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Los Angeles

**Design and Manufacture
of a Laparoscopic Telesurgical and
Telementoring Robot Manipulator**

A dissertation submitted in partial satisfaction
of the requirements for the degree
Doctor of Philosophy in Mechanical Engineering

by

Stephen William Prince

2012

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ABSTRACT OF THE DISSERTATION

**Design and Manufacture
of a Laparoscopic Telesurgical and
Telementoring Robot Manipulator**

by

Stephen William Prince

Doctor of Philosophy in Mechanical Engineering

University of California, Los Angeles, 2012

Professor Tsu-Chin Tsao, Chair

The LapaRobot is the result of a research collaboration between the Mechatronics and Controls Laboratory at the University of California, Los Angeles and the Center for Advanced Surgical and Interventional Technology (CASIT) at UCLA, to develop a surgical platform capable of performing telesurgical and telementoring surgical procedures. As part of this research effort, we have designed and manufactured a novel, minimally invasive laparoscopic robot with telesurgical and telementoring capabilities. Through meticulous mechanical design iterations and high precision fabrication techniques, we have developed a reliable and robust platform for telerobotic surgery. Through computer control, we are able to provide accurate master-slave tracking, gravity compensation, and position based force feedback for both mentor and mentee operators. Due to these enhanced features, the LapaRobot offers a transparent master-slave experience to those seeking enhancements to his or hers laparoscopic skill-sets while providing a highly reliable platform for FLS training and certification.

The dissertation of Stephen William Prince is approved.

Daniel C.H. Yang

E. Carmack Holmes

Robert T. M'Closkey

Tsu-Chin Tsao, Committee Chair

University of California, Los Angeles

2012

To my Mother . . .
who—among so many other things—
saw to it that I made my bed everyday.
To my dear sweet Wife, Eugene. . .
who—simply puts up with me.
To my Family and Friends. . .
who supported and encouraged me
through these long years.

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LIST OF ABBREVIATIONS

<i>A.F.</i>	Applied Force
<i>ABS</i>	American Board of Surgery
<i>ANSI</i>	American National Standards Institute
<i>AoM</i>	Axes of Rotation
<i>ASME</i>	American Society of Mechanical Engineers
<i>ASTM</i>	American Society for Testing and Materials
<i>BoM</i>	Bill of Materials
<i>CAD</i>	Computer Aided Design
<i>CAE</i>	Computer Aided Engineering
<i>CAM</i>	Computer Aided Machining
<i>CASIT</i>	Center for Advanced Surgical and Interventional Technology
<i>CM</i>	Center of Mass
<i>CNC</i>	Computer Numerical Control
<i>DDFTS</i>	Dual Diaphragm Fast Tool Servo
<i>DoF</i>	Degree of Freedom
<i>ECM</i>	Electro-Chemical Machining
<i>EDM</i>	Electrical Discharge Machining

<i>EMC</i>	Eisenhower Medical Center
<i>FBD</i>	Free Body Diagram
<i>FEA</i>	Finite Element Analysis
<i>FEM</i>	Finite Element Method
<i>FLS</i>	Fundamentals of Laparoscopic Surgery
<i>FTS</i>	Fast Tool Servo
<i>HLDR</i>	High-Level Design Requirements
<i>HSS</i>	Hexapod Surgical System
<i>I.D.</i>	Inner Diameter
<i>IP</i>	Internet Protocol
<i>IRISS</i>	Intraocular Robotic Interventional Surgical Station
<i>ISO</i>	International Organization for Standardization
<i>JSEI</i>	Jules Stein Eye Institute
<i>MAE</i>	Mechanical and Aerospace Engineering
<i>MIS</i>	Minimally Invasive Surgery
<i>MMC</i>	Maximum Material Condition
<i>MTS</i>	Mouse Tail Surgery
<i>O.D.</i>	Outer Diameter
<i>Ra</i>	Surface Roughness Average

<i>RCM</i>	Remote Center of Motion
<i>RoM</i>	Range of Motion
<i>SAGES</i>	Society of American Gastrointestinal and Endoscopic Surgeons
<i>SINAM</i>	Center for Scalable and Integrated Nanomanufacturing
<i>TATRC</i>	Telemedicine and Advanced Technology Research Center
<i>TCP</i>	Transmission Control Protocol
<i>UDP</i>	User Datagram Protocol
<i>VAS</i>	Vascular Access System
<i>VRSM</i>	Variable Reluctance Spherical Motor

ACKNOWLEDGMENTS

With the completion of this dissertation, I find myself not at a crossroad, but rather someplace different... a place where I never been before... a place where few have been... and now that I am here, I am strengthened by feelings of gratitude and accomplishment...

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The road traveled has been full of high points... low points... and everything in between... and now that this particular road has ended, I realize that I would have never reached the end without the love and support of my family. They have prayed for me and brought me great comfort... and... great peace during times of almost unbearable stress. I am eternally grateful to my parents, for their unconditional love and support... and... for their patience and understanding through these long years. It is because of my mother's example that I was able to persevere and weather many challenges. She taught me from a very young age the principles of hard work and dedication... and for that I am so very grateful. I would also like to thank my sisters for their continued encouragement and support... and for lifting me up on a daily bases.

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ionship, her presence, and her unconditional love. . . has allowed me to endure to the end. I love her with all my heart. She is my Jagiya and Everlasting Love.

Learning about sacred things should come first, providing a context and a need for secular learning. If we want to return to our Heavenly Fathers presence, our first priority should be to learn about his ways and his plan. The world might fool you into believing there is insufficient time to engage in both spiritual and secular learning. I want to warn you not to be deceived by these philosophies of men. Your learning about sacred things will facilitate, even accelerate, your secular learning, Elder L. Tom Perry

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Preferred Pump & Equipment

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PATENTS

2006 Magnetorheological Fluid Compositions and Prosthetic Knees
(*US20060178753A1(i9)*)

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CHAPTER 1

Introduction

1.1 Introduction

The requirements for board certification in general surgery in the United States changed in 2010 to include demonstration of proficiency in basic laparoscopic tasks. For the first time in the history of surgical training, Chief Residents must now pass a test of manual skills in laparoscopy known as Fundamentals of Laparoscopic Surgery (FLS)-prior to being eligible to sit for the written exam put forth by the American Board of Surgery (ABS) [1]. Not all residents have access to highly qualified instructors to prepare them for this exam, thus there has been a predictably high failure rate among residents who do not have such access.

As such, we have developed a telerobotic system that can provide distance training for those seeking FLS certification. The research in this dissertation outlines design and development of a unique laparoscopic surgical manipulator known as the *LapaRobot*. The LapaRobot system consists of two surgical stations; namely, the master surgeon station, and the slave robot station. The LapaRobot has five degrees-of-freedom (DoF) motion-control over two commercially available laparoscopic instruments. The Master-Slave pair of robot manipulators allows 2 users at different physical locations to perform interactive teaching (telementoring) and interactive learning in laparoscopic procedures, as well as cooperative

telesurgery. In other words, the LapaRobot Surgical System allows less experienced or new surgeons to be taught and/or guided through laparoscopic procedures via a more experienced master surgeon, so that the newly trained surgeons can go on to independently perform the procedures without the aid of the robot or teaching surgeon.

The novel LapaRobot mechanical design consists of two circular arcs that rotate on independent axes. The laparoscopic tool is held between the arcs, thereby constraining the tool motion at the holding point to a spherical surface. Another attractive design quality of the LapaRobot is its modularity in accepting a wide field of surgical instruments. Due to the complexity of the LapaRobot design and precision requirements of laparoscopic surgery, manufacturing tolerances in the range of ± 0.0005 inches has to be maintained. In order to obtain this tolerance band, the manufacturing process requires high precision CNC machining coupled with a well-seasoned operator. These design requirements lead to narrow constraints for system integration due to manufacturing cost and manufacture time; consequently, all components were manufactured in house and the tolerance bands were met. The unique LapaRobot design resulted in a high precision machine that not only serves the purpose of master-slave operation via surgeon visual feedback, but also provides the precision and accuracy required for current standards in automated surgery.

1.1.1 Background

1.1.2 Laparoscopic Surgery

Laparoscopic surgery, also known as minimally invasive surgery (MIS), is a modern surgical technique in which operations are performed through small incisions (typically 3/16in to 5/8in) in the abdomen or pelvic cavities; whereas, laparo-

tomy, consists of larger incisions [2, 3]. Closely related to Laparoscopy surgery is thoracoscopic surgery. In Thoracic surgery, procedures are performed on the chest cavity. Both laparoscopic and thoracoscopic surgery fall under a more comprehensive field known as endoscopy [2–4].

Additional components to laparoscopy include a trocar (a medical instrument with a sharply pointed end, used as entry port into the abdomen for laparoscopic tools) and video source (laparoscope or endoscope). To view the work inside the abdomen, a trocar is used to gain access and serves as entry point during the laparoscopic surgery. Also, the abdomen is typically insufflated with carbon dioxide gas; which in turn expands the abdominal area to increase access to internal organs and increase surgeons workspace and field-of-view [4]. An illustration of laparoscopic surgery with some necessary medical instruments, is seen below.

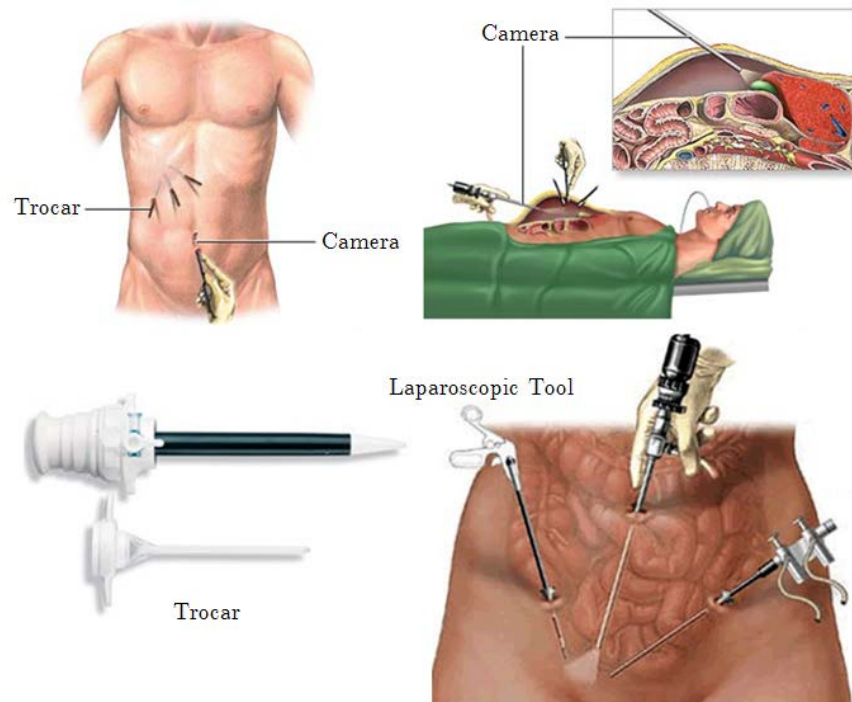


Figure 1.1: An Illustration of Laparoscopic Surgery with some Medical Instruments [5, 6]

The main advantages of laparoscopic surgery over traditional open surgery include:

- Reduced pain due to smaller incision points.
 - Since smaller incisions are made, less hemorrhaging occurs.
 - Less pain medication is needed.
- Patient Hospital stay time is less (same day discharges occurs).
- Reduced exposure to external foreign contaminants; which helps reduce chances of infections.
- Less scarring occurs.

While there are clear and profound benefits to laparoscopic surgery, some disadvantages and risks still exist. The leading disadvantage is the surgeon's field-of-view and perspective of operating field [2,4]. Since the surgeon is working in a confined workspace and looking at a two-dimensional monitor, the following are a direct consequence:

- The surgeon must use tools to manipulate and interact with the work specimen. As a result, the surgeon loses the tactile feedback of manipulating the object in his or hers hands. This also makes it more difficult to judge how much force the surgeon applies at the end-effector level.
 - Because of the trocar's entry/pivot point, the tool motions themselves move in reverse-direction to the surgeon's hand gestures; which forces the surgeon to learn and react in a non-intuitive manner.
- Reduced depth perception.
- Limited range of motion.

1.1.2.1 Robotic Surgery

With the introduction of robotic surgical systems in the late 1990's, surgeons were able to overcome some limitations in traditional approaches to laparoscopic surgery. Such limitations include: rudimentary instrumentation, poor video quality, and limited access to the patient's body cavities [7]. The progressing surgical systems gave surgeons improved range of motion, increased degrees of freedom and enhanced surgical instrumentation. The developing technology allowed the surgeon to implement better hand and wrist gestures-along with the capability of scaling surgical gestures to conquer natural hand tremors and translate precise movements at the end-effector level [8,9]. As digital communication devices became standard in the world, it was recognized that performing surgery from two different locations was possible and the benefits thereof seem endless. One such benefit is remote surgery, or telesurgery; which is the ability to translate information from a Master Surgical station to a separate Slave station or end-effector. By having the Master and Slave stations at different physical locations in the world, communication between the two devices becomes an important factor. To test this concept, on September 7, 2001, a team from France [Master Surgeon(s)] and another surgeon [Slave Surgeon] located in the United States in New York City, successfully removed a gallbladder (laparoscopic cholecystectomy) from a patient in Strasbourg, France. From this experiment, successive procedures have been performed between various parts of the world [10].

A new subset of robotic surgery and telesurgery is telementoring surgical training. Telementoring surgical training is a virtual classroom for novice surgeons seeking assistance from an experienced surgeon. Studies have shown that the rate at which technical complications occur during laparoscopic surgical learning only stabilizes after 80 to 100 procedures [8,11,12]. In other words, most surgeons only

become proficient in a a given surgical task after repeated exposure and extended practice. As such, surgeons must pass a test of manual skills in laparoscopy known as Fundamentals of Laparoscopic Surgery (FLS). The FLS examination consists of five training tasks that focus on the following skill sets [13]:

1. Peg Transfer, (Developed by Society of American Gastrointestinal Endoscopic Surgeons (SAGES) [14].
2. Precision Cutting
3. Placement and Securing of Ligating Loop
4. Simple Suture with Intracorporeal Knot
5. Simple Suture with Extracorporeal Knot

All of the above training tasks are practiced on an inanimate box trainer, as seen in Figure 1.2. This type of box trainer allows student surgeons to practice low-level, psychomotor skills; however, in order to train higher-level skills, box trainers may be inadequate [12, 15].



Figure 1.2: Fundamentals of Laparoscopic Surgery Box Trainer [13]

1.1.2.2 Previously Developed Technologies

There are a variety of surgical robots that are effectively being employed in various surgical settings. All of these manipulators have differing mechanisms for their motion requirements and have been extensively reviewed by [16]. Listed below are a various types of mechanisms that offer robot assisted surgery.

- Zeus Surgical Endoscopy Robot by Computer Motion is a master-slave eight degree of freedom system for specialized use in abdominal and thoracic cavities. The Zeus robot preformed the world's first transatlantic telerobotic procedure and is also driven by a separate joystick controls [17].



Figure 1.3: The Zeus Surgical Endoscopy Robot [17]

- The *da Vinci* Surgical System by Intuitive Surgical Inc. is a complete master-slave six degree of freedom manipulator that is controlled by the operator's wrist and fingertip motions. The da Vinci offers surgical specialties in urology, cardiothoracic surgery, head and neck surgery, etc. Bladder Cancer, Colorectal Cancer, Coronary Artery Disease, and Endometrioses, Gynecologic Cancer, Kidney Disorders, and Prostate Cancer are many conditions that the *da Vinci* Surgical System can treat [18, 19].



Figure 1.4: The *da Vinci* Surgical System by Intuitive Surgical Inc. [18]

- **SOFIE:** Surgeons Operating Force-Feedback Interface Eindhoven robot from the Eindhoven University of Technology. The SOFIE system, differing from the above, is a robot-assisted device that has force feedback that is felt through the joystick controls [20].



Figure 1.5: SOFIE: Surgeons Operating Force-Feedback Interface Eindhoven Robot [20]

- **EndoBot:** The Endobot, or Robot Assisted Suturing and Automation System is a collaborative robot in which operations between surgeons and the robot are possible. The Endobot has two modes, namely the manual mode and collaborative mode. The manual mode allows surgeons to directly manipulate the robot through remote controls; whereas the collaborative mode permits predictive motion control under the supervision of the surgeon. In other words, the Endobot has autonomous computer control.

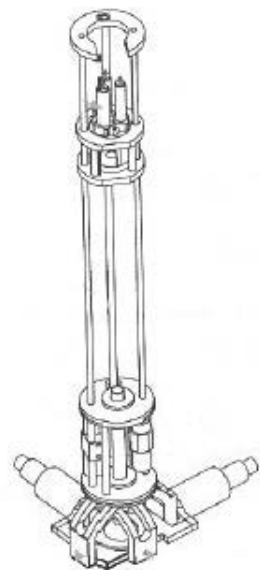


Figure 1.6: The Endobot, or Robot Assisted Suturing and Automation System [16]

- The Highly Versatile Single-Port System is a six degree of freedom passively controlled single port platform that employs two hollow manipulators and a five degree of freedom telescope in order to perform minimally invasive surgery [21].

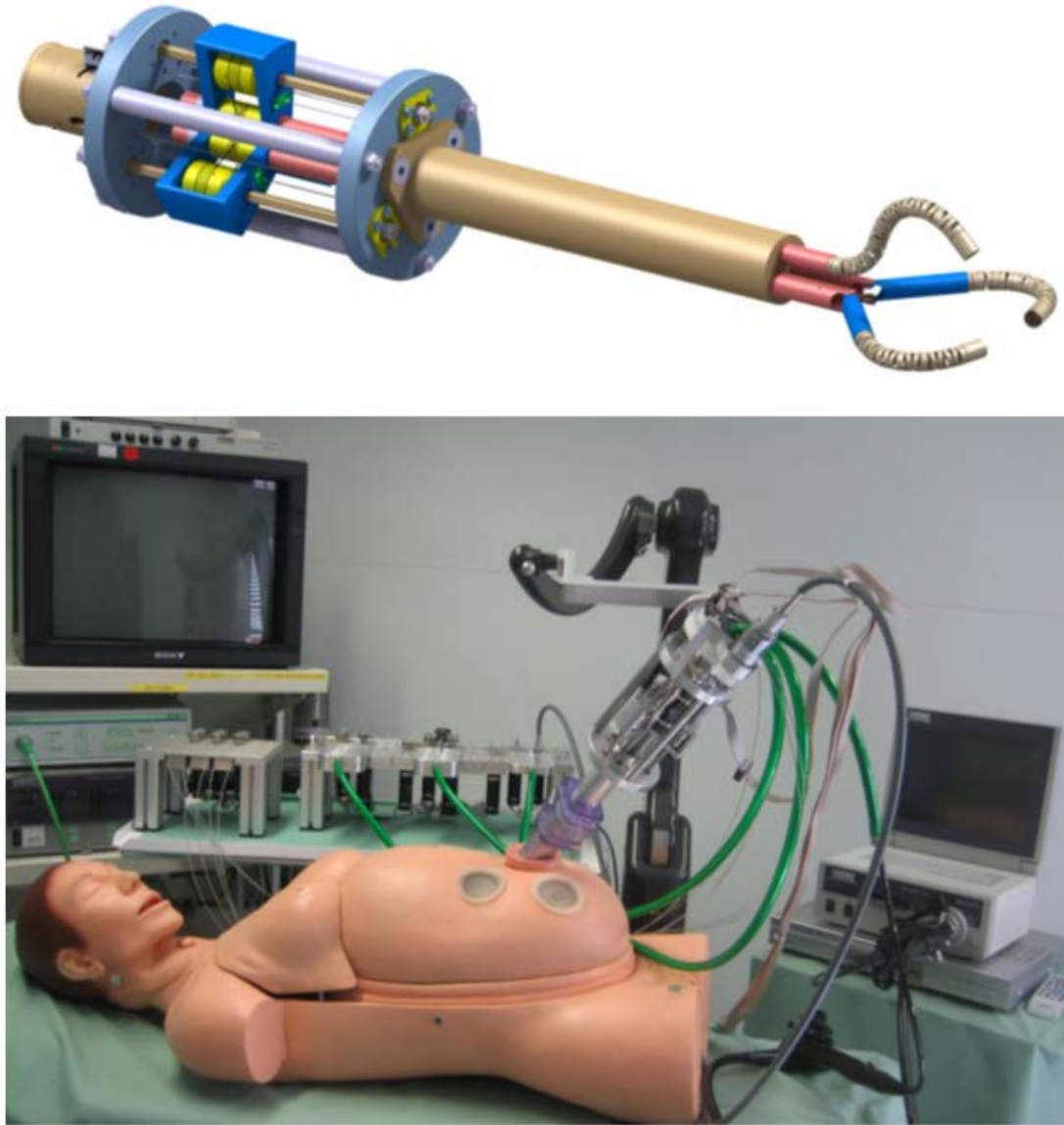


Figure 1.7: The Highly Versatile Single-Port System for Minimally Invasive Surgery [21]

- Teleoperated Robotic Surgery System: This single-port access, teleoperated robotic system is a compact modular system for Laparoendoscopic Single Site Surgery [22, 23].

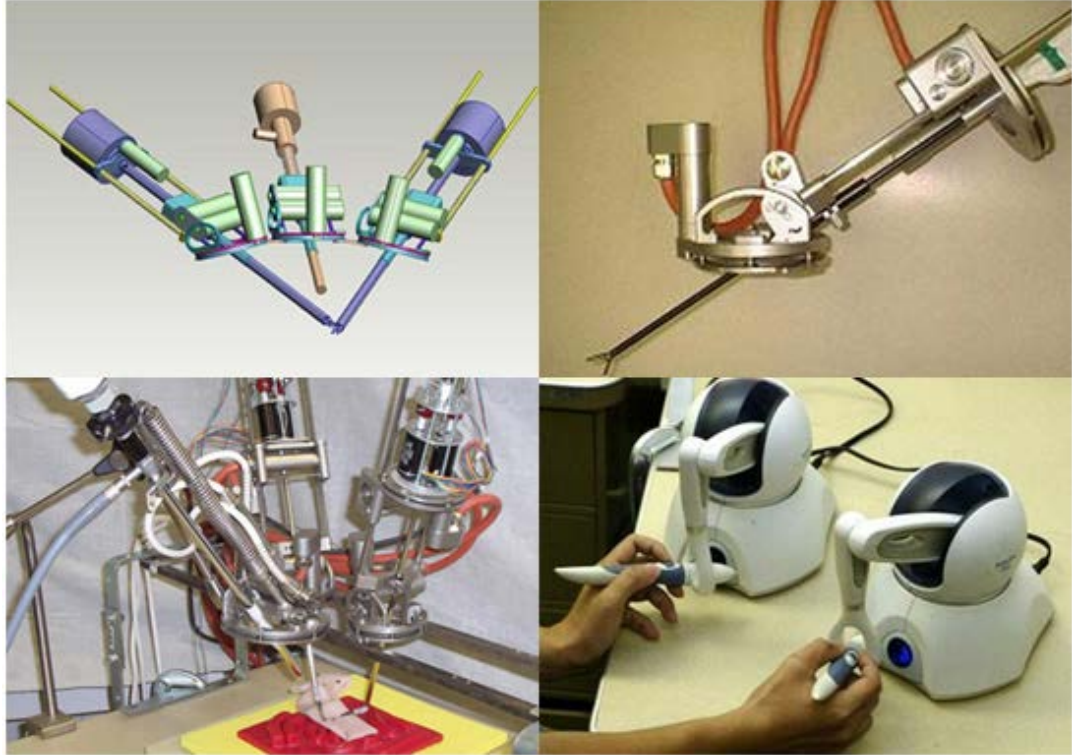


Figure 1.8: Teleoperated Robotic Surgery System used in Laparoendoscopic Single Site Surgery [22, 23]

- Raven: A Surgical Robot System for Open and Minimally Invasive Surgery. The Raven Surgical Robot is a seven degree of freedom cable-actuated surgical manipulator used in MIS or open surgery [24, 25].



