yields a platform that occupies an order of magnitude less space than the commercial bench mark system (DaVinci) and achieves an operating volume reduction of approximately 53% over the previous multi-port system developed at UH and an approximate reduction of 81% over comparable research systems (RAVEN). The reduction in size is made in addition to reducing the number of operative incisions from three to one thereby further reducing patient trauma, post-operative scarring, and recovery times. The substantial reduction in size yields demonstrable advantages in portability compared to the bench mark systems. Portability of the system has also been dramatically improved compared to previous UH work through the design of a single, compact robotic base incorporating two instrument manipulators and an endoscope manipulator. Streamlining the design in this manner reduces both the complexity of the overall system by reducing the number of independent components that must be setup and torn down pre and post procedure. The method by which improved compactness has been designed into the surgical system presented also allows for additional DOF’s to be
incorporated further extending the range and reach of the instrument inside the operative field. This allows this system to also perform exploratory oriented tasks that must typically be done manually with existing commercial and research systems as well as the previous UH multi-port system. Finally the design of the presented system achieves the above results while maintaining full modularity of instruments. A quick disconnect system has been retained as the primary interface between instrument and manipulator that allows rapid tool changes without additional calibration. Additionally the overall modularity of the system has been greatly improved above the bench mark and previous UH systems by an improved instrument design that supports interchangeable tool tips. This eliminates the redundancy of requiring multiple sets of entire instrument assemblies for the sole purpose of utilizing different tool tips.

The primary cost reduction goal has been addressed through the method of manufacture employed in designing the current single-port robotic surgical system. The system has been designed to fully capitalize on the manufacturing advantages offered by 3D printing technology. Traditional, intricate, and costly components manufactured from high grade stainless steel, aluminum, and titanium have been replaced by inexpensive, easy to produce 3D printed ABS components. The use of plastics as the primary manufacturing material allows a dramatic reduction in the complexity of joint structures, elimination of fasteners, reduction in assembly complexity and maintenance costs, as well as the utilization of complex geometries capable of reducing component weight and size. Preliminary control performance assessments using high fidelity optical tracking equipment have shown that properly designed 3D printed structures, manipulators, rotational, and prismatic joints can precisely position and control instrument end-effector positions within acceptable positional error thresholds. This suggests that 3D printing can be used as a valid design and manufacturing method for quickly and inexpensively producing entire surgical robots. A sea change that offers new opportunities to practically introduce robotically assisted surgery to a number of new procedures and health care markets.

Functional validation of the single-port surgical robot was completed by investigating teleoperated performance in standard laparoscopic surgical training tasks.
selected from the Society of American Gastrointestinal and Endoscopic Surgeons Fundamentals of Laparoscopic Surgery (SAGES FLS). Standard FLS peg transfer tasks were performed with the single-port system presented and the commercial benchmark system. The results were compared with transfer data existing data collected from the previous UH and RAVEN systems. A number of additional variables were incorporated into these preliminary performance evaluations in addition to the primary independent variable tested. Although the presence of additional uncontrolled variables limits direct comparison of the sample data these variables do provide valuable insight into the baseline competency of the presented system, the upside potential of said system, and direction for continued development. The peg transfer trials are performed by executing a series of timed, two-instrument peg transfers. However due to limitations in the present iteration of the control architecture utilized for evaluating the single-port system these two-instrument transfers were unable to be completed reliably. Therefore the trials were carried out using a single instrument with a simplified control algorithm and reduced DOFs. When directly comparing the results from this evaluation to the transfer time data collected in previous work on the previous UH system there exists parity in the performance of the two systems. Additionally the two UH systems outperform the comparably developed RAVEN system which did not meet the FLS completion time criteria. However if the results of the two UH systems are controlled for the experience level of the operators conducting the trials it can be seen that the previous multi-port UH system outperforms the presented single-port system. There also exists a much larger standard deviation in peg transfer times between the experienced user operating the presented system compared with the experienced user operating the previous system. These discrepancies can be primarily attributed to the difficulties shown by the current system in executing repeatable tasks. This stems directly from functional limitations of the current control design. Despite the performance gap shown between the presented and previous UH system the parity in performance across multi-experienced users and the underlying design similarities between the two systems suggests that further refinement of the control design can ultimately yield performance parity across equally experienced users.
The same peg transfer trials were executed on the bench mark commercial system, the Intuitive DaVinci. There are a number of interesting aspects in the comparison of performance data from the bench mark system, previous UH system, and the presented system. It is important to note that the standard deviation of peg transfer times performed on the DaVinci system is substantially smaller than that achieved on the other systems. This is primarily due to the small sample of operators used during the trials as well as less diversity in the experience of the operator group. The best understanding of the performance gap between the bench mark system and the UH systems can be found when controlling for experience level in the data gathered on peg transfer trials with the previous UH system. Under these constraints the performance edge held by the bench mark system is eroded considerably. The remaining difference can be attributed to the difference in quality of optics utilized by the different systems and the precision in control achieved by the commercial system. The DaVinci uses a full 3D endoscope which views the operative field at an angle providing good visibility and functional depth perception. The previous UH system uses a 2D endoscope which views the field and an angle which provides good visibility but no depth perception. The lack of depth perception substantially increases the difficulty in precisely locating and grasping pegs during the transfer trials. The single-port system presented utilizes the same 2D endoscope as the previous UH system but views the operative field from directly above the site. This eliminates any triangulation in the image and affords no depth perception. Additionally the level of control precision achieved by the DaVinci allows the operators to perform the transfers with greater confidence in the reliability and predictability of slave motion and thus execute the trial at a faster pace. This precision is a function of very robust control design as well as a polished, production mechanical systems and stands in stark contrast to the prototype UH systems. These discrepancies in optics, hardware, and software between the DaVinci and UH systems suggests that should those variables be controlled in subsequent testing the remaining performance gap shown in the evaluations conducted for this research could effectively be eliminated. This would achieve an acceptable level of performance parity between the single-port system presented operating with improved control, the previous UH multi-port system, and the bench mark DaVinci system. It is also important to note that the peg transfer
times achieved with the DaVinci system by the experienced user (author) and the trained surgeon are roughly equivalent suggesting that the clinical performance of the previous and current UH systems can be reasonably extrapolated from the data gathered by experienced users operating these systems in the SAGES FLS evaluations discussed.