Figure 1.9: The Raven: A Surgical Robot System for Open and Minimally Invasive Surgery [24,25]

While it is true that existing commercial systems benefit from specialized areas of surgery, it is important to note that all of the aforementioned manipulators do not allow the user to enhance his or hers skills on basic laparoscopic tasks. This is mainly due to the cost of the system and time and cost of employing an expert surgeon to teach less-experienced surgeons on these machines. To date, there is little focus on telesurgical devices being used in teleoperated training. Most of the robotic systems designed for telesurgery are intended to stabilize the surgeons hand motions and tremors; such advantages are useful in a surgical setting, nevertheless these systems are limited as a formal training toolbox in laparoscopic surgery [12,26].



Figure 1.10: The PHANTOM® Omni™ Haptic Joystick by Sensable®

It is also important to note that all of the systems listed above use a joystick for the master controls-in order drive the robot slave. The main disadvantage to this approach is from the fact that the surgeon has to become efficient with two pieces of hardware: the master joystick, and standard laparoscopic tools. While most of the devices use the Phantom joystick [because of its haptic features], the surgeon still has to become proficient with wide-array of standard laparoscopic tools.

The current Fundamentals of Laparoscopic Surgery (FLS) experience is labor intensive both for the teaching hospital and for the student surgeon. While standard metrics and protocols exist in the evaluation of the student's FLS performance, these metrics and protocols still are time consuming, slow, and most notable, they do not offer clear skill acceptability placement or criteria for the learning student. The LapaRobot, A Laparoscopic Telesurgical and Telementoring Robot, attempts to build on current methods of FLS certification to remain transparent; to be beneficial to the teaching surgeon and those seeking FLS certification.

A *Learning Curve:* To learn more quickly and efficiently

B *Skill Acceptability or User Feedback:* Analysis and evaluation built into the system, allowing for the system to be completely web-based

C *Portability:* FLS proctor or metering is not required to be with the trainer

1.1.3 Dissertation Outline

This dissertation is organized as follows: Chapter 2 discusses the design requirements for implementing a telesurgical and telementoring laparoscopic system. Our main objective here is to confer the complexity and the issues surrounding surgical robot manipulators. Chapter 3 introduces our conceptual design, while Chapter 4 details the high level design subsystems. Chapter 5 verifies the design requirements and design integrity of the LapaRobot System through Finite Element Methods (FEM) and Computer Aided Engineering (CAE) analysis. Due to the intricacy of the perceived surgical system, Chapter 6 covers details in manufacturing and the associated precision that is required for the realization of this system. In Chapter 7, an investigation in the propagation of error for various manufactured components is given, plus an overview on tolerance classification. Listed in Chapter 8 is an illustration and schematic breakdown of teleoperated/telementoring laparoscopic surgery, and an overview of the clinical demonstration and evaluation performed with LapaRobot manipulators. Chapter 9 concludes with a summary of both the LapaRobot System, and the accomplishments of this research. In closing, Chapter 10 summarizes and outlines other research endeavors (not related to this research) that have completed.

CHAPTER 2

Design Requirements

2.1 Introduction

The design requirements for this system were defined in part by its predecessor, namely, the UCLA LapaRobot version 1 system [12]. The LapaRobot v1. is UCLA's first surgical manipulator to support teleoperation and manual skills assessments. The surgical system consists of a master surgeon station and robot slave station. The LapaRobot v1. design, seen in Figure 2.1, uses a delta mechanism combined with a spherical ball joint. The master device incorporates sensors for position, axial rotation, and grip; while the slave station provides five degree-of-freedom (DoF) control over altered laparoscopic instruments [12]. The LapaRobot v1. system is able to separate different laparoscopic surgical skill-sets by off-line evaluation of the tool kinematics from recorded skill performances [12,27]. Another study performed using the LapaRobot v1. was the characterization of the surgeon's performance as novice or expert. By using the LapaRobot v1., the study showed an increased improvement in skill assessment tracking by 7%, 12%, and 14% for the tasks examined [9,12,27].

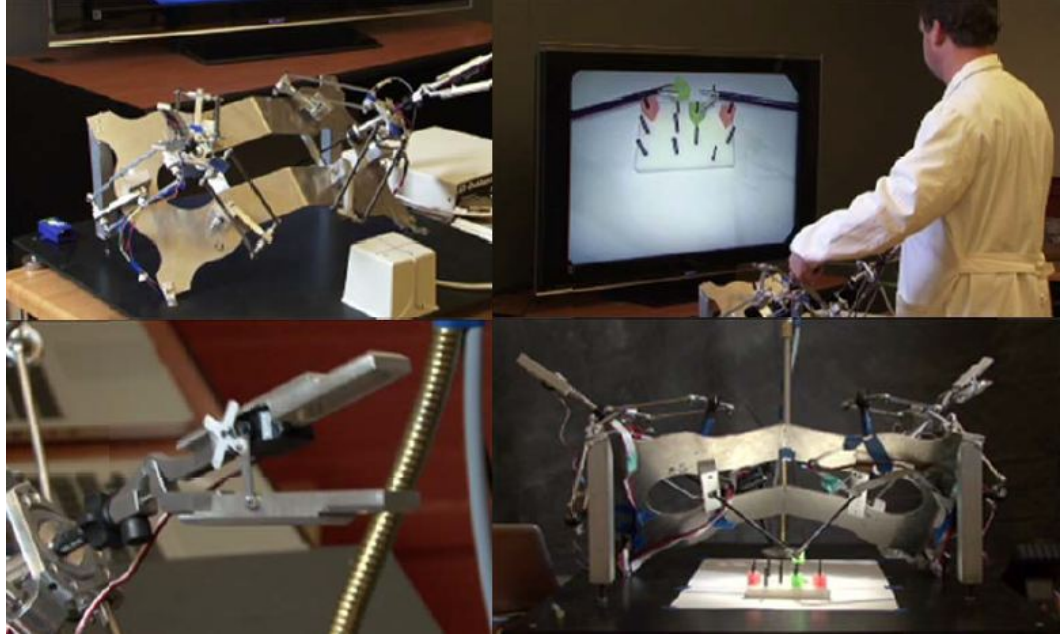


Figure 2.1: The UCLA LapaRobot Version 1 System: The Master Station (Top Left). The Slave Station (Top Right), follows the surgeon's movements at the Master Station (Bottom Right) during a remote peg transfer operation. The Slave's instrument's handle (Bottom Left) [12].

2.2 Design Requirements

The LapaRobot v1. served its purpose in investigating the aspects mentioned above; however, improvements in its range of motion, tool modularity, mechanical integrity, position accuracy, ergonomics, durability, and ease-of-use are required to further and enhance the reliability and performance of the LapaRobot. Consequently, the LapaRobot version 2 design project was initiated to address and overcome these shortcomings. The problem statement now becomes to design, manufacture, and implement a five degree-of-freedom telerobotic/telemnetoring

surgical manipulator that has following design characteristics:

- The surgical system must have five degrees-of-freedom; specifically, roll, pitch, yaw, depth, and grab.
- It is also necessary for the manipulator to maintain a remote center of motion (RCM) through the central axis of the laparoscopic instrument with a tolerance of $\pm 3/16in$ ($0.5cm$) throughout its entire range of motion
- The range of motion of the laparoscopic tool must reach at least a 50 degree plane and be able to operate in cone-sweeping through this inclination. For reference, see Figure 2.1.
- All motors must satisfy torque requirements for each mechanism and also be back-drivable.
- The laparoscopic tools are to be commercially available tools that surgeons are accustomed to using in the surgical setting. Note: this requires the grasping mechanism to be non-destructive to the instrument handles and to be retrofitted to the handle geometry.
- The robot must be able to change laparoscopic end-effectors for a given task evaluation.
- The manipulator will allow for bilateral motion.
- The tool tip, or end-effector, must not displace more than $1/32in$ ($1mm$) from applied forces from the instrument handles.
- The components and overall design assemblies are to be mechanically reliable and failsafe.

- Lastly, the master and slave stations are required to be ergonomic and portable.

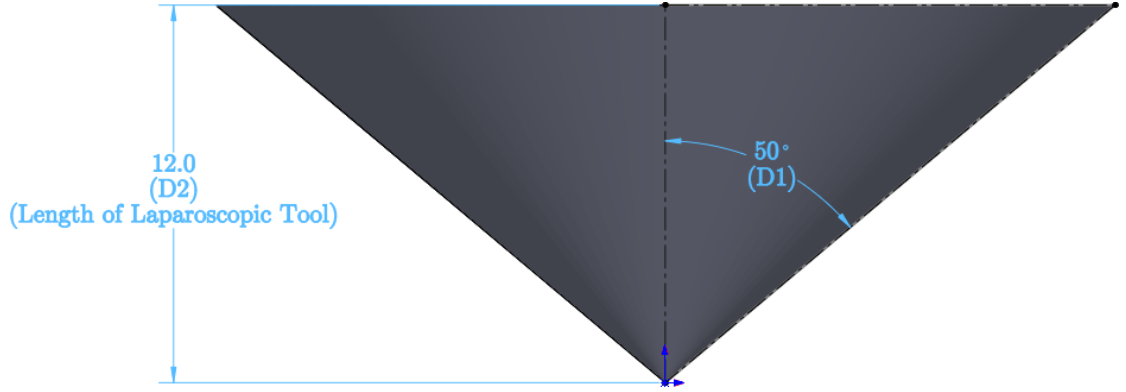


Figure 2.2: LapaRobot Version 2 Range of Motion Design Requirement(s)
(Dimensions are in inches)

2.2.1 Principles of Surgical Robots

The basic principle of surgical robots consists of mounting small modular robots above the abdomen of a patient in order to perform a given laparoscopic procedures [28]. As a result, the RCM must not be consumed in the manipulator design. This means that the RCM would be contained in a usable workspace; thus allowing clearance for the trocar and increasing the overall range of motion for the laparoscopic tools. This principle can be visualized in following schematic:

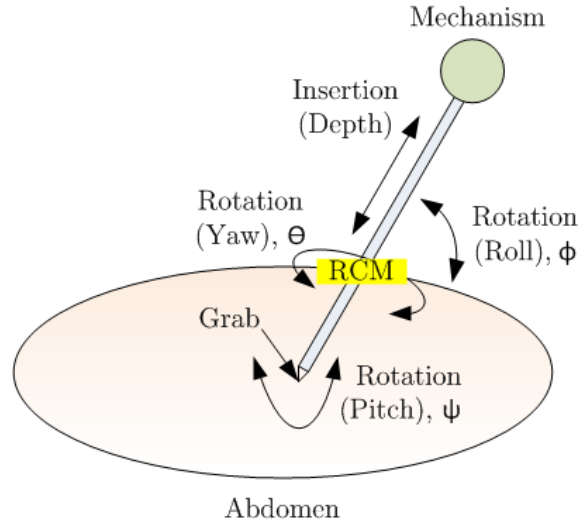


Figure 2.3: Principles of Surgical Robots Schematic

We see in Figure 2.3 that mounting the mechanism above the abdomen is a uniquely challenging task, but an important aspect in replicating the traditional laparoscopic setting.

CHAPTER 3

Conceptual Design

In order to address improvements in the LapaRobot's capabilities, we have developed two conceptual designs. Conceptual design#1, seen in Figure 3.1, consists of two motors connected serially in order to achieve a pivoting motion around a mechanically fixed remote center for each hand. Two additional motors, also mounted serially, provide depth motion in and out of the patient or specimen and wrist twist motion. With this design, we are able to achieve four degrees-of-freedom in a much simpler and more reliable manner than compared with parallel mechanism designs.

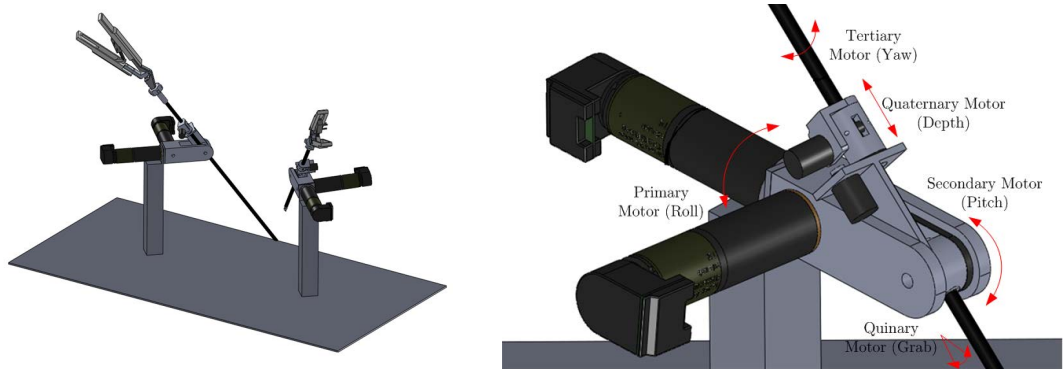


Figure 3.1: LapaRobot Conceptual Design #1 CAD Model

After further design considerations, it was determined that the conceptual design shown above did not meet all the design requirements set forth in Chapter 2; specifically, the remote center did not lie outside the mechanism and the design

would require additional gearboxes and belt drives to provide desired motions. Thus a 2nd conceptual design was contrived, which was selected over the 1st conceptual design-as it meets all of the design prerequisites. This design consists of two circular arcs that rotate on independent axes (Figure 3.2). The laparoscopic tool is held between the arcs, thereby constraining the tool motion at the holding point to a spherical surface. This design inherently guarantees a remote center at the geometric center of this spherical surface. The improved range of motion covers a half-cone region with 60 degree inclination measured from vertical. We have demonstrated the feasibility of this design by building a moving conceptual prototype actuated by servomotors (Figure 3.2, (Right)).

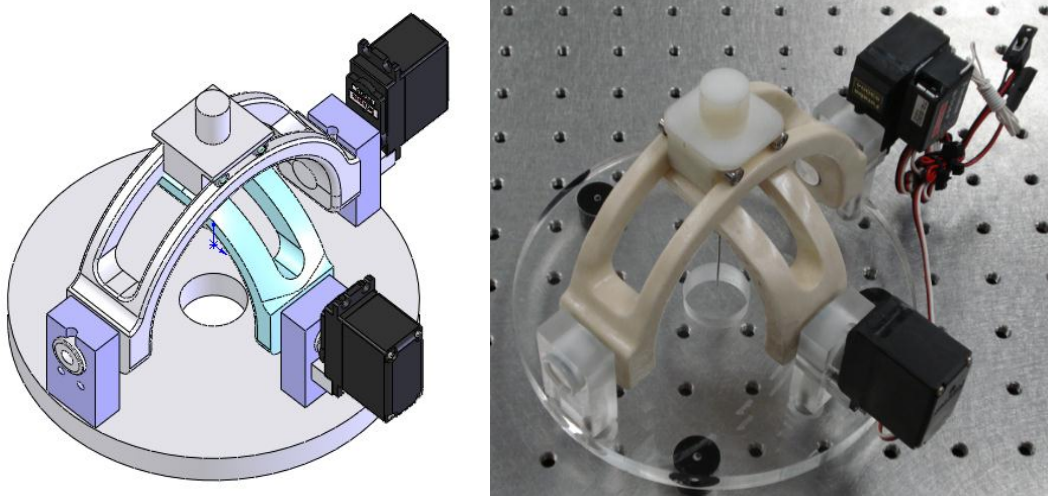


Figure 3.2: LapaRobot Conceptual Design #2: CAD Model (Left), Prototype (Right)

The motivation in using a spherical mechanism came from [29, 30] work on a Variable Reluctance Spherical Motor design. By using a spherical mechanism, similar to Figure 3.3, we are able to achieve three degrees-of-freedom (roll, yaw, and pitch) in a single joint. Moreover, this spherical design approach permits direct-drive connections that generate smooth, singularity-free, precision motion

through the travel range [29].

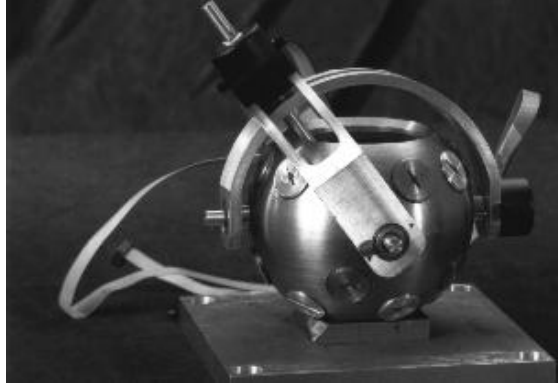


Figure 3.3: Variable Reluctance Spherical Motor [29]

By fabricating a moving version of the arcs, we learned that the main challenge in this spherical concept, is how to transfer motion from each arc, while maintaining a relatively simple and compact design. The fundamental structure is similar to how a traditional roller coaster and gimbal transmits their motions; in that, the mechanism requires a component(s) that moves independent to the path of each arc while attached to the other arc. One approach or method is to have a track or groove on parallel surfaces of the arc, thus providing a path/surface for the mechanism to *slide* in/on. (Figure 3.4). This relative twist motion offers one-to-one movement at the hand control level and ensures the separate master-slave stations are mechanically identical.

The rest of the conceptual design, reading left to right in Figure 3.5 on page 26, are the insertion, twist-rotation, and grasping mechanisms, respectively. The insertion mechanism utilizes a friction drive configuration with urethane rollers; combined with a gearbox-comprised of pinion and bevel gears. The entire insertion mechanism is connected directly to the twist mechanism, but each DoF is driven independently with motors. The following illustration shows the arrange-

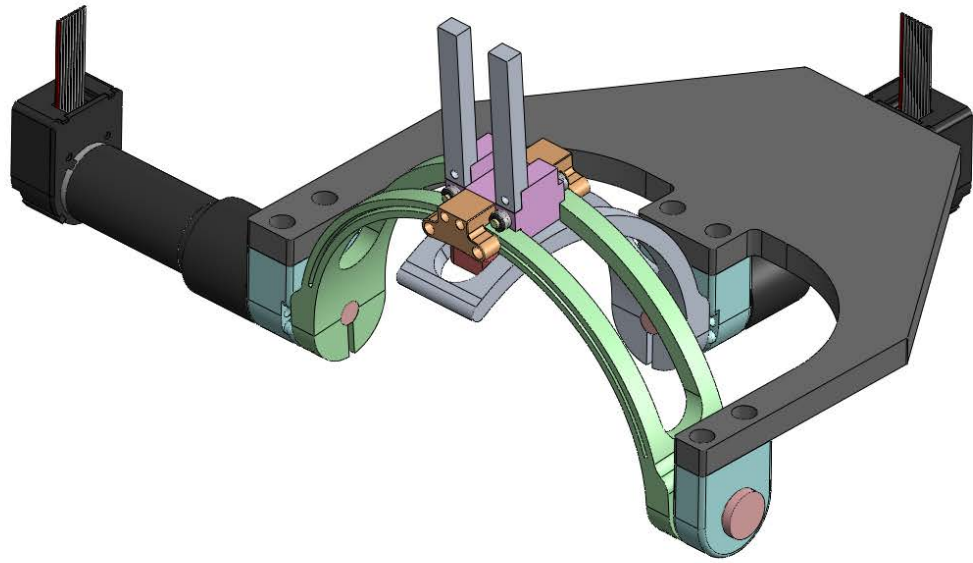


Figure 3.4: CAD Model of the Spherical Mechanism Concept

ment:

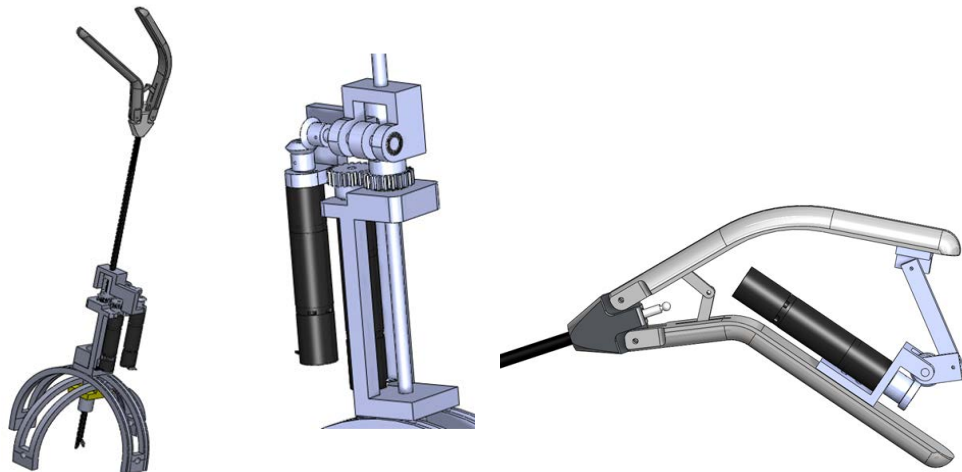


Figure 3.5: Design Concepts for the Insertion, Rotation (Twist), and Grasping Mechanisms

This top-down level design allows us to break-down each subsystem and move forward with the detailed design as well as aid in the production of proof-of-concepts models. Also, each subsystem will be modeled with assembly-level features until each subsystem is refined in detail—allowing us to form a bottom-up level design.

CHAPTER 4

Detailed Engineering & Manufacture Design

4.1 Introduction

The figures below illustrate the overall detailed design for the conceived LapaRobot system. The system will be broken down into three subassemblies, namely the spherical mechanism, insertion mechanism, and rotation mechanism. The grasping mechanism will be treated as a separate assembly and will be discussed near the end of this chapter. This is important because, by treating the laparoscopic tool as a *black-box*, we have the ability to scale the system for future revisions and enhancements. Also presented are design revisions that came about after manufacture and system testing took place.

Figure 4.1 shows the Axes of Rotation for LapaRobot System. The reader should note that where the 3 axes coincide, is the remote center of motion (RCM) for this scheme. Also, Figure 4.2 shows the the bill of materials and the corresponding balloons depict the important components referred to throughout this work.

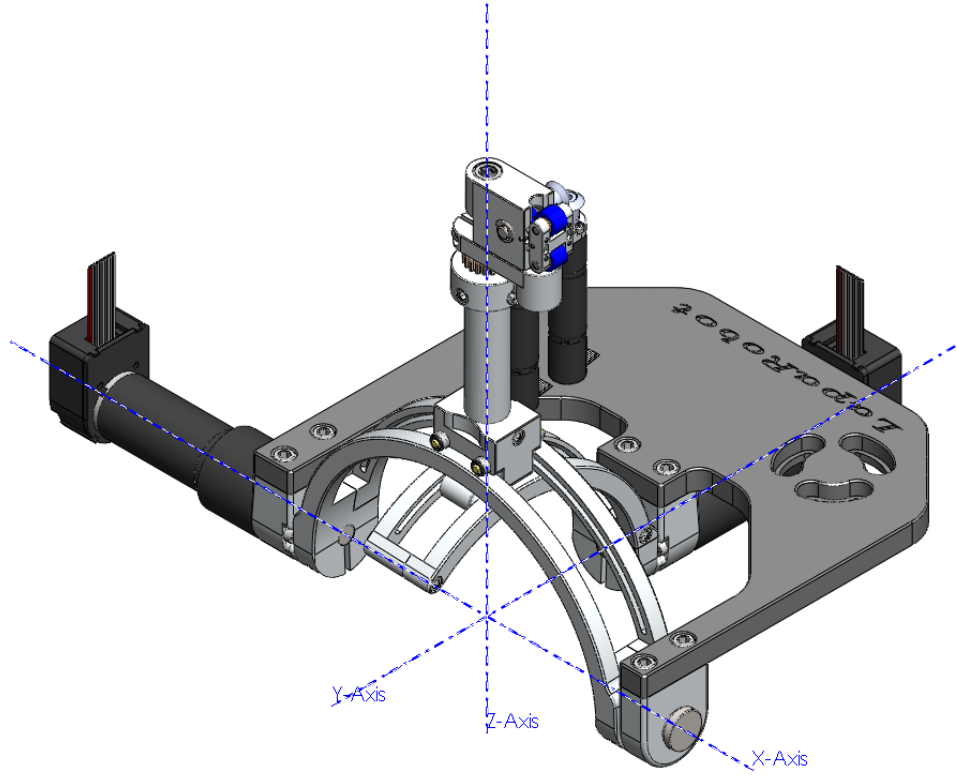
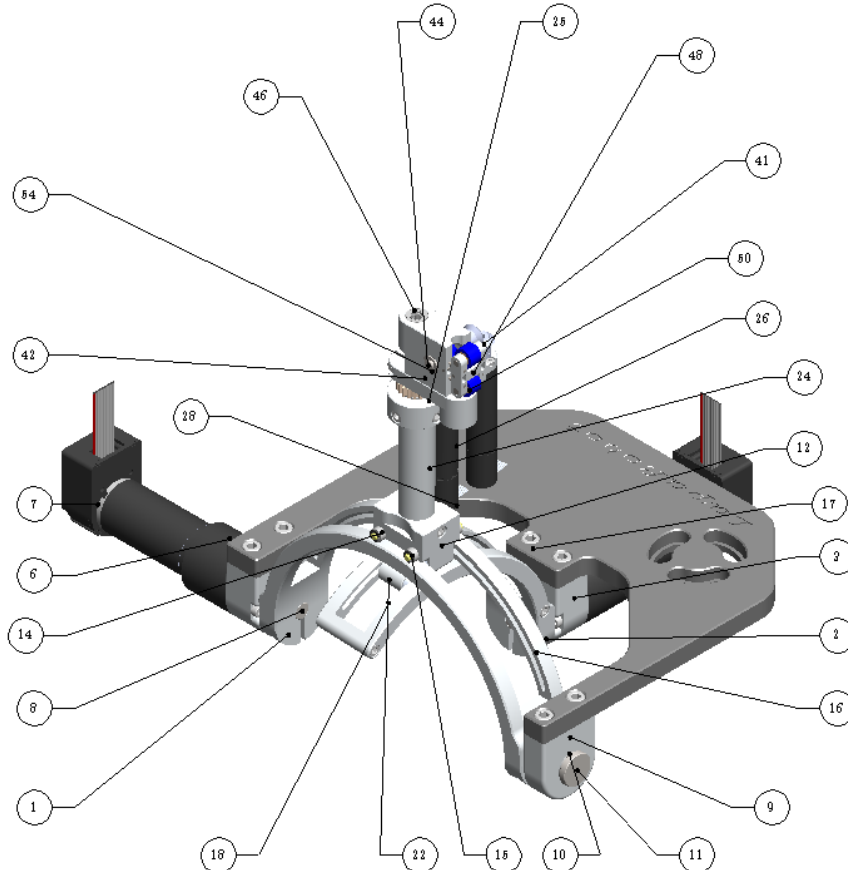


Figure 4.1: LapaRobot 2.1 CAD Model, Axes of Rotation, Trimetric View



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Primary Rotation Arc	Primary Rotation Arc	1
2	Secondary Rotation Arc	Secondary Rotation Arc	1
3	Primary Motor Mount	Primary Motor Mount	2
4	67155K325		2
5	Primary Motor 118743		2
6	Primary Gearhead 166165		2
7	Primary Encoder 110812		2
8	Primary Motor Coupler	Primary Motor Coupler	2
9	Primary Arc Mount	Primary Arc Mount	1
10	67155K327		2
11	Primary Arc Coupler	Primary Arc Coupler	1
12	Primary Castor Slider RevD	Primary Castor Slider	1
13	E-Clip Shaft 0.1240 OD 98278A904	E-Clip Shaft (0.1240" OD)	2
14	67155K382		4
15	98408A116		2
16	Primary Rotation Arc Insert	Primary Rotation Arc Insert	1
17	Mounting Platform Right Hand RevB	Mounting Platform Right Hand	1
18	Secondary Rotation Arc Insert	Secondary Rotation Arc Insert	1
19	Ball Transfer Shell 2440T31	Description Here	8
20	92605A042	Description Here	8
21	Ball Transfer Ball Bearing 2440T31	Description Here	8
22	Secondary Arc Motion Transfer Mount	Secondary Arc Motion Transfer Mount	1
23	67155K375		1
24	Castor Extension	Castor Extension	1
25	Tertiary Motor Mount RevC	Tertiary Motor Mount	1
26	Tertiary Motor 118520		2
27	Tertiary Gearhead 110315		2
28	Tertiary Encoder 222054	Description Here	2
29	Pinion Gear PW32S 20A		1
30	Pinion Gear Primary PW32S 20A		1
31	92196A242		6
32	92192A039		8
33	92196A194		2
34	92196A151		4
35	92196A144		5
36	92196A143		1
37	92192A004		4
38	94238A228		2
39	Quaternary Motor Mount Right RevB	Quaternary Motor Mount	1
40	Bevel Gear MHN 1S1		1
41	Bevel Gear MHN 1S2		1
42	Drive Friction Wheel Housing RevD	Drive Friction Wheel Housing	1
43	67155K16		2
44	Drive Roller Shaft RevE	Drive Roller Shaft	1
45	Drive Roller 0.500 OD 0.1875 ID 2489K34	Description Here	1
46	61205K72		2
47	Drive Friction Wheel Housing Guide Pin 0.0625 OD 0.500 L 90145A419	Drive Friction Wheel Housing Guide Pin	4
48	Idler Roller Housing RevB		1
49	Idler Roller Shaft 0.125 OD 0.600 L 6252K49	Idler Roller Shaft	2
50	Idler Roller 0.375 OD 0.125 ID 2482K61	Description Here	2
51	Idler Roller Spacer		4
52	Drive Roller Spring Retention Pin 0.0625 OD 0.14375 L 90145A414		2
53	Idler Roller Spring Retention Pin 0.0625 OD 0.1875 L 90145A414		2
54	98408A116		1
55	92615A210		1

Figure 4.2: LapaRobot 2.1 Nomenclature and Bill of Materials

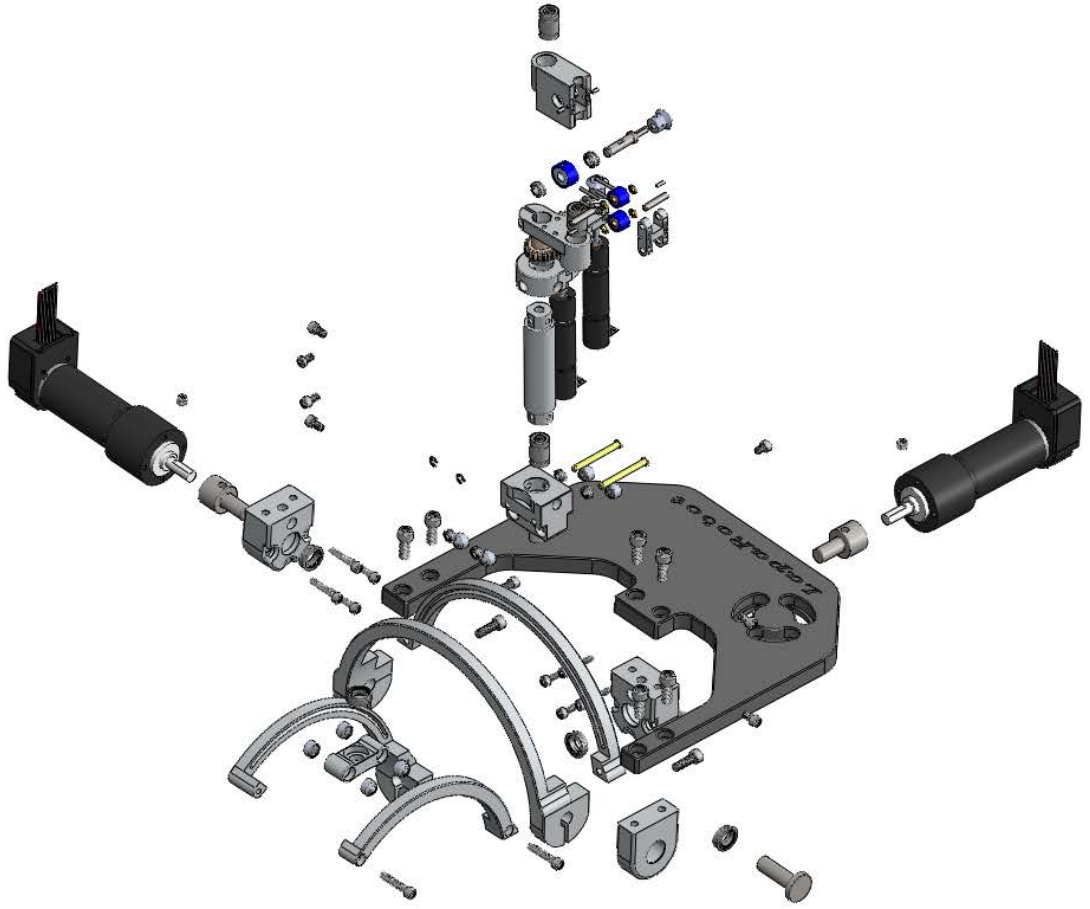


Figure 4.3: LapaRobot 2.1 CAD Model, Exploded Trimetric View

4.2 LapaRobot 2.1 Design

4.2.1 Spherical Mechanism (Pitch and Roll Motions)

The spherical mechanism, referred to in Figure 4.4 as the pink and red colored components, locates and guides the laparoscopic tool through the RCM using the *pitch* (ψ) arc and *roll* (ϕ) arc as two-dimensional planar guides. Together they form a spherical joint that has no singularity points in the entire range of

motion. The pitch (ψ) arc has a 120 degree RoM and the roll (ϕ) arc has RoM of 80 degrees. The *primary castor slider* (pink component), has four ball-transfer-bearing units that serve to functions:

1. Center the primary castor to to the pitch (ψ) arc.
2. Guide and roll in a v-groove track that is concentric to the outer radial surface of the pitch (ψ) arc.

The *secondary arc motion transfer mount* (red component), uses the same ball-transfer-bearing units to produce the motion on the roll (ϕ) arc. The *primary castor slider* connects radially to the center of the *secondary arc motion transfer mount* via a cartridge ball bearing; this configuration forms the spherical mechanism and allows the two components to twist relative to one another. Additionally, four ball bearings are mounted to the *primary castor slider* to ride on the pitch (ψ) arcs outer-diameter's surface to absorb the normal force exerted on the system.

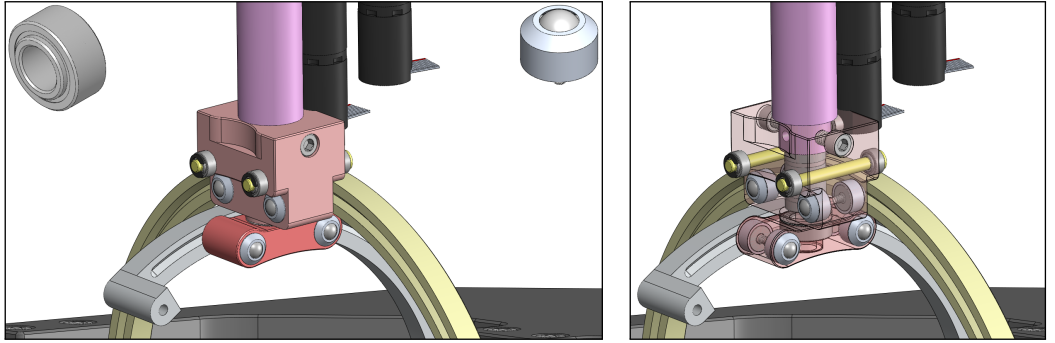


Figure 4.4: LapaRobot 2.1 CAD Spherical Mechanism: The Left picture has the cartridge ball bearings and the ball-transfer units in in the upper left and right hand corners, respectively. The right picture is a transparent-zoomed image of the spherical mechanism.

The pitch (ψ) and roll (ϕ) arc's motors are mounted via motor mounts (purple components or balloon 3) that are coupled to the arcs via sperate motor couplers (balloon 8). The motor couplers are axially-aligned to the AoR of each arc; while ball bearings house the matted shaft and coupler to absorb the normal forces exerted on the arcs. A side view of this configuration is seen in the next figure. The inner diameter (I.D) of the pitch (ψ) arc is 5.375 inches while the I.D. of the roll (ϕ) arc is 5.0625 inches. These diameters where chosen so that the path the hand travels throughout the RoM will not feel too large.

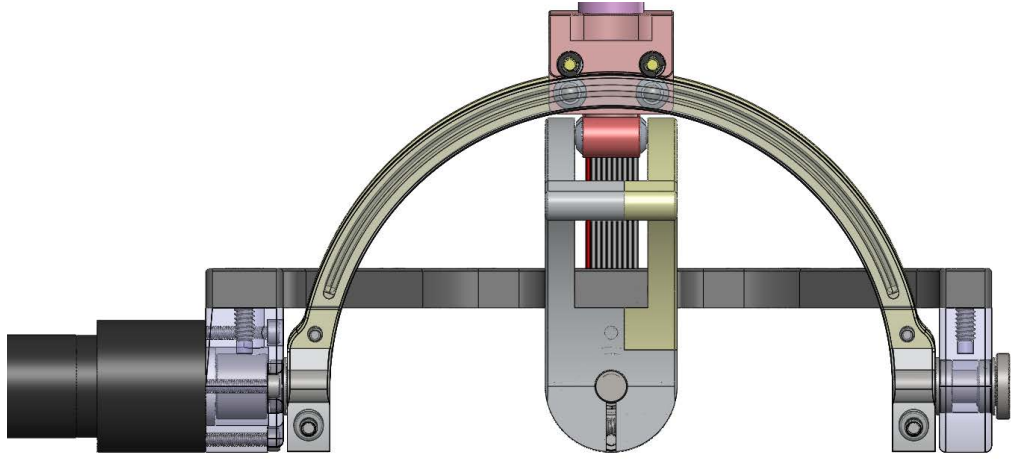


Figure 4.5: LapaRobot 2.1 CAD Model, Motor Mounts and Coupling, Side View

The mounting platform (balloon 6) provides a rigid structure for the arcs and motor components to attach to, and also allows the orientation of the arcs relative to the operator to be adjusted in 2 DoF. This adjustability allows for easy coordination of the master and slave device pairs to one another. The platforms themselves attach to an angled standoff that mounts directly to standard breadboard optical plates. This feature was designed such that the left and right hand pairs could be positioned in the same coordinates as their mirrored coun-

terparts. Another benefit of this arrangement is how the workspace is centered to the object task and creates a V-shape environment. Since the spherical arcs are axially driven and the spherical mechanism has very fine tolerance width ($+0.0046 - 0.0000$) between the interfaces, the gear-head backlash felt at the laparoscopic tool hand-control level is minimal.

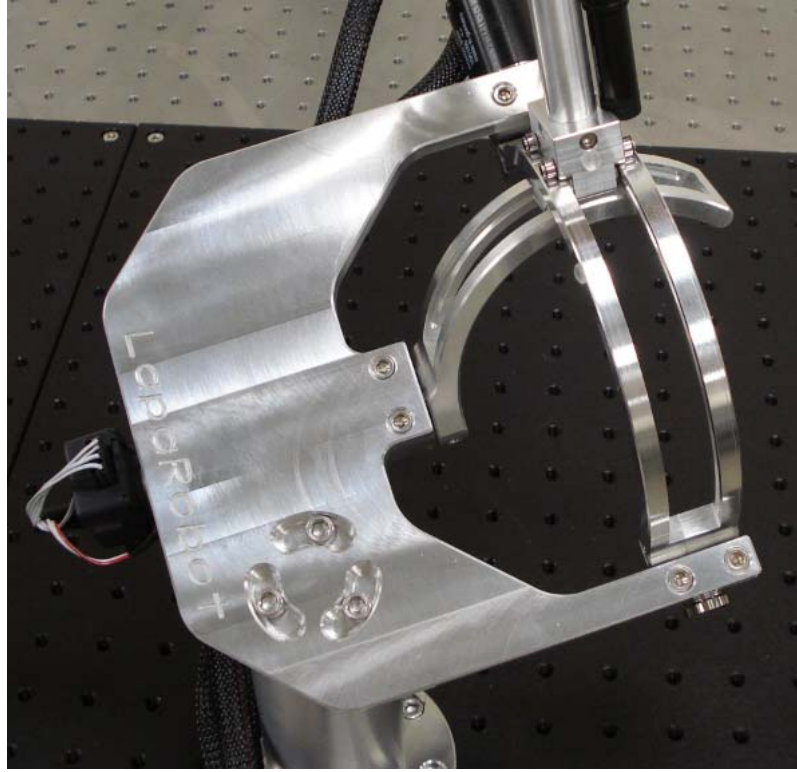


Figure 4.6: LapaRobot 2.1 Spherical Rotation Arc(s) Mechanism Prototype

At the time of motor selection, the design was not complete, and so any unknown mechanisms were treated as black boxes and given overestimated dimensions and mass properties so that the spherical drive motors would have sufficient torque to drive the arcs while at the same time giving our design a factor of safety. The torque required to lift the pitch (ψ) and roll (ϕ) arcs was

then approximated with the following relations:

$$\vec{\tau} = \vec{r} \times \vec{F} \quad (4.1)$$

The magnitude of the torque is given by:

$$\tau = |r \cdot F \cdot \sin(\Phi)| \quad \Rightarrow \tau = r \cdot F_{\perp} \quad (4.2)$$

Where F is the applied force vector, r is the displacement vector or the moment arm between the torque point of interest and the applied force, and Φ is the angle between the two vectors or the moment arm and the line-of-action (Seen in Figure 2.3). Using the configuration seen in Figure 4.7 and the component mass properties from the design, we determined the location of the center of mass for the system and used the weight of the components as the input force on the system. By means of equation 4.2, we calculated the torque required to lift the components is 1.209. Once the design was completed, correct dimensions and masses were replaced and the torque was recalculated and found to be 0.509 Nm. Seen in the top image of Figure 4.7 is the end of travel range for the roll arc; whereas the bottom image is the position of the roll arc that produces the largest moment arm from the roll arcs' origin. This position produces the largest torque and was used in the calculation above.

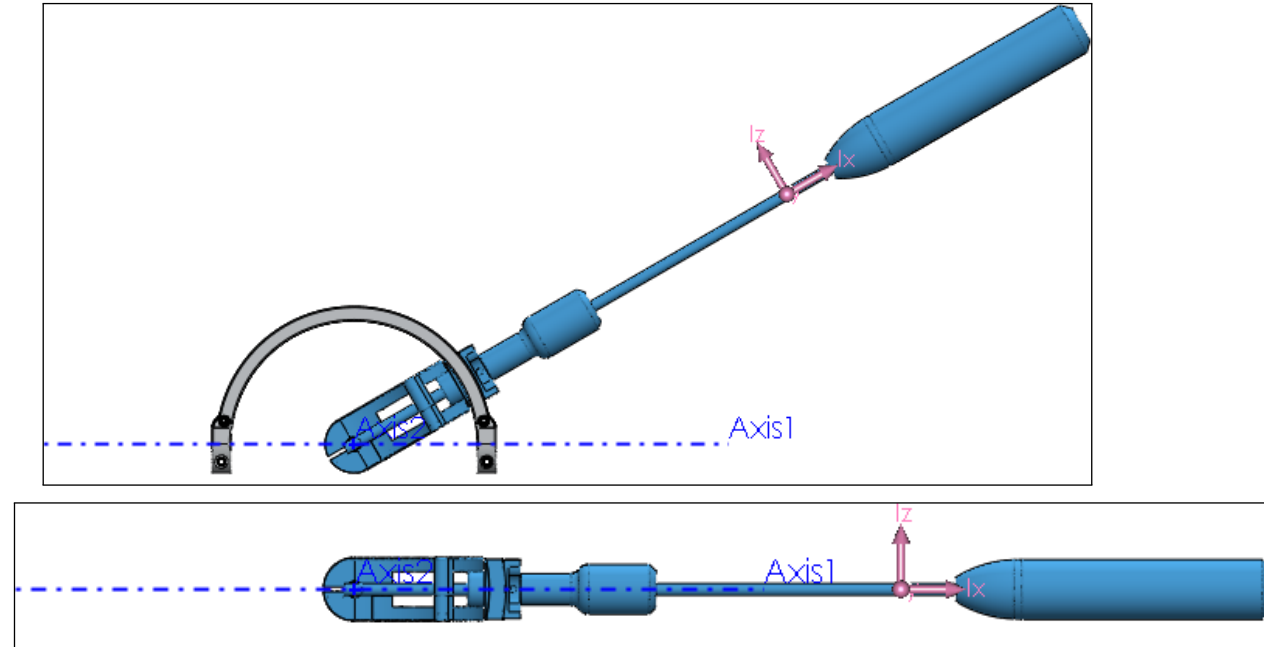


Figure 4.7: Pitch (ψ) and Roll (ϕ) Arc Torque Orientation: The top image is when the roll (ϕ) arc is at its end of travel range, and the bottom image is the position of the roll (ϕ) arc that produces the largest moment arm.