It is also important to consider the relevant concept of sufficient performance in conjunction with the measures of absolute performance. Although the accuracy and speed of the present iteration of the UH single port system does not match that of the commercial benchmark DaVinci system it is still sufficient to complete the FLS peg transfer trial within the allowable time. Thus the total value proposition for the single port UH system is defined as a dramatically smaller, lighter, more portable platform that can sufficiently complete standard surgical tasks with a much simpler setup and at significantly reduced operating costs. Expanding the measured performance parameters beyond pure accuracy and speed to encompass the broader goals of overall system design begins to more fully describe the total capability of the UH single port system in meeting the high level research goals of expanding access to robotically assisted laparoscopic procedures.
5. CONCLUSION

In conclusion the single-port laparoendoscopic robotic surgical system presented in this thesis has successfully met the goals associated with minimizing physical size, improving modularity, and increasing the compactness and simplicity of the system. The use of 3D printed components and structures offers exciting new opportunities to reduce cost, simplify hardware design, and provides an effective pathway towards accessible, cost-effective robotic surgical systems. Optical tracking data confirms that the hardware platform exhibits minimal hysteresis during operation and is capable of accurately and repeatedly positioning end-effector tool tips based upon master controller inputs over short periods of operation. Additional evaluations are needed to assess and confirm the practical viability of the hardware when operating for extended periods of time. Life cycle and longevity assessments will be able to quantify any degradation in motion control due to wear occurring in press and friction fit joints. Further analysis can determine ideal clearances and tolerances to minimize joint friction and wear without compromising positional accuracy and repeatability through artificially introduced hysteresis. The results can be incorporated in redesign work to improve the robustness of the system hardware, improve the life cycle, and optimize motion control.

Although the preliminary hardware goals have been accomplished additional control design work is required to achieve full functional parity with both the previous UH multi-port system and existing commercial systems. Ensuring an acceptable level of functional performance in a variety of typical operative tasks is a fundamental validation requirement that must be met before broad conclusions about the clinical efficacy of the presented system can be substantiated. First steps towards designing a robust control structure include developing a simulation environment for the system. This allows experimentation and analytical analysis of control designs independent of physical hardware and would provide a valuable resource in the timely and effective refinement of control algorithms. While a number of control strategies have presently been explored there exist additional approaches that may improve the responsiveness of the system, the intuitiveness of the control, and potentially reintroduce DOF’s compromised through the
physical constraints of single-port minimally invasive instrument geometry. Meeting these design challenges will allow validation of system performance and pave the way towards the next stages of pre-clinical development.

In summary the overall research contribution of this thesis is a novel, compact, modular, single-site teleoperated laparoendoscopic surgical robot prototype with encouraging results from preliminary performance evaluations. The robot design and construction utilizes a number of emerging technologies such as 3D printing to reduce manufacturing costs. The small physical size and modular instrument design reduce setup, tear down, and operational complexity thereby improving the viability of the system in broader range of procedures. The incorporation of multiple, independently operated manipulators sharing a common articulated base gives the robot extended ranges of motion in the operative site suitable for performing the types exploratory tasks unsupported by existing systems. While additional control refinement is necessary preliminary optical tracking and SAGES FLS peg transfer trails demonstrate the system is capable of achieving sufficient performance as defined by the SAGES.

The hope is that the research contribution of this thesis will serve to provide more surgeons better access to the benefits of teleoperated laparoendoscopic surgical robotics by demonstrating a dramatically less expensive and more versatile system than existing commercial alternatives.
4. BIBLIOGRAPHY