4.2.2 Insertion Mechanism (Depth Motion)

The insertion mechanism relies on various components to provide linear motion to the laparoscopic tool. The main parts that make up this subassembly are balloons 25, 42, 47-54. The friction drive mechanism, seen in Figures 4.8 and 4.9, is broken down in the following way:

1. The laparoscopic tool housing is offset to a roll (ϕ) circular guide shaft that lies parallel and coincident to the AoR. (Note: Motion is one-to-one)
2. A separate drive urethane roller is connected to a drive shaft; which is coupled to beveled pinion gears and a motor.
3. When the laparoscopic tool moves, the guide shaft moves between the drive roller and a pair of spring-loaded urethane idler rollers providing a three-point-contact on the shaft.

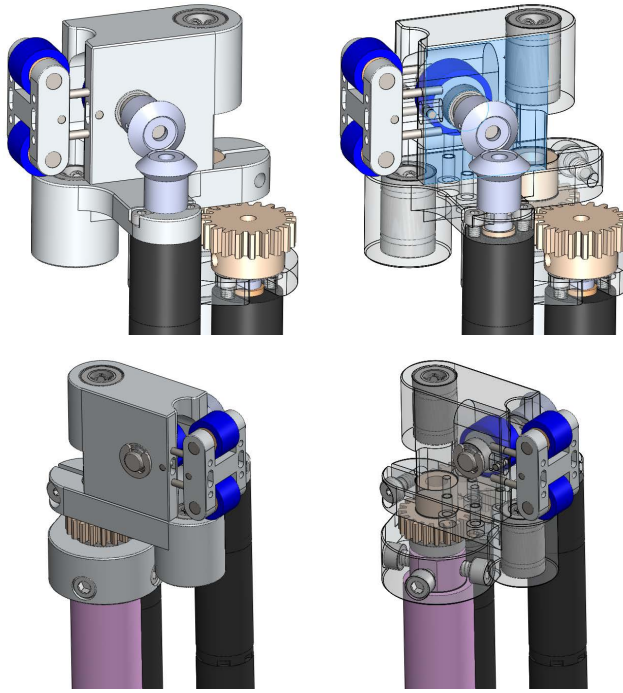


Figure 4.8: LapaRobot 2.1 CAD Model, Insertion Mechanism: (Top Left: Side View); (Top Right: Transparent Side View); (Bottom Left: Mirror Side View); (Bottom Right: Mirror Transparent Side View)

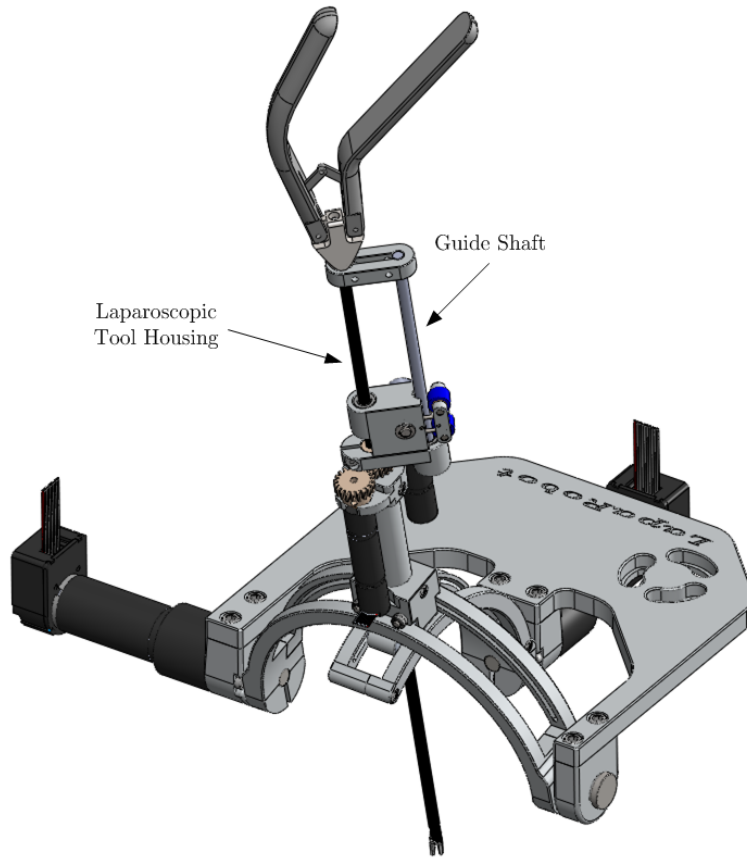


Figure 4.9: LapaRobot 2.1 CAD Model with Laparoscopic Tool

4.2.3 Rotation Mechanism (Yaw Motion)

Coupled directly to the insertion mechanism is the rotation assembly (balloons 25 and 39). Refereing again to Figures 4.8 and 4.9, we see that the insertion mechanism is mounted directly atop the rotation components. The quaternary motor mount (balloon 39) houses additional linear bearings that provide a smooth pathway for both the laparoscopic tool and the insertion guide rail. When a hand rotation occurs, a normal force is exerted perpendicular to the AoR, thus

a force is exerted on the insertion guide rail-which causes the mount and tool to rotate. Driving the rotation on the master-slave pairs are subsequent motors and straight pinion gears. The one-to-one pinion gears [32 tooth, 20° pressure angle] were chosen for their relatively small pitch and stock availability. The torque required to rotate the mechanism is $0.040Nm$.

4.2.4 Grasping Mechanism

Our initial design consisted of using the commercially available Karl Storz 26XXX series laparoscopic instruments (See Figure 4.10). The main reason for this is that there is a large footprint within the handle area that could potentially house our gripping/diving mechanism. This particular tool has a fixed tool shaft and non-removable end-effector. The 26XXX series instrument also has an added force-clutch feature that gives the user the ability to increase the force and lock the tool at the end-effector. Because of these features and the fact that the handle curvature conforms nicely to one's hands, we attempted to implement many designs that would give us control over this DoF.



Figure 4.10: LapaRobot 2.1 with Karl Storz 26XXX Laparoscopic Instrument

In order to use this tool-set, our conceived mechanism required the following: manufacturing custom handles; using a motor with a large enough gear ratio to overcome the clutch-force; and a way of changing the end-effectors from procedure

to procedure. Since these demands lie outside the design requirements set forth in Chapter 2, we decided to use the Karl Storz 33000 *CLICK'line* series instruments. Note: the laparoscopic tools in the next figures were used as place-holders to test the completed LapaRobot 2.1 system.

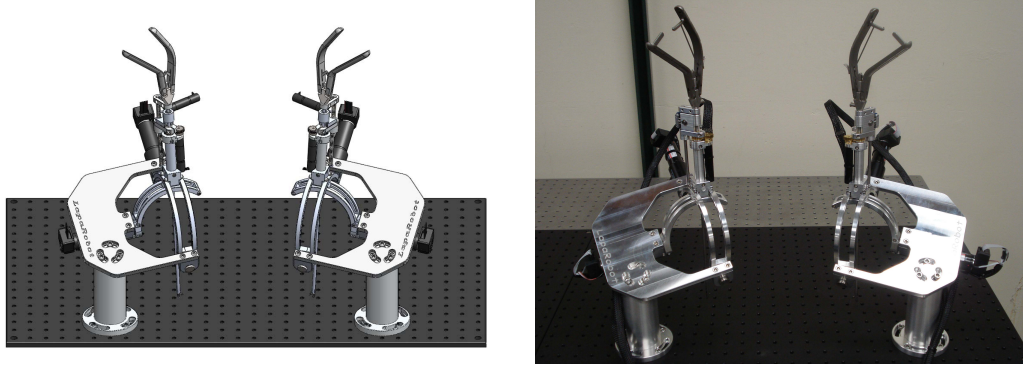


Figure 4.11: LapaRobot 2.1 CAD Model and Prototype System, Front View

4.2.4.1 Universal Grasping Mechanism

In order to provide quick, reliable, and repeatable tool changes, the LapaRobot uses the industry standard $5mm$ diameter Karl Storz instrument housing. This provides a standard interface between the holding mechanism and the surgical end-effector. The instrument housing itself connects to the Karl Storz 33000 *CLICK'line* system (See Figure 4.12); this system accepts a wide-array of handles. The Karl Storz 33138 *QLICK'line* Handle subsystem utilizes a straight handle design which can be more easily adapted to accept a mechanical closing system that is required for telesurgery. This is accomplished using the conceived four-bar mechanism shown below. The fulfilled mechanism facilitates a way for the handles to open and close, which in turn opens and closes the active end-effector (needle driver, scissors, etc).



Figure 4.12: Karl Storz 33XXX CLICK'line Laparoscopic Instrument Series

There are many advantages in using the Karl Storz 33XXX series instrument; such advantages include:

- Handles and components can be disassembled for sterility issues (Autoclave or disposable).
- Housing inserts/end-effectors are interchangeable (Various surgical procedures).
- Closing mechanism can be adapted without modifying handles (Standard tools can be used).
- Laparoscopic tools are widely accepted in the laparoscopic surgical industry. (Familiarity for teaching surgeons).

To effectively open and close the end-effector for the Karl Storz 33XXX series instrument, a *double rocker* four-bar linkage is given. This novel design meets all of the design requirements set-forth in Chapter 2, and most [importantly], this approach does not require the handles to be modified. The four-bar design schematic for the grasping mechanism is as follows:

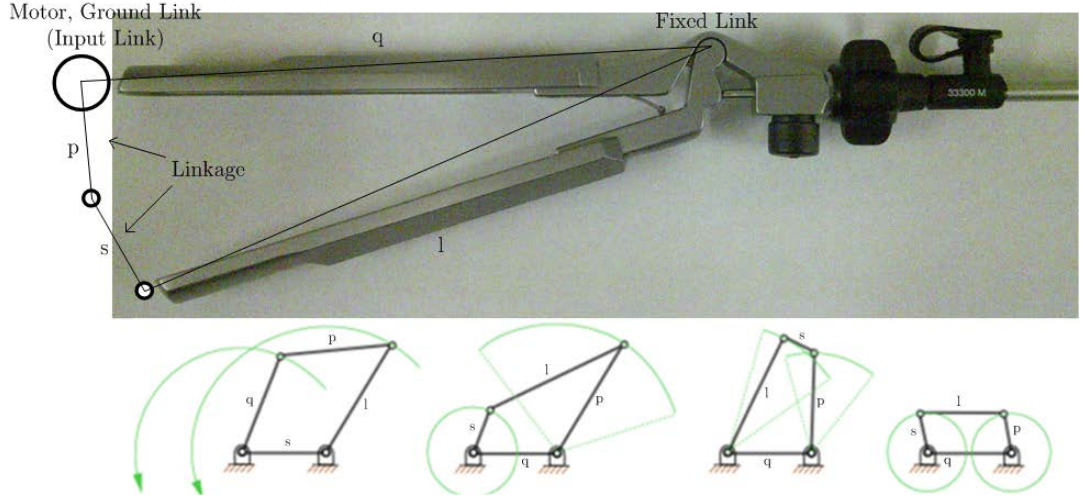


Figure 4.13: Four-Bar Mechanism Schematic for the Karl Storz 33XXX CLICK'line Laparoscopic Instrument Series

We have to determine the minimum lengths of p and s , such that, the mechanism does not pass through any of the possible singularity points. An example of singularity is when linkages p and s become co-linear and the angle between them becomes greater than 180 degrees. The problem statement is, given the proceeding constraints, find the minimum lengths of p and s :

1. Joint handle lengths: r_q and r_l
2. The opening and closing angle range for the handles: $\Theta_{min} \leq \Theta_1 \leq \Theta_{max}$.
3. The linkage lengths are equal: $p = s$

To do this, we must first design feasible linkages, motor mounts, pin-joints, and a method for attaching the mounts to the undercarriage of the handles. From these designs, we can calculate the handle lengths, as well as the minimum and maximum angles the handles can open and close.



Figure 4.14: Four-Bar Mechanism CAD Model for the Karl Storz 33XXX
CLICK'line Laparoscopic Instrument Series

In order to attach the mounting hardware (balloons 1-4, 18, 20, 21: Figure 4.19) to the handles, 12mm radius half-cylinders (yellow components) are mated to the underside-curvature and bonded in-place use industrial strength 3M DP – 420 epoxy. This design feature is seen below:

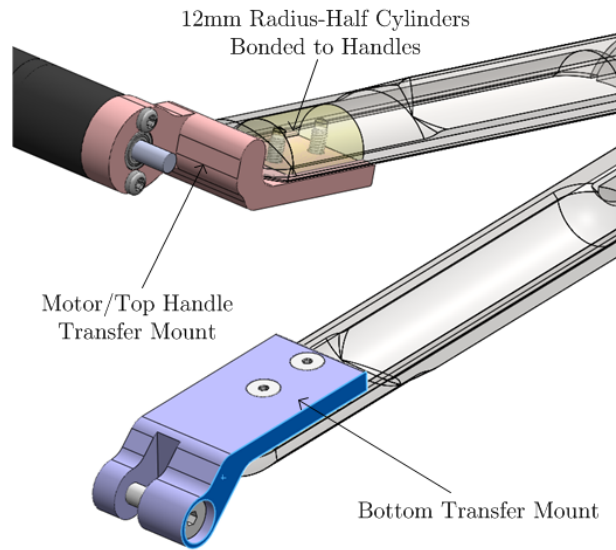


Figure 4.15: Four-Bar Mounting Mechanism CAD Model

Now that the handle mounts are designed, we can determine the opening and closing angle ranges for Θ_1 . It is important to note that the opening and closing angle range is also a function of the pull-bar joint length that is connected to the end-effector. That is to say, the handles are considered fully open and shut when the end-effector is, respectively opened and closed completely. This is important, as the handles can be closed past the stroke of the end-effectors closing range. This buffer-gap distance, when the end-effector is fully closed, is measured at 0.1065in from mount-to-mount. From Figure 4.16, we see that the range for Θ_1 is approximately between 6° and 22° .

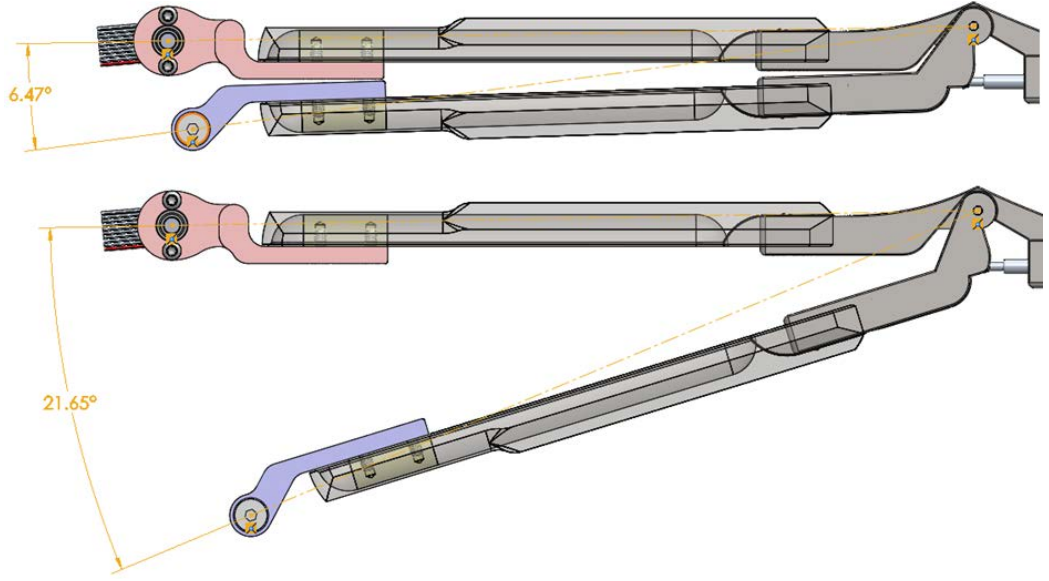


Figure 4.16: Four-Bar Mounting Mechanism, Θ_1 Handle Range CAD Model

Using the notation seen in Figure 4.17 for the four-bar diagram, combined with the law of cosines and the law of sines, we can effectively determine the linkage lengths r_3 and r_4 . To do so, we must check the angle between the linkage lengths and the angles between the handles and the linkages themselves. This will insure there are no singularity points throughout the stroke.

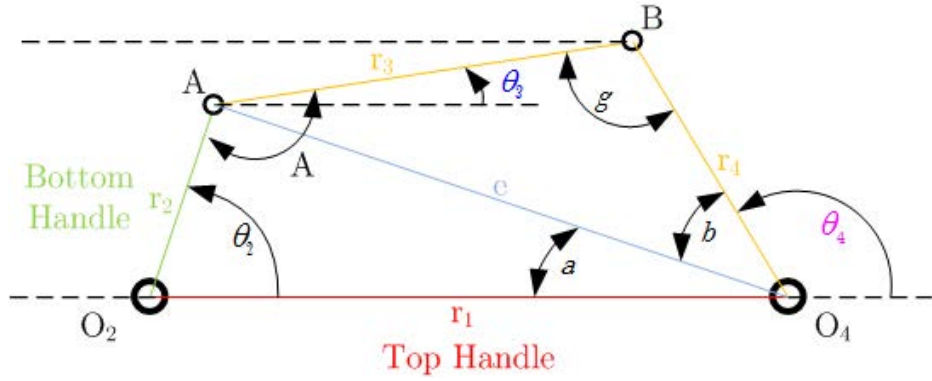


Figure 4.17: Four-Bar Double Rocker Schematic [31]

$$e^2 = r_1^2 + r_2^2 - 2r_1r_2 \cos(\Theta_2) \quad (4.3)$$

$$\frac{\sin(a)}{r_1} = \frac{\sin(\Theta_2)}{e} \quad (4.4)$$

$$e^2 = r_3^2 + r_4^2 - 2r_3r_4 \cos(g) \quad (4.5)$$

$$\frac{\sin(b)}{r_3} = \frac{\sin(g)}{e} \quad (4.6)$$

The four unknowns, e , a , g , and b are determined from the above equations and then used to tabulate a range for Θ_3 and Θ_4 from an array of input crank angles [31, 32]. The following relations are then used to determine the angle between the bottom handle and the adjoining linkage arm, $\langle A$, as well as the angle between the linkage arms, $\langle B$. Note: $\langle B = g$

$$\Theta_4 = 180^\circ - a - b \quad (4.7)$$

$$\Theta_3 = \Theta_4 - g \quad (4.8)$$

The angle analysis shown in Figure 4.18 shows a range for $\langle A$ and $\langle B$ for the handle angle range. This method was repeated until a minimized linkage length was obtained. The determined linkage length is $r_3 = r_4 = 1.32in$. The linkage length was also verified directly in the CAD software by defining angle-limit mates and then incrementing the linkage lengths by $0.0025in$ until an undefined or singular point was reached.

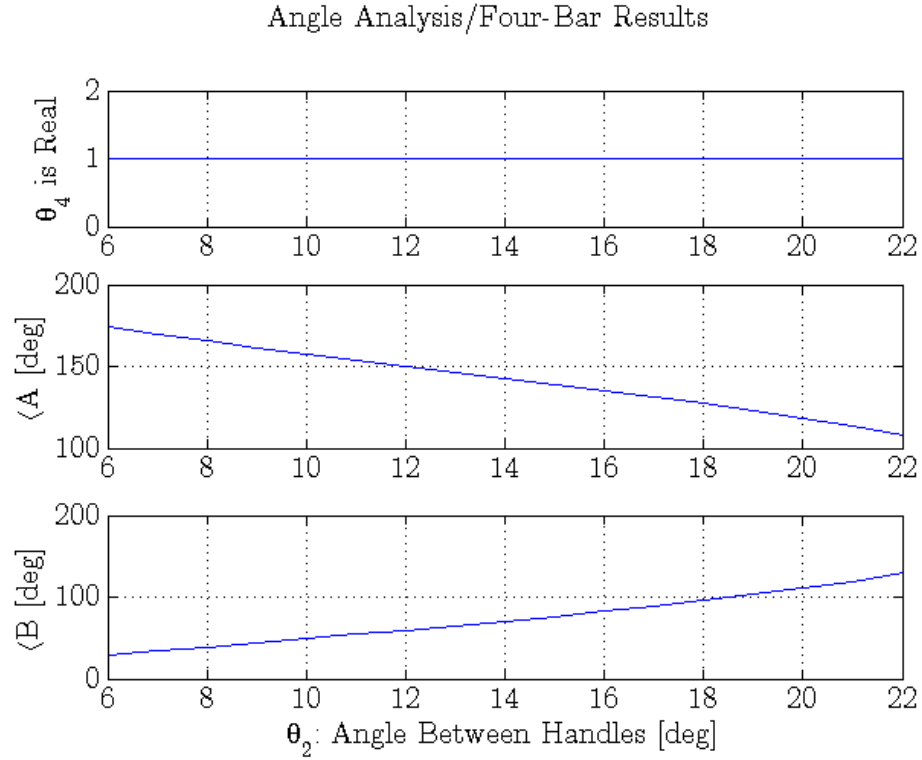
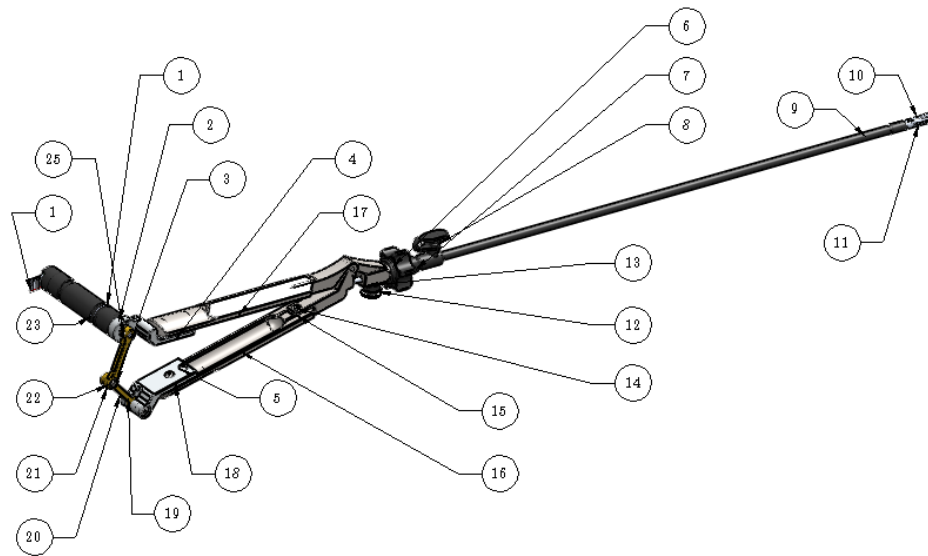


Figure 4.18: Four-Bar Angle Analysis Plot

The rest of the completed mechanism and the corresponding nomenclature is found in Figures 4.19 and 4.20 on pages 49 and 50, respectively. Also shown in Figure 4.21 is the fabricated prototype. Testing shows that the four-bar mechanism offers smooth actuation throughout the stroke of the end-effector and the in-line form-factor gives the user easy control over the handles.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Tertiary Motor 118520		1
2	92832A111		2
3	E-Clip Shaft 0.1240OD'L 9837 8A904	E-Clip Shaft (0.1240" OD)	1
4	Grasping Motor Mount Right	Grasping Motor Mount (Right Hand)	1
5	92210A077		4
6	Adjustment Knob		1
7	Shaft		1
8	Port Plug		1
9	Top Gripper Closer Mechanism		1
10	Top Gripper		1
11	Bottom Gripper		1
12	Port Cap		1
13	Top Hinge		1
14	Bottom Hinge		1
15	92125A083		2
16	Bottom Handle Straight RevA		1
17	Top Handle Straight RevA		1
18	Bottom Handle Transfer Plate Right	Bottom Handle Transfer Plate (Right Hand)	1
19	97345A419		1
20	Bottom Handle Linkage Arm	Bottom Handle Linkage Arm	1
21	Quinary Motor Linkage Arm	Quinary Motor Linkage Arm	1
22	98408A116		2
23	Tertiary Gearhead 110315		1
1	Tertiary Encoder 323054		1
25	94355A142		1
26	91430A056		1
27	Shaft Hinge Alignment End		1
28	Handle Insert Attachment RevA	Handle Insert Attachment	2
29	7804K124		1
30	Shim Bearing 0.250OD' 0.125 ID' 0.01T 93574A186		3

Figure 4.19: Four-Bar Mechanism/Karl Storz 33XXX Series Instrument Nomenclature and Bill of Materials



Figure 4.20: Four-Bar Mechanism CAD Model for the Karl Storz 33XXX CLICK'*line* Laparoscopic Instrument Series (Left, Front Isometric View); (Right, Rear Isometric View)

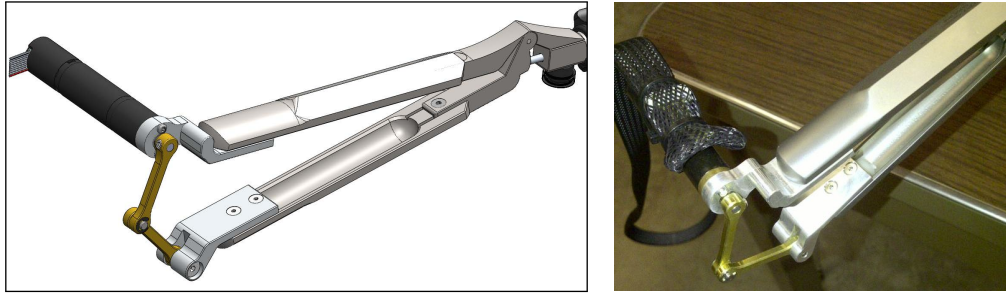


Figure 4.21: Four-Bar Mechanism CAD Model and Prototype for the Karl Storz 33XXX CLICK'*line* Laparoscopic Instrument Series

Four-Bar Static and Dynamic Analysis The motor torque required to open and close the end-effectors is dependent on the end-effector being used—as each end-effector has differing pull-force characteristics. In other words, each FLS task requires an object to be manipulated in some way by the end-effector and thus requires a holding force from the motor. So, the motor has to overcome the pull-force of the end-effector [combination of closing the end-effector mechanism plus the friction in the the end-effector mechanism] and the holding force of the particular end-effector. Since the FLS examination requires the use of three

end-effectors, namely needle drivers, forceps, and scissors, experimental force measurements were conducted to determine the closing force of the handle for each end-effector. The measured average force required to close the handle is $0.253N$. Using this force along with the following static and dynamic analysis, we can determine the required motor torque to close the handles. To set up the problem, we are using the following four-bar analysis schematic:

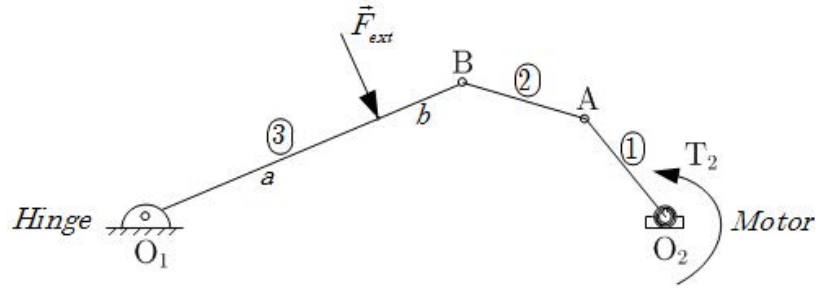


Figure 4.22: Four Bar Analysis Schematic

Four-Bar Static Analysis

The static problem is setup as follows:

Given:

- External Force, $\vec{F}_{ext}$, where the direction, magnitude, & application point are known
- Links (Body): 1, 2, 3
- Nodes: O_1 , O_2 , A , B

Find: Torque of the driving motor, T_2

Using the free body diagram (FBD) representation of the four bar schematic, we have,

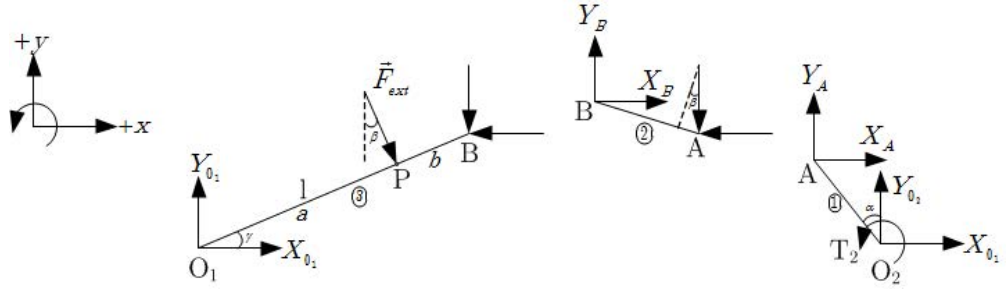


Figure 4.23: Four Bar Static Analysis Free Body Diagram Schematic

Equilibrium: Statics $\implies \Sigma \vec{F} = m \vec{a} = \vec{0}$

$$\begin{aligned}
 & \boxed{\text{BODY ①}} \quad \left\{ \begin{array}{l} \Sigma F_x = 0 : \\ \Sigma F_y = 0 : \\ \Sigma M_{O_2} = 0 : \end{array} \right. \\
 \\
 \implies & \left\{ \begin{array}{ll} X_{O_2} + X_A & = 0 \\ Y_{O_2} + Y_A & = 0 \\ T_{O_2} - X_A \cdot \underbrace{\overline{AO_{2,y}}}_{|\overline{AO_2}| \cdot \cos \alpha} - Y_A \cdot \underbrace{\overline{AO_{2,x}}}_{|\overline{AO_2}| \cdot \sin \alpha} & = 0 \end{array} \right. \quad (4.9) \\
 \\
 & \boxed{\text{BODY ②}} \quad \left\{ \begin{array}{l} \Sigma F_x = 0 : \\ \Sigma F_y = 0 : \\ \Sigma M_A = 0 : \end{array} \right.
 \end{aligned}$$

$$\Rightarrow \begin{cases} -X_A + X_B & = 0 \\ -Y_A + Y_B & = 0 \\ X_B \cdot \overline{AB_y} - Y_B \cdot \overline{AB_x} & = 0 \end{cases} \quad (4.10)$$

$$\boxed{\text{BODY } \textcircled{3}} \quad \left\{ \begin{array}{l} \Sigma F_x = 0 : \\ \Sigma F_y = 0 : \\ \Sigma M_B = 0 : \end{array} \right.$$

$$\Rightarrow \begin{cases} -X_B + X_{O_1} + F_{ext,x} & = 0 \\ -Y_B + Y_{O_1} - F_{ext,y} & = 0 \\ X_{O_1} \cdot \overline{BO_{1,y}} - Y_{O_1} \cdot \overline{BO_{1,x}} + F_{ext} \cdot b & = 0 \end{cases} \quad (4.11)$$

System of 3 equations and 3 unknowns

$$A \begin{bmatrix} X_{01} \\ Y_{01} \\ X_{02} \\ Y_{02} \\ \vdots \\ T \end{bmatrix} = \begin{bmatrix} \vdots \\ \underline{b} \\ \vdots \end{bmatrix} \quad (4.12)$$

$$\implies \boxed{\underline{x} = A^{-1} \cdot b} \quad (4.13)$$

Four-Bar Dynamic Analysis

The dynamic problem is setup as follows:

Given:

- External Force, $\vec{F}_{ext}$, where the direction, magnitude, & application point are known
- Kinematic Equations: $\vec{v}$, $\vec{a}$, $\vec{\omega}$, $\vec{\alpha}$

Find: Torque of the driving motor, T_2

The following figures are the schematics for the dynamic analysis:

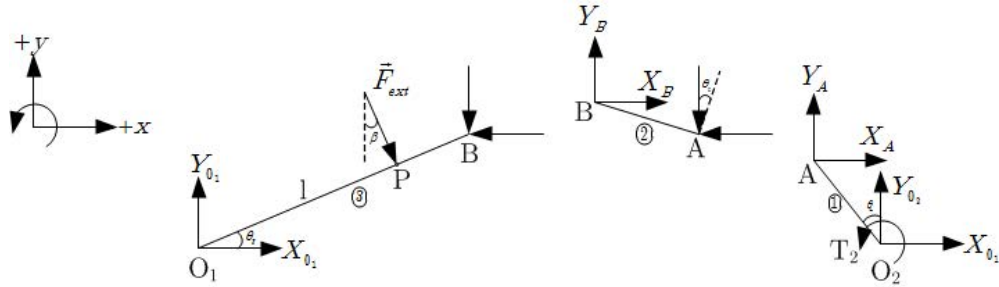


Figure 4.24: Four Bar Dynamic Analysis Free Body Diagram Schematic

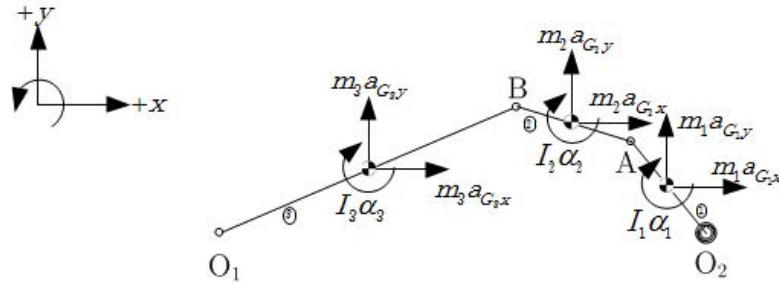


Figure 4.25: Four Bar Dynamic Analysis Kinetic Diagram Schematic

$$\text{Equilibrium: Dynamics} \Rightarrow \begin{cases} \Sigma \vec{F} &= m \vec{a}_G \\ \Sigma \vec{M}_Z &= I_G \vec{\alpha} \end{cases}$$

$$\begin{aligned}
& \boxed{\text{BODY ①}} \quad \left\{ \begin{array}{lcl} \Sigma F_x & = & m_1 a_{G_1 x} \quad : \\ \Sigma F_y & = & m_1 a_{G_1 y} \quad : \\ \Sigma M_z|_{G_1} & = & I_1 \alpha_1 \quad : \end{array} \right. \\
\Rightarrow & \left\{ \begin{array}{lcl} X_{O_2} + X_A & & = m_1 a_{G_1 x} \\ Y_{O_2} + Y_A & & = m_1 a_{G_1 y} \\ -T_2 + X_A \cdot \overline{AG_1}|_y + X_A \cdot \overline{AG_1}|_x + \\ -X_{O_2} \cdot \overline{O_2 G_1}|_y - Y_{O_2} \cdot \overline{O_2 G_1}|_x & & = I_1 \alpha_1 \end{array} \right. \quad (4.14)
\end{aligned}$$

$$\begin{aligned}
& \boxed{\text{BODY ②}} \quad \left\{ \begin{array}{lcl} \Sigma F_x & = & m_2 a_{G_2 x} \quad : \\ \Sigma F_y & = & m_2 a_{G_2 y} \quad : \\ \Sigma M_z|_{G_2} & = & I_2 \alpha_2 \quad : \end{array} \right. \\
\Rightarrow & \left\{ \begin{array}{lcl} -X_A + X_B & & = m_2 a_{G_2 x} \\ -Y_A + Y_B & & = m_2 a_{G_2 y} \\ X_B \cdot \overline{BG_2}|_y + Y_B \cdot \overline{BG_2}|_x + \\ -X_A \cdot \overline{AG_2}|_y + Y_A \cdot \overline{AG_2}|_x & & = I_2 \alpha_2 \end{array} \right. \quad (4.15)
\end{aligned}$$

$$\boxed{\text{BODY ③}} \quad \left\{ \begin{array}{lcl} \Sigma F_x & = & m_3 a_{G_3 x} \quad : \\ \Sigma F_y & = & m_3 a_{G_3 y} \quad : \\ \Sigma M_z|_{G_3} & = & I_3 \alpha_3 \quad : \end{array} \right.$$

$$\Rightarrow \begin{cases} -X_B + X_{O_1} + F_{ext,x} & = m_3 a_{G_3x} \\ -Y_B + Y_{O_1} - F_{ext,x} & = m_3 a_{G_3y} \\ -X_{O_1} \cdot \overline{O_1 G_1}|_y + Y_{O_1} \cdot \overline{O_1 G_1}|_x + \\ + F_{ext} \cdot \overline{P G_1} - X_B \cdot \overline{B G_1}|_y + \\ + Y_B \cdot \overline{B G_1}|_x & = I_3 \alpha_3 \end{cases} \quad (4.16)$$

$\therefore$ We have linear system with 9 equations and 9 unknowns: (X_{0_1} , Y_{0_1} , X_A , Y_A , X_B , Y_B , X_{0_2} , Y_{0_2} , and T_2)

The minimum motor torque [necessary to close the handles] is $1.8mNm$. Note: This calculation was made using the derived maximum closing angle requirement, combined with the *averaged* measured external closing handle force values.

4.3 LapaRobot Design Revisions

In this section we focused on design improvements to make the LapaRobot system more robust. We redesigned and refabricated the insertion mechanism-along with adding an in-house digital-to-analog board to our amplifier housings. Originally the insertion motion used a friction drive mechanism, however with use, it was determined that a rack-and-pinion setup would eliminate the possibility for slip. These improvements required several key components to be remanufactured and reassembled. It was decided early on that we would like to anodize certain motion components in order to enhance their durability against wear and use; we decided against this route because we ultimately changed the pitch (ψ) and roll (ϕ) arcs motion spherical mechanism. The previous spherical mechanism utilized 4 ball-transfer bearings that rolled in a v-groove on the inner surface of each arc

(see Figure 4.4). Because the arcs are made out of aluminum and the balls are hardened steel, the inside v-grooves exhibited signs of wear and thus a loss of tolerance developed. We decided to change this design to a new sliding mechanism; this sliding mechanism is made out of a natural bushing material called Delrin[®]. Because Delrin has a very low friction coefficient, the new components allow for a sliding motion on the top and inner surface of the arcs. This design change was implemented and the actuation that this new sliding approach alleviates the wear seen on the arcs and provides a better feel for the user. Furthermore, this approach reduces both the manufacture and hardware cost by over 75 percent.

4.3.1 LapaRobot 2.2 Revisions

The LapaRobot 2.1 friction drive mechanism suffers from the possibility of drive-wheel slippage during use. Furthermore, the mechanism itself requires many fabricated components-all of which require precision manufacture and assembly. Also, the retention springs the pull on the idler wheel assembly, involve separate tooling for installation. As such, a rack-and-pinion design was incorporated in the design. Also, the insertion motor configuration was changed from having a perpendicular alignment using beveled gears to a coaxial alignment with the pinion gear. This new mechanism is seen next to the LapaRobot 2.2 CAD model on the following page.

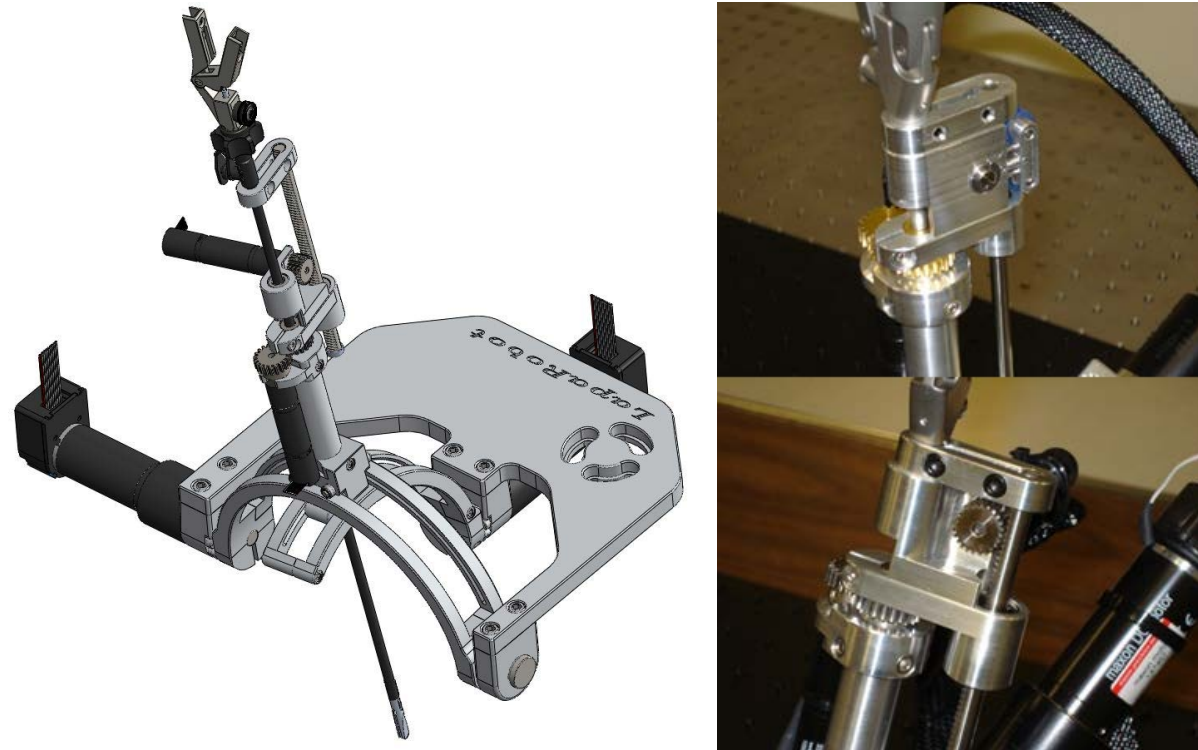


Figure 4.26: LapaRobot 2.2 CAD Model (Left) and Rack and Pinion Insertion Mechanism Prototype (Bottom Right) and Friction-Drive Insertion Mechanism Prototype (Top Right)

The cross-section of traditional racks are rectangular and square in geometry. Intrinsically, this particular shape makes it difficult to offset and align parallel with our laparoscopic tool configuration. As such, we employed a round-circular rack in our design, so that the the setup would use four surface contacts to provide smooth-parallel actuation throughout the stroke of the tool insertion. From Figure 4.27, we see that the laparoscopic tool is in constant contact with a linear bearing and the spherical mechanism; while the motor pinion gear and an additional linear bearing are in constant contact with the circular rack. This configuration constrains the rack to the laparoscopic tool's axis of rotation

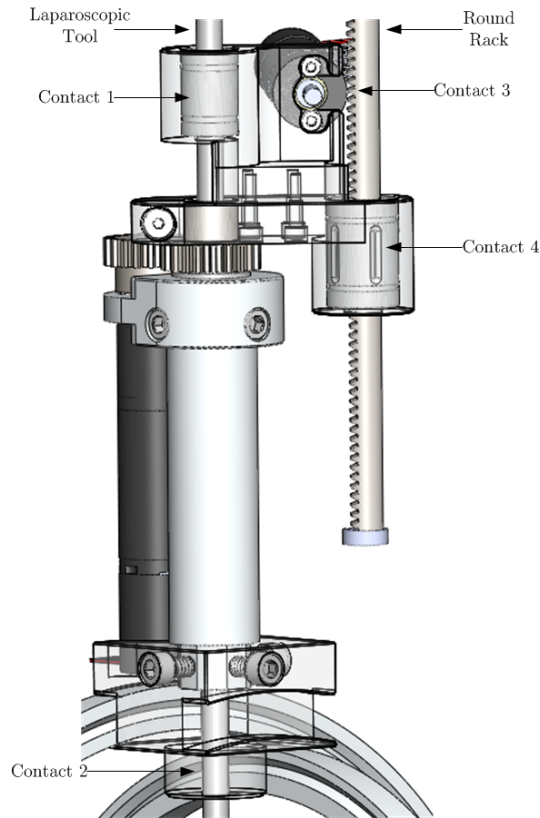


Figure 4.27: Rack and Pinion Alignment Configuration

From the proceeding equations, the maximum linear speed of the rack can be

calculated; and since the tool is coupled to the rack, the speed of the laparoscopic tool is directly realized.

$$\omega = (\tau_s - \tau) \left(\frac{\omega_n}{\tau_s} \right) \quad (4.17)$$

$$V_{rack} = \omega_{pinion} r_{pinion} \quad (4.18)$$

Where ω is the angular velocity of the pinion at maximum loading, τ_s is the stall torque, τ is the maximum torque, and ω_n is the no load angular velocity. The speed of the tool is: $V_{Tool} = 2.50in/sec$ or $63.5mm$.

Motor Dynamics of Maxon Motors [33]

The speed of rotation or input speed is given by:

$$n_{in} = \frac{60}{p \cdot z} \cdot v_L \quad (4.19)$$

Where p is the pitch of the rack, z is the number of teeth of the pinion gear, and v_L is the load velocity.

Input Torque:

$$M_{in} = \frac{p \cdot z}{2\pi} \cdot \frac{F_L}{\eta} \quad (4.20)$$

Where F_L is the output load force, and η is the efficiency.

Additional Torque for Constant Acceleration (Speed change Δn_{in} during period Δt_a):

$$M_{in,a} = \left(J_{in} + J_P + \frac{m_L + m_Z}{\eta} \cdot \frac{p^2 \cdot z^2}{4\pi^2} \right) \cdot \frac{\pi}{30} \cdot \frac{\Delta n_{in}}{\Delta t_a} \quad (4.21)$$

Where J_{in} is the moment of inertia of the motor, J_p is the moment of inertia of the pinion, m_L is the mass of the load, and m_Z is the mass of the rack.

Position Error:

$$\Delta\varphi_{in} = \Delta s_L \cdot \frac{2\pi}{p \cdot z} \quad (4.22)$$

Where Δs_L is the mechanical play.

4.3.2 LapaRobot 2.3 Revisions

It was decided early on that we would like to anodize certain motion components in order to enhance their durability against wear and use; we decided against this route because we ultimately changed the pitch (ψ) and roll (ϕ) arcs motion spherical mechanism. The previous spherical mechanism utilized four ball-transfer bearings that rolled in a v-groove on the inner surface of each arc (see Figure 4.4). Because the arcs are made out of aluminum and the balls are hardened steel, the inside v-grooves exhibited signs of wear and thus a loss of tolerance developed. As seen in Figure 4.28, different types of protective tapes (Polytetrafluoroethylene (PTFE) or Teflon®, PEEK, Fiberglass) were employed to protect and build-up the damaged surfaces; but, ultimately, the transfer balls would wear through the tapes. Another considered approach was to re-machine the arcs out of 17-4 stainless steel and heat treat the components. This method would provide increase yield strength, hardness, and durability. The major downside to this approach, is the cost of material and time to required to machine the components.

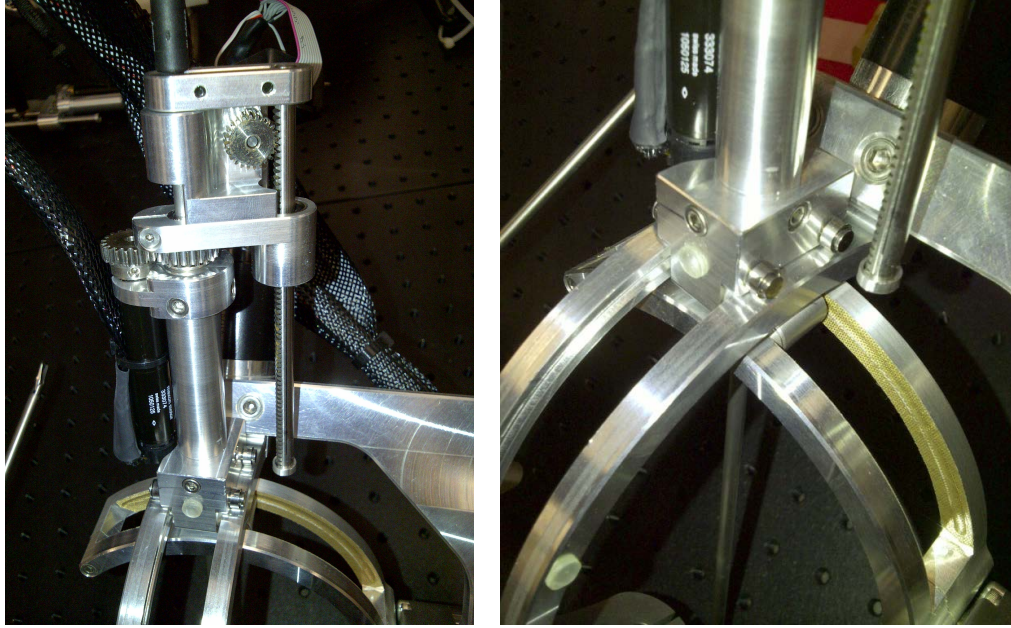


Figure 4.28: LapaRobot 2.2 Exhibited Wear Patterns

Taking all these factors into consideration, we decided to change the rolling-spherical design to a new sliding mechanism; this sliding component is made out of a natural bushing material called Delrin®. Since Delrin has a very low friction coefficient, the new components allow for a sliding motion on the top, bottom, and inner surfaces of the arcs. This design change was implemented and the results indicate that this new sliding approach alleviates the wear seen on the arcs and provides a better feel for the surgeon. Furthermore, this approach reduces both the manufacture and hardware cost by over 75 percent.

Delrin, which is a thermoplastic has the following characteristics [34, 35]:

- Relatively High Stiffness
 - Young’s Modulus: $E = 420,000psi, (2.9GPa)$
- Good Bearing Surface

- Low Friction Coefficient: $\mu = 0.12$
- High Abrasion Resistance: $K = 111 \frac{in.min}{ft.lbs.hr}$
- Good Machinability
 - Holds Dimensional Tolerances Well

The problem statement then becomes to design a sliding spherical mechanism that would be fit to the I.D/O.D and inner surfaces of the pitch (ψ) rotation arc-while being able to rotate in the roll (ϕ) rotation arc. This means the component(s) must have a running fit along all of the surfaces. The following figures illustrate this detailed design.

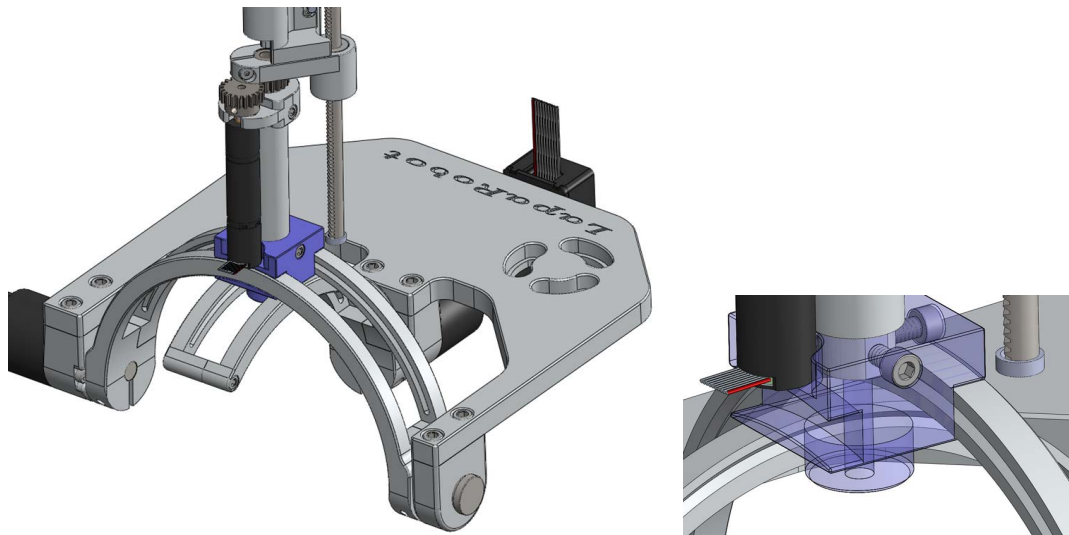


Figure 4.29: LapaRobot 2.3 Spherical Mechanism CAD Model



Figure 4.30: LapaRobot 2.3 Spherical Mechanism Prototype

With the preceding design enhancements, the LapaRobot version 2 design is complete. The next figures shows the completed CAD model and the corresponding fabricated prototype system. The next chapter will highlight some of the manufacture challenges associated with this design, and present a few case studies that are pertinent in the realization of this robotic system.

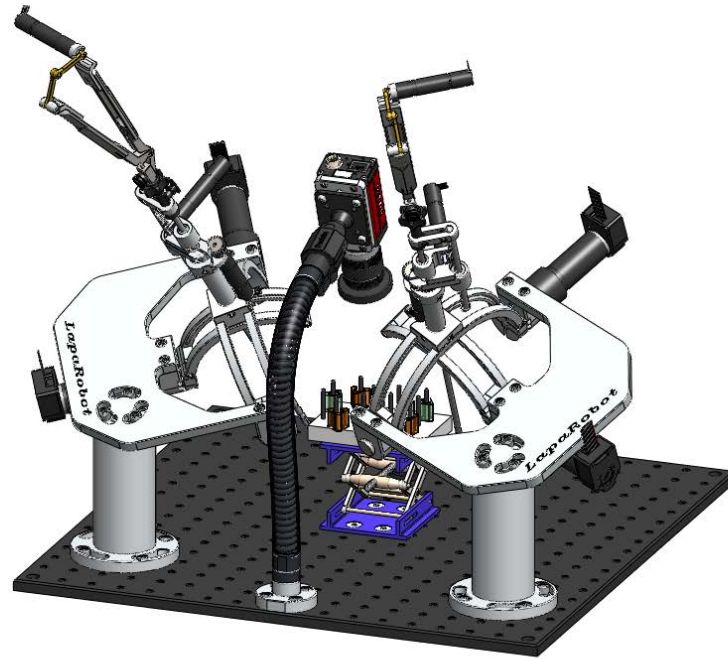


Figure 4.31: LapaRobot 2.3 Surgical CAD Model (Final Design)

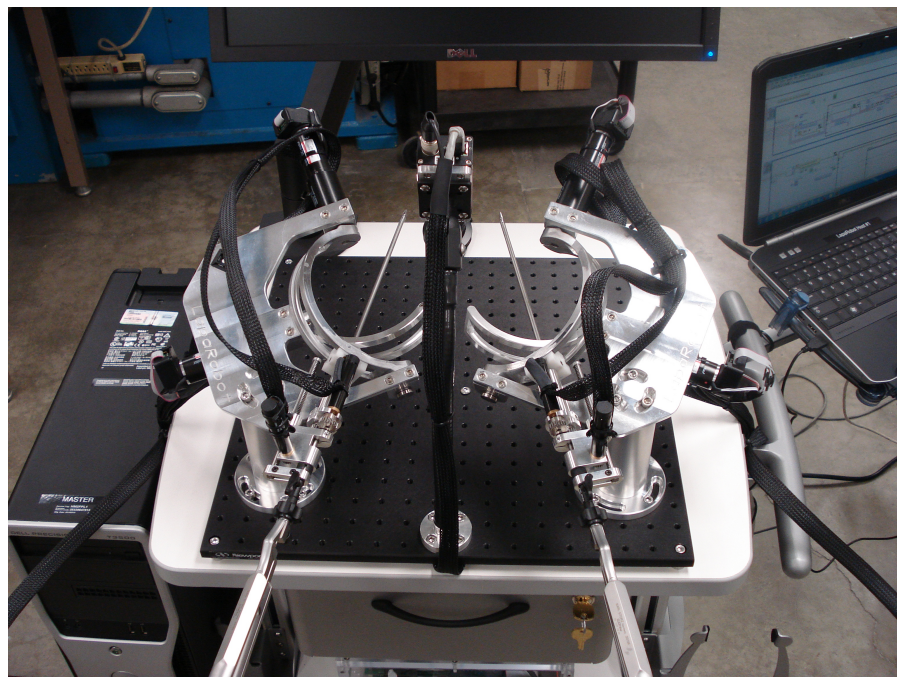


Figure 4.32: LapaRobot 2.3 Surgical System Prototype (Final Design)

CHAPTER 5

Force and Displacement Analysis

5.1 Introduction

In this chapter we will verify the design requirements and the design integrity of the LapaRobot system(s) using Finite Element Methods (FEM) and Computer Aided Engineering (CAE). We are interested in the displacement of the instrument tool tip and the corresponding forces on the instrument shaft as applied forces are given to the instrument handles. We are also interested in the torque seen at the shaft of the roll ϕ rotation arc; the friction forces produced between the pitch (ψ) rotation arc and slider castor; the applied forces on the rotation arcs, motor mounts, and instrument shaft-cause by the distributed forces exerted through the laparoscopic instrument handle. Because of the complexity of the mechanism, SolidWorks' Simulation toolkit and SolidWorks' Motion Analysis toolkit are employed. The SolidWorks Simulation toolkit allows us to evaluate the static and dynamic response(s) of the LapaRobot Assembly; whereas, the SolidWorks Motion Analysis toolkit allows us to use the pre-configured mates used to defined the assembly model-to accurately determine reaction forces produced on the LapaRobot system(s) without adding or removing the degrees-of-freedom of the system. We can then combine the two toolboxes-using SolidWorks Motion simulation to determine forces and then export these forces to SolidWorks Simulation to perform a specified stress analysis.

5.1.1 Finite Element Methods & Computer Aided Engineering

5.1.1.1 FEM Model Setup

To reduce the computational resource requirements, all non-essential components (parts) were removed from the model and mass-representable parts were used in their place. The FEM assembly model includes all critical components, necessary to assess the displacement of the tool tip due to a force applied to the handle. The FEM assembly model was defined with the following characteristics:

- Meshed using roughly 33,000 standard solid elements [brick]
- Appropriate material properties were applied to all parts (See Tables 5.2 and 5.3)
- The motor mounts were assumed fixed and a load of $10N$ and $100N$ was applied to the handle and at an angle perpendicular to the ground floor
- Analysis were performed at various roll (ϕ) arc angles, namely, 0° , 10° , 25° , 40° , 60°

Many studies have been conducted to determine handle forces on both laparoscopic surgical tools and conventional surgical forceps. These studies conclude that forces are higher when using laparoscopic tools when compared to conventional surgical tools [36]. As an example, Figure 5.1 shows the difference in mean *closing* handle forces between laparoscopic and conventional surgical tools for different grasping exercising. To further investigate this topic, we estimated the lift and push force of the 4 LapaRobot instrument arms using a calibrated Shimpo force gauge and average the results. To lift the laparoscopic instrument vertically requires a [initial] maximum force of $3.25N$; whereas, to push the instruments

inwards, requires less than half this amount ($1.45N$). It is important to note that these values were measured when the LapaRobot was powered (i.e. the motors are under control). Using the force data in Figure 5.1 couple with the experiential *lift-push* force data of the LapaRobot instruments, we have chosen to use an applied force of $10N$ with an extreme force of $100N$ for the FEM analysis.

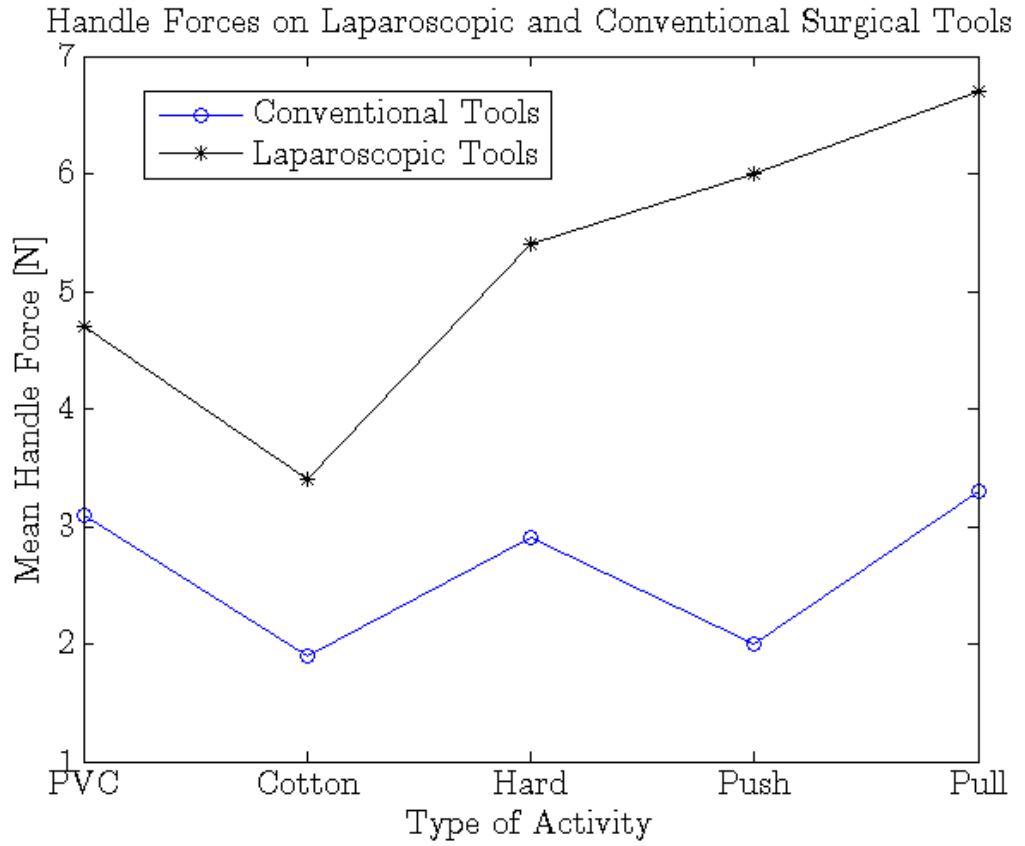


Figure 5.1: Handle Forces on Laparoscopic and Conventional Surgical Tools

[36]

Table 5.1: Material Properties for Aluminum 6061 used in the FEM Analysis:
Inches Units (Top), SI Units (Bottom) [37]

Property	Value	Units
Elastic Modulus	10007603.9	psi
Poissons Ratio	0.33	N/A
Shear Modulus	3770981.18	psi
Density	0.0975437	lb/in ³
Tensile Strength	17996.86	psi
Compressive Strength in X		psi
Yield Strength	7998.61	psi
Thermal Expansion Coefficient	1.333333333e-005	/°F
Thermal Conductivity	0.00227371	Btu/(in·sec·°F)
Specific Heat	0.3105	Btu/(lb·°F)
Material Damping Ratio		N/A

Property	Value	Units
Elastic Modulus in X	69000	N/mm ²
Poisson's Ration in XY	0.33	N/A
Shear Modulus in XY	26000	N/mm ²
Mass Density	2700	kg/m ³
Tensile Strength in X	124.08	N/mm ²
Compressive Strength in X		N/mm ²
Yield Strength	55.15	N/mm ²
Thermal Expansion Coefficient in X	2.4e-005	/K
Thermal Conductivity in X	170	W/(m·K)
Specific Heat	1300	J/(kg·K)
Material Damping Ratio		N/A

Table 5.2: Material Properties (inches units) for FEM Analysis: AISI 304 Stainless Steel (Top Left), 6061 – T6 Aluminum Alloy (Top Right), 360 Brass (Bottom Left), Delrin 2700 NC010 (Bottom Right) [37]

Property	Value	Units
Elastic Modulus	27557170.16	psi
Poissons Ratio	0.29	N/A
Shear Modulus	10877830.32	psi
Density	0.289018	lb/in ³
Tensile Strength	74986.98	psi
Compressive Strength in X		psi
Yield Strength	29994.82	psi
Thermal Expansion Coefficient	1e-005	/°F
Thermal Conductivity	0.000213996	Btu/(in-sec-°F)
Specific Heat	0.119423	Btu/(lb-°F)
Material Damping Ratio		N/A

Property	Value	Units
Elastic Modulus	14503773.77	psi
Poissons Ratio	0.33	N/A
Shear Modulus	5366396.29	psi
Density	0.307082	lb/in ³
Tensile Strength	69387.94	psi
Compressive Strength in X		psi
Yield Strength	34763.95	psi
Thermal Expansion Coefficient	1e-005	/°F
Thermal Conductivity	0.00147122	Btu/(in-sec-°F)
Specific Heat	0.0931499	Btu/(lb-°F)
Material Damping Ratio		N/A

Property	Value	Units
Elastic Modulus in X	10007604	psi
Poisson's Ration in XY	0.33	N/A
Shear Modulus in XY	3770981.2	psi
Mass Density	0.0975437	lb/in ³
Tensile Strength in X	44961.7	psi
Compressive Strength in X		psi
Yield Strength	39885.38	psi
Thermal Expansion Coefficient in X	1.333333333e-005	/°F
Thermal Conductivity in X	0.00223225	Btu/(in-sec-°F)
Specific Heat	0.214006	Btu/(lb-°F)
Material Damping Ratio		N/A

Property	Value	Units
Elastic modulus	420609.44	psi
Poisson's ratio	0.3	N/A
Shear Modulus in XY		psi
Mass density	0.0509395	lb/in ³
Tensile strength	5903.04	psi
Compressive Strength in X		psi
Yield strength	9137.38	psi
Thermal Expansion Coefficient in X		/°F
Thermal Conductivity in X		Btu/(in-sec-°F)
Specific Heat		Btu/(lb-°F)
Material Damping Ratio		N/A

Table 5.3: Material Properties (SI units) for FEM Analysis: AISI 304 Stainless Steel (Top Left), 6061–T6 Aluminum Alloy (Top Right), 360 Brass (Bottom Left), Delrin 2700 NC010 (Bottom Right) [37]

Property	Value	Units
Elastic Modulus in X	190000	N/mm ²
Poisson's Ration in XY	0.29	N/A
Shear Modulus in XY	75000	N/mm ²
Mass Density	8000	kg/m ³
Tensile Strength in X	517.02	N/mm ²
Compressive Strength in X		N/mm ²
Yield Strength	206.81	N/mm ²
Thermal Expansion Coefficient in X	1.8e-005	/K
Thermal Conductivity in X	16	W/(m·K)
Specific Heat	500	J/(kg·K)
Material Damping Ratio		N/A

Property	Value	Units
Elastic Modulus in X	110000	N/mm ²
Poisson's Ration in XY	0.37	N/A
Shear Modulus in XY	40000	N/mm ²
Mass Density	8900	kg/m ³
Tensile Strength in X	394.38	N/mm ²
Compressive Strength in X		N/mm ²
Yield Strength	258.65	N/mm ²
Thermal Expansion Coefficient in X	2.4e-005	/K
Thermal Conductivity in X	390	W/(m·K)
Specific Heat	390	J/(kg·K)
Material Damping Ratio		N/A

Property	Value	Units
Elastic Modulus in X	69000	N/mm ²
Poisson's Ration in XY	0.33	N/A
Shear Modulus in XY	26000	N/mm ²
Mass Density	2700	kg/m ³
Tensile Strength in X	310	N/mm ²
Compressive Strength in X		N/mm ²
Yield Strength	275	N/mm ²
Thermal Expansion Coefficient in X	2.4e-005	/K
Thermal Conductivity in X	166.9	W/(m·K)
Specific Heat	896	J/(kg·K)
Material Damping Ratio		N/A

Property	Value	Units
Elastic Modulus in X	2900	N/mm ²
Poisson's Ration in XY	0.3	N/A
Shear Modulus in XY		N/mm ²
Mass Density	1410	kg/m ³
Tensile Strength in X	40.7	N/mm ²
Compressive Strength in X		N/mm ²
Yield Strength	63	N/mm ²
Thermal Expansion Coefficient in X		/K
Thermal Conductivity in X		W/(m·K)
Specific Heat		J/(kg·K)
Material Damping Ratio		N/A

Figure 5.2 shows the meshed version of the LapaRobot Assembly with applied boundary conditions.

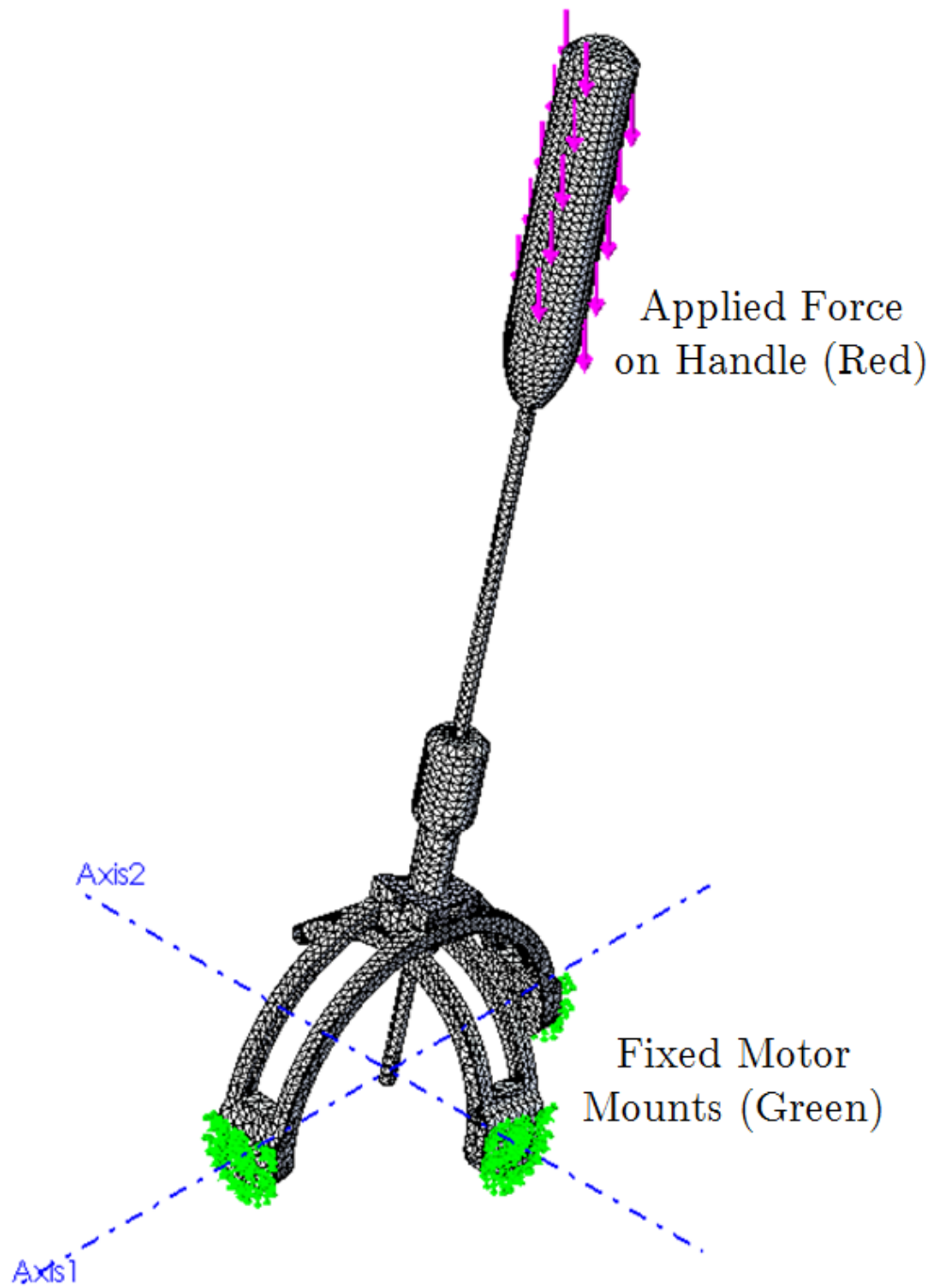


Figure 5.2: LapaRobot FEM Meshed Assembly

The laparoscopic tool is extended to the mechanism's full extension; that is, the longest moment arm [between the applied force(s) and the RCM] occurs when the tool is extended to its maximum travel range. This insures that maximum bending forces are applied to the interference joint of the tool shaft and the created pivot point. Sweeping through the various tilt angles (see Figure 5.3) with a force of $10N$, we can realize the the displacement of the tool tip and the maximum von Mises Stress(s) on the LabaRobot Assembly.

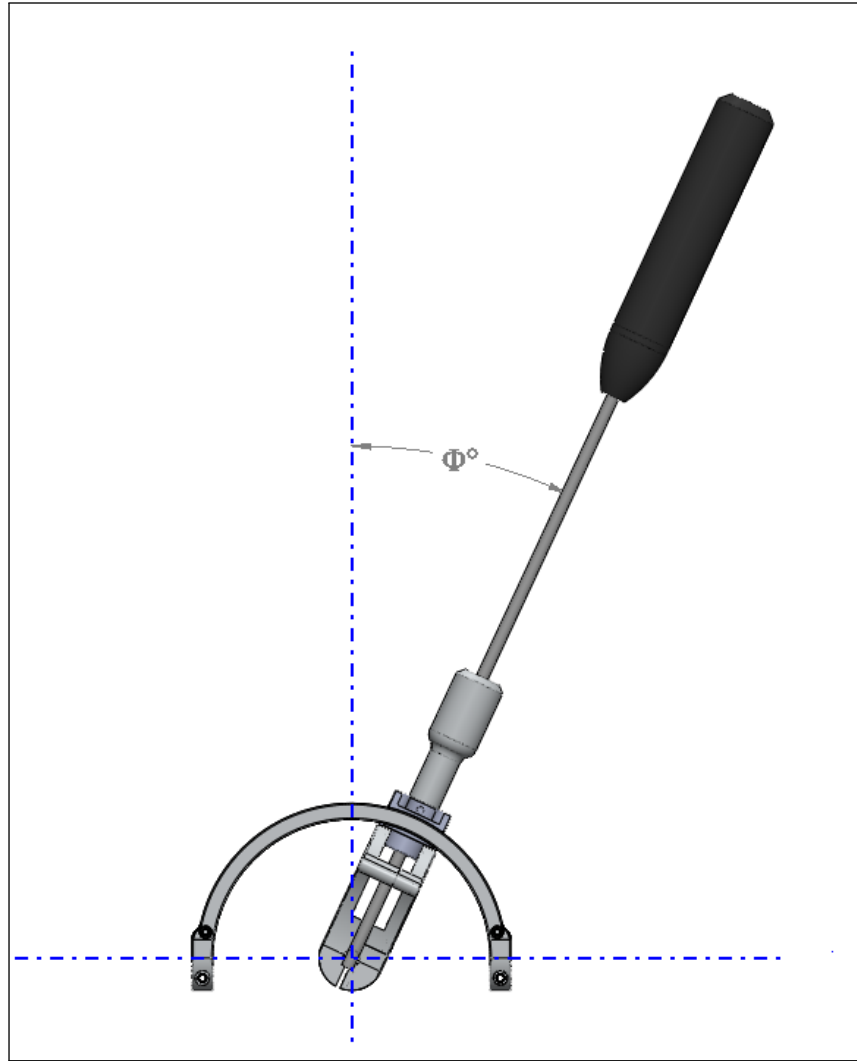


Figure 5.3: LapaRobot FEM Tilt Angle Measurement Schematic

5.1.2 Maximum Displacement & Stress Analysis

5.1.2.1 Maximum Displacement & Stress Analysis at Various Tilt Angles with a 10N Applied Force

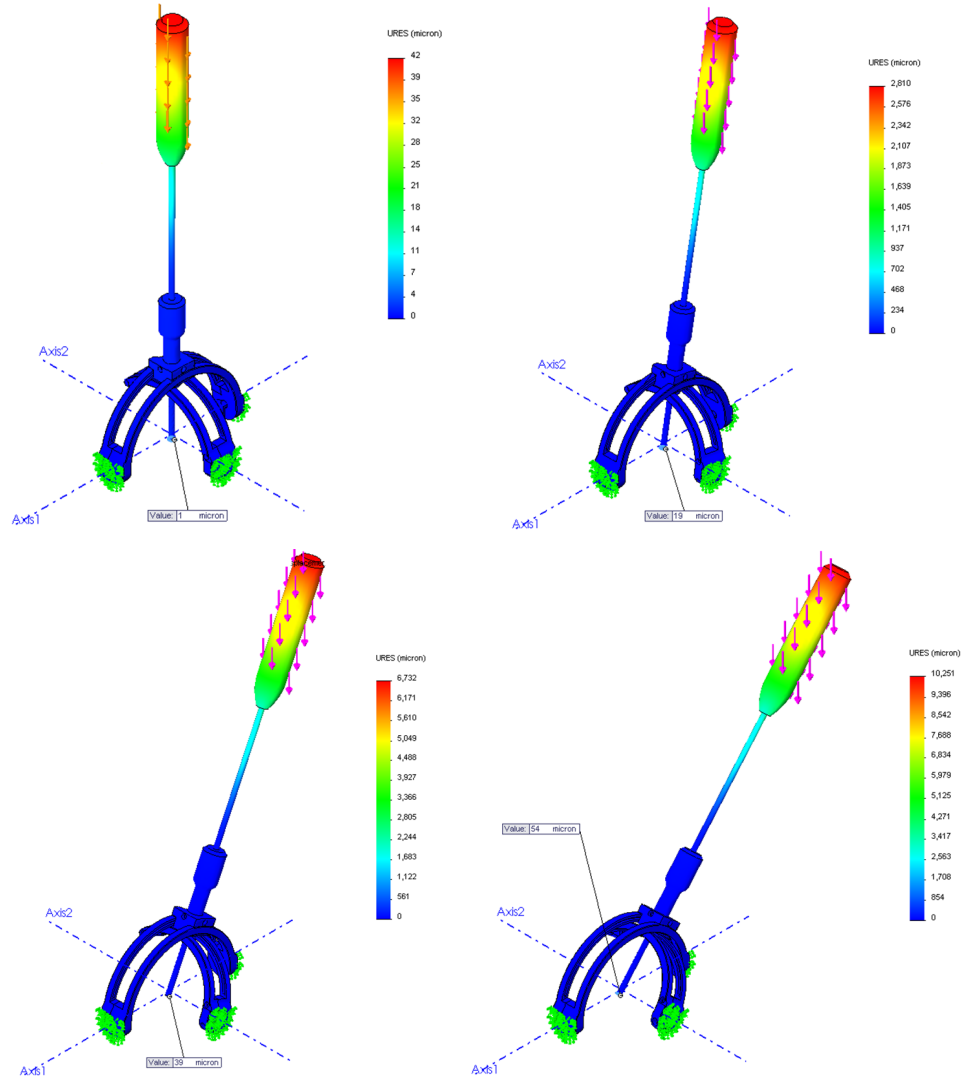


Figure 5.4: LapaRobot FEM Static Displacement Analysis for Various Tilt Angles with a 10N Applied Force: (Top Left: 0°, 10N); (Top Right: 10°, 10N); (Bottom Left: 25°, 10N); (Bottom Right: 40°, 10N)

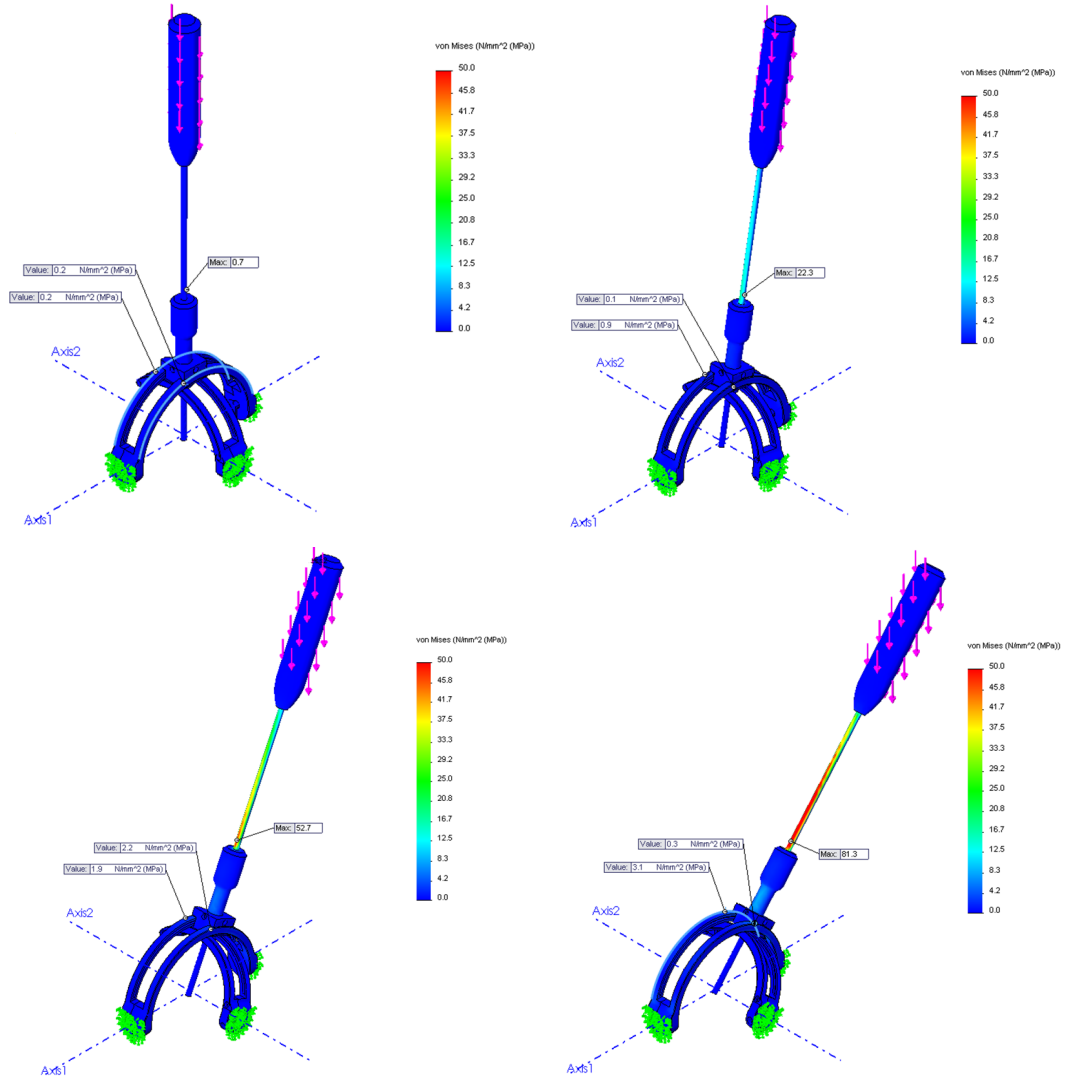


Figure 5.5: LapaRobot FEM Static Stress Analysis for Various Tilt Angles with a 10N Applied Force: (Top Left: 0°, 10N); (Top Right: 10°, 10N); (Bottom Left: 25°, 10N); (Bottom Right: 40°, 10N)

Taking a closer look at the 60° case seen in Figures 5.6 and 5.7, we can visualize the displacement and the stress of the LapaRobot subsystems.

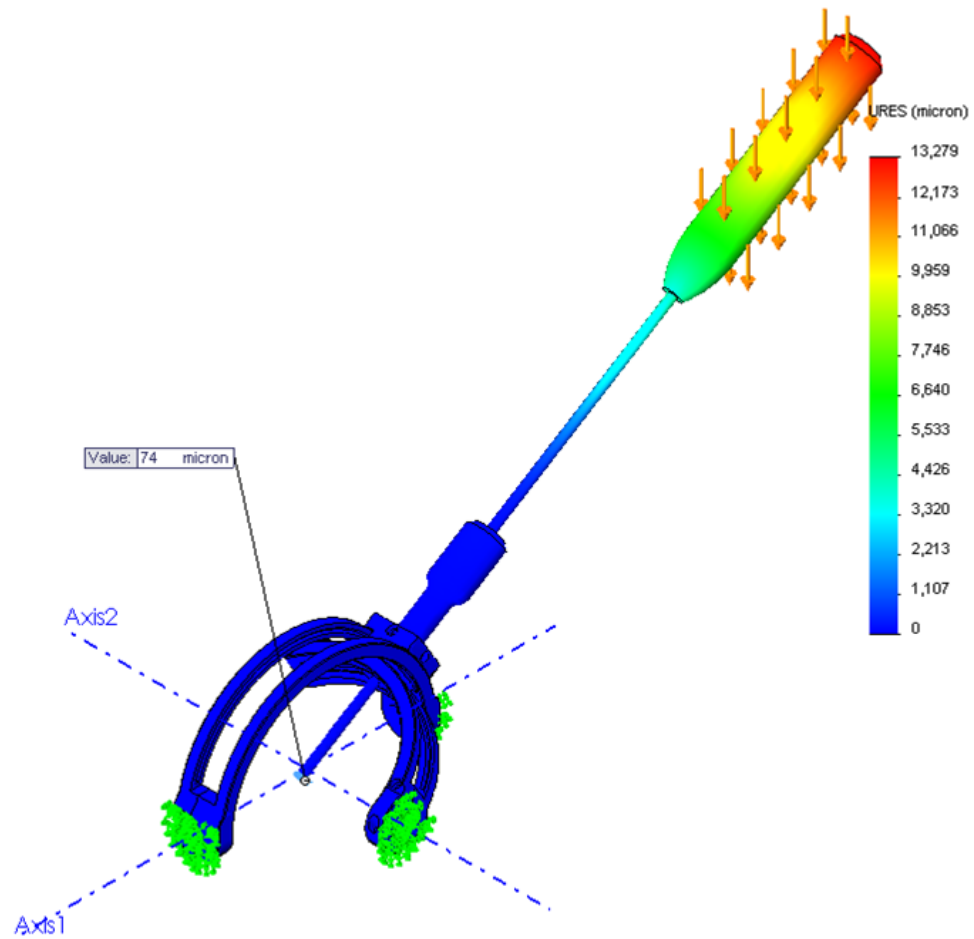


Figure 5.6: FEM Static Displacement Analysis at 60° with a 10N Applied Force

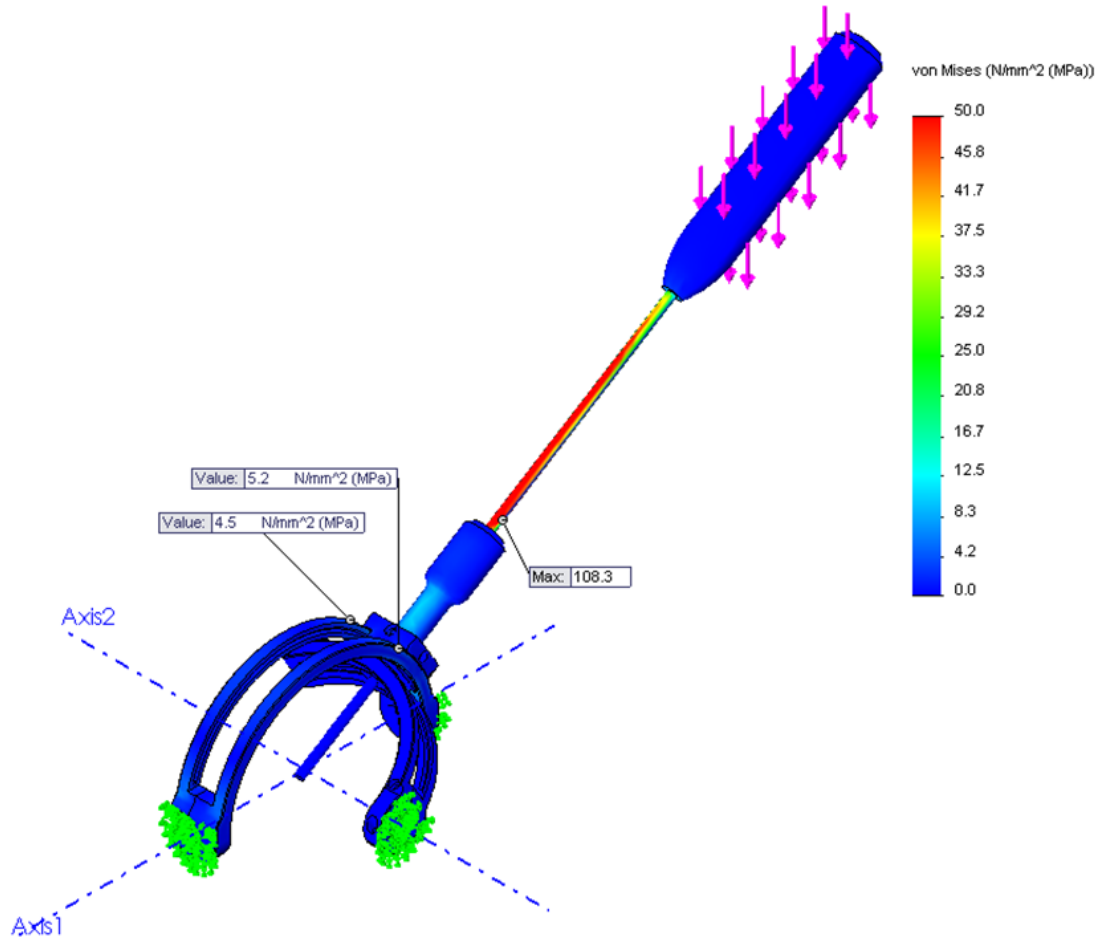


Figure 5.7: FEM Static Stress Analysis at 60° with a 10N Applied Force

Using MATLAB, we can fit a set of data points to a polynomial. To do this we are to model a curve to fit the data using the least squares polynomial method. Recall that the equation for a polynomial line is:

$$f(x) = a_0x^n + a_1x^{n-1} + a_2x^{n-2} + \dots + a_{n-1}x + a_n \quad (5.1)$$

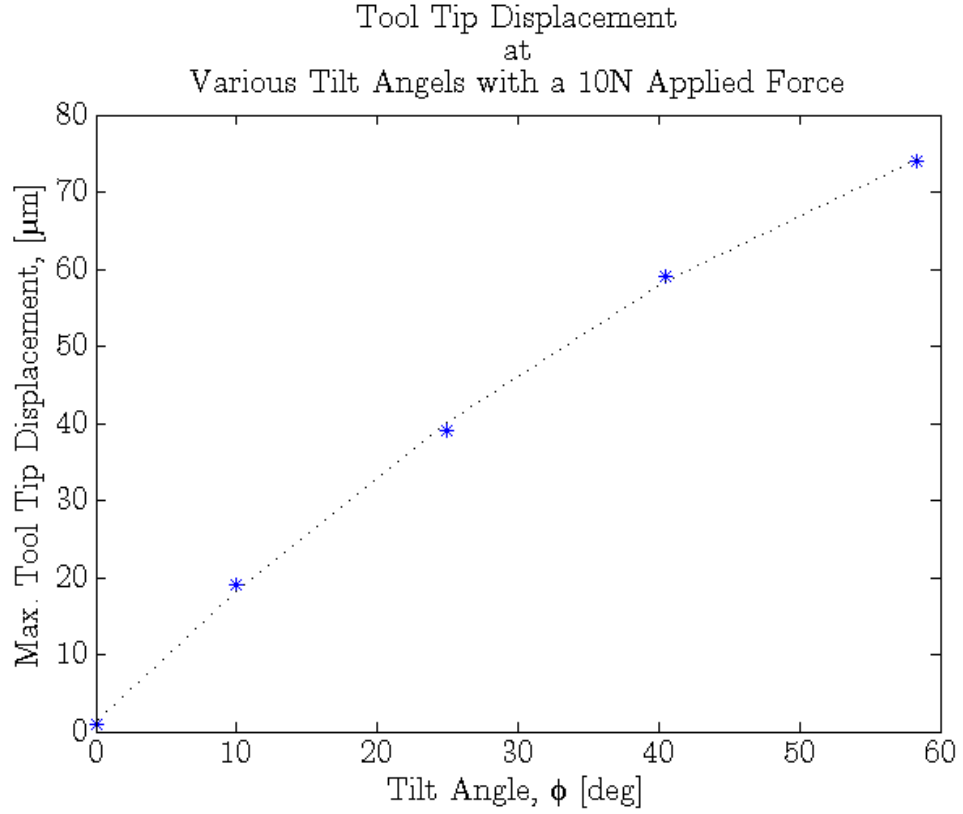


Figure 5.8: Tool Tip Displacement for Various Tilt Angles with a 10N Applied Force Plot

The equation for the curve fit of the displacement data is $y_{displ.}(tooltip) = -0.0091x^2 + 1.7798x + 1.2849$. For the given input tilt angles and applied load of 10N, the tool tip displacement has a minimum value of $1\mu\text{m}$ and maximum value of $74\mu\text{m}$. If we recall from the Design Requirements' chapter the maximum allowable tool-tip displacement, we will see that the displacements are well-below the 1mm requirement.

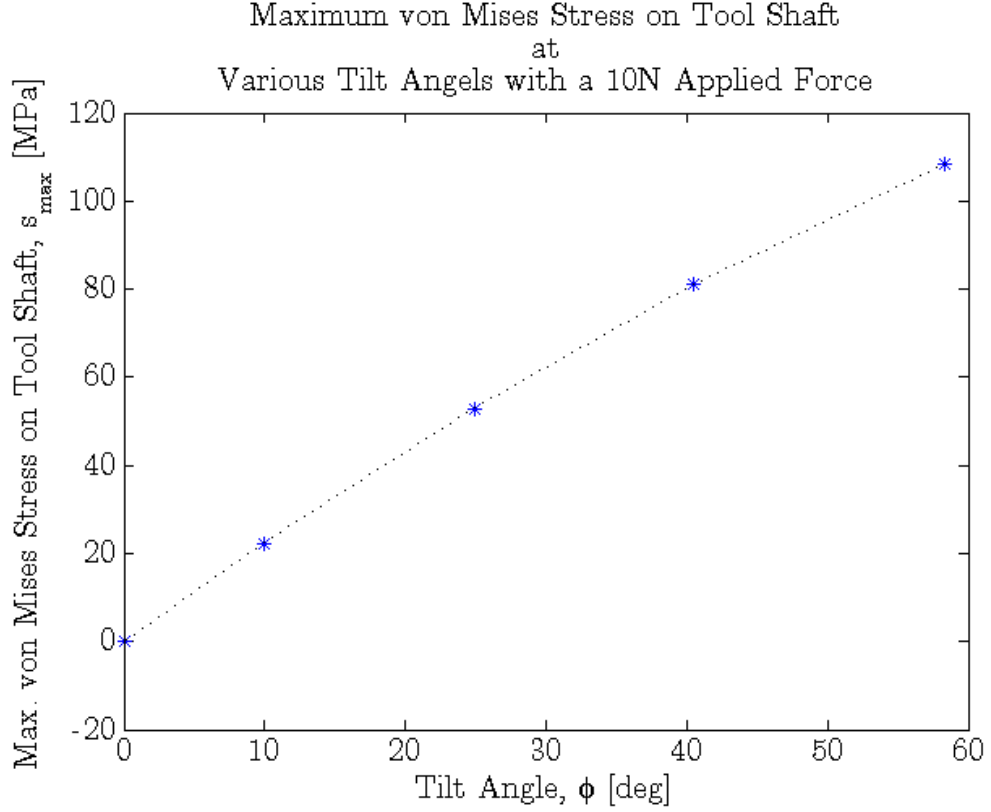


Figure 5.9: Maximum von Mises Stress on the Tool Shaft at Various Tilt Angels with a 10N Applied Force Plot

The equation for the curve fit of the maximum von Mises Stress on the tool shaft is $y_{s_{\max}}(tool\ shaft) = -0.0075x^2 + 2.2927x + 0.4428$. The maximum von Mises Stress on the instrument shaft is $s_{\max} = 108.3MPa$. We recall from Table 5.3 that the yield strength for Aluminum 6061-T6 is around $275MPa$, which is nearly three times the maximum stress amount seen in the FEA; as such, the shaft does not come to close to yielding. Furthermore, the instrument shaft was modeled as a *hollow* 6061-T6 aluminum shaft, but in fact, the part has a surgical steel insert housed within the shaft. This added material would increase the stiffness of the shaft even further. Note: The surgical steel insert was omitted

from the FEA model to save on computational cost.

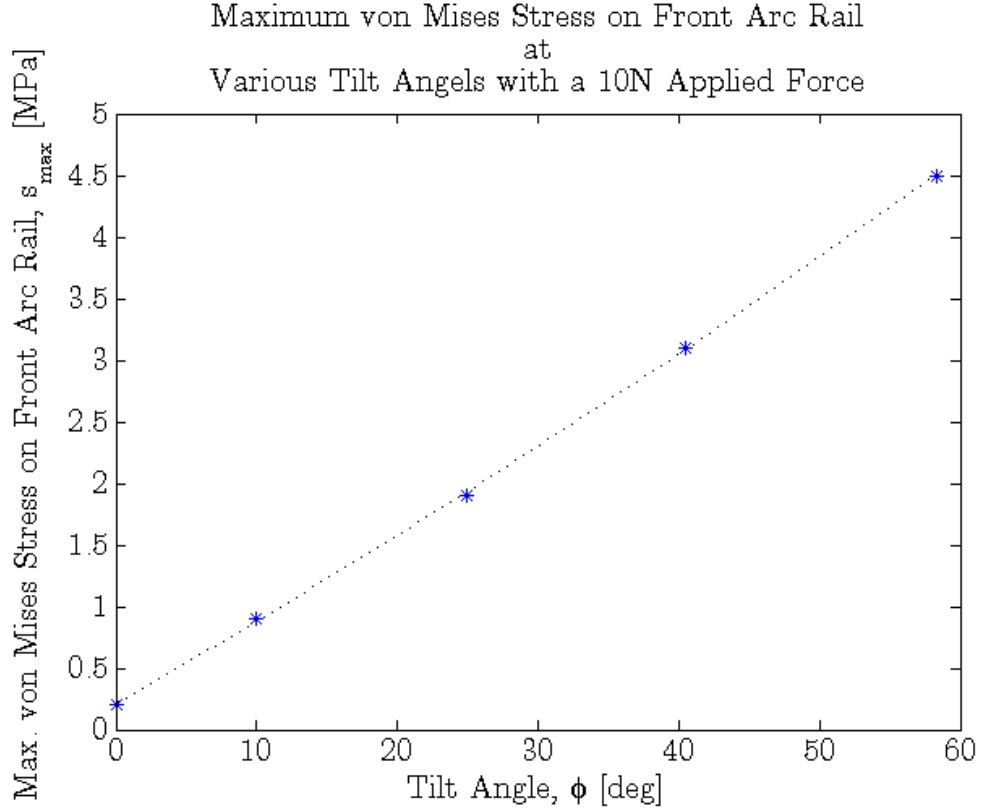


Figure 5.10: Maximum von Mises Stress on the Front Arc Rail at Various Tilt Angels with a 10N Applied Force Plot

The maximum max. von Mises Stress on the pitch (ψ) arc rail [throughout the entire swept angle motion] is $s_{max} = 4.5MPa$ Comparing this the yield strength of 6061 Al found in Table 5.1, we see that the arc will fail. The curve fit for the data is $y_{s_{max}}(arcrail) = 0.0001x^2 + 0.0654x + 0.2085$.

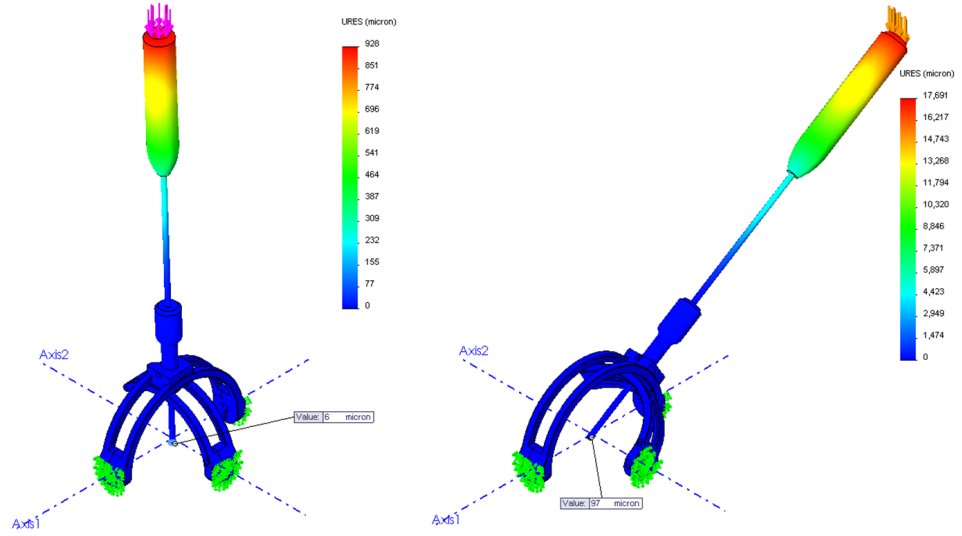


Figure 5.11: LapaRobot FEM Static Displacement Analysis for Various Tilt Angles with a $10N$ Applied Force at the Handle End: (Left: 0° , $10N$); (Right: 60° , $10N$)

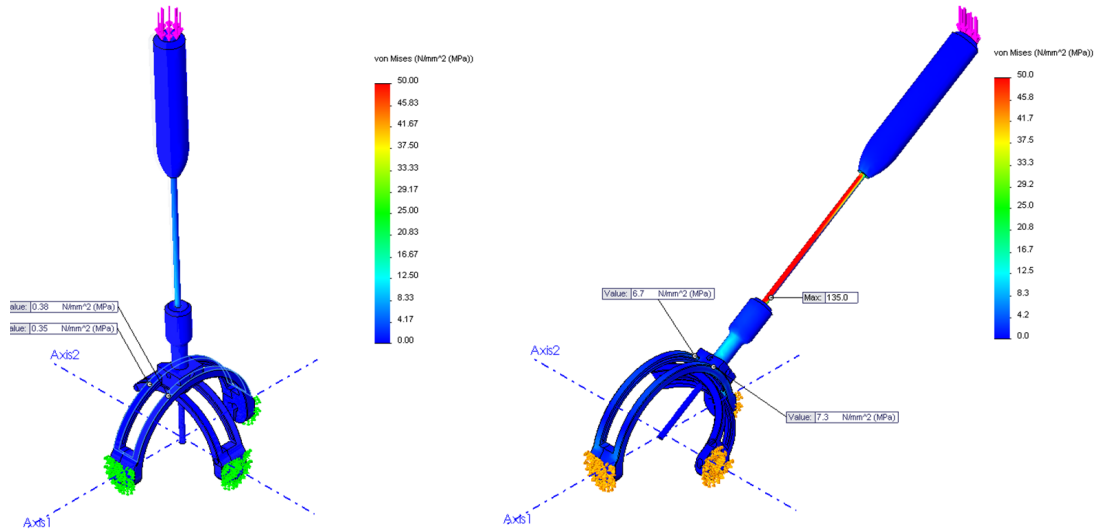


Figure 5.12: LapaRobot FEM Static Stress Analysis for Various Tilt Angles with a $10N$ Applied Force at the Handle End: (Left: 0° , $10N$); (Right: 60° , $10N$)

5.1.2.2 Maximum Displacement & Stress Analysis at 0° & 60° Angles with a $100N$ Applied Force

The following analysis is an extreme scenario case, where a dangerous $100N$ force is given to the LapaRobot system, and we wish to determine if any yielding and/or fracture occurs to the mechanical components. The $100N$ magnitude force was chosen as an extreme applied force for two reasons: one, this amount is ten times the normal operating forces permitted for the LapaRobot system; and two, the average mass of an adult human arm is approximately $3.35kg$ or $7.39lbs$; which translates into a $32.86N$ applied force to the system [38]. With the arms resting on the laparoscopic instruments]—and by using a factor of safety of three, a an applied force of $98.58N$ [$100N$] is given. In isolation, we will only look at the 0° and 60° tilt angle positions. Also, the force applied to the handle is now placed at the handle end (closest to the wrist), as compared to the previous used distributed force. The static displacement and static stress plots can be seen below.

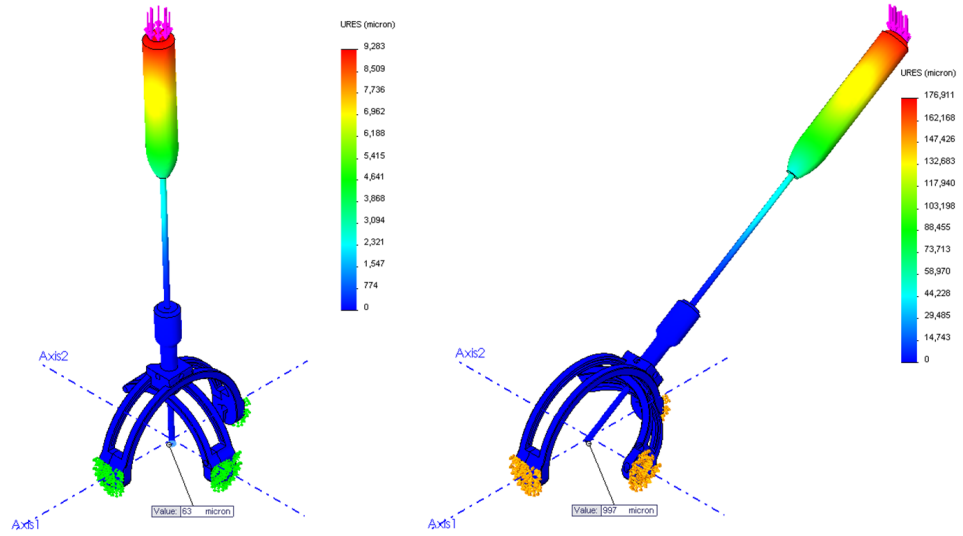


Figure 5.13: LapaRobot FEM Static Displacement Analysis for Various Tilt Angles with a 10N Applied Force at the Handle End: (Left: 0°, 100N); (Right: 60°, 100N)

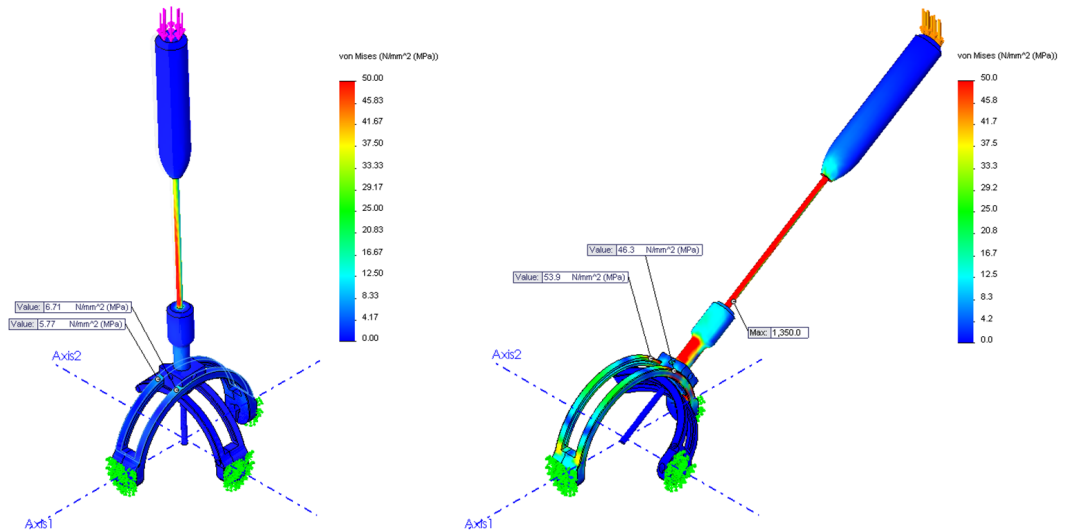


Figure 5.14: LapaRobot FEM Static Stress Analysis for Various Tilt Angles with a 100N Applied Force at the Handle End: (Left: 0°, 100N); (Right: 60°, 100N)

Looking closer at the 60° - $100N$ displacement/stress case, we can clearly see that many components reach and pass their plastic yielding point(s); which will result with the mechanism failing. Furthermore, the tool shaft and arc slider components surpass their respective ultimate strengths and if strained long enough will fracture.

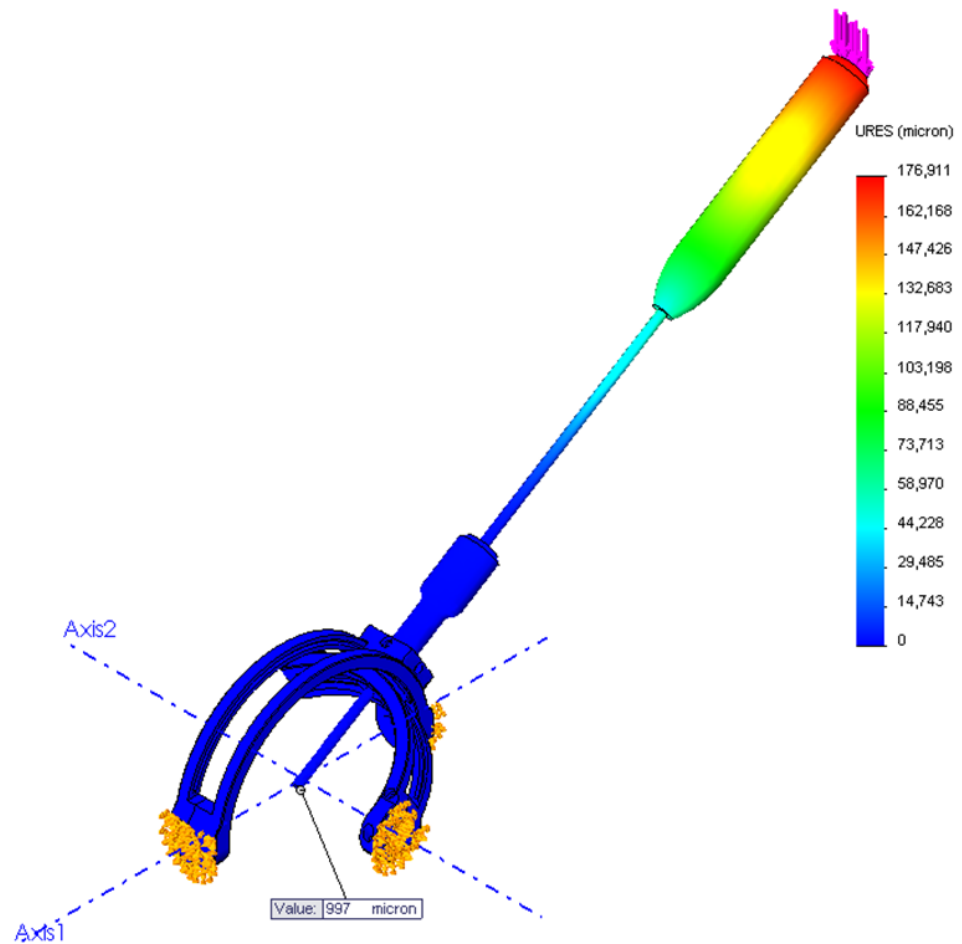


Figure 5.15: FEM Static Displacement Analysis at 60° with a 100N Applied Force

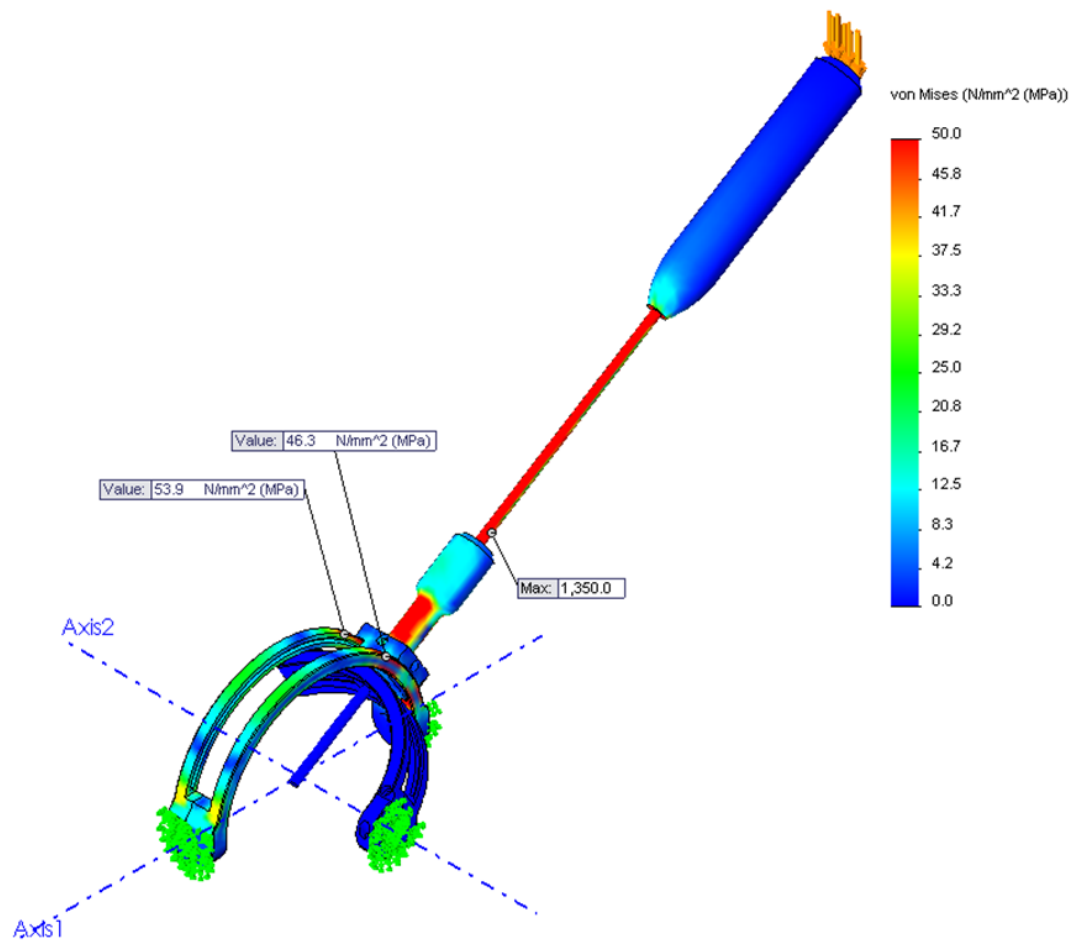


Figure 5.16: FEM Static Stress Analysis at 60° with a 100N Applied Force

5.1.3 Motor Torque Verification

In order to determine the minimum required motor torques for moving the two spherical arcs, a motion analysis study was conducted. Due to the geometric complexity of the system, we used a simulation analysis tool (Solidworks Motion Analysis) to determine the forces and torques as function of position of the arcs. Since the two spherical arcs are configured as a parallel-link mechanism for holding and manipulating laparoscopic tools in two planes [creating a remote center of motion], it is highly desirable to verify the maximum torque output as the spherical arc motor(s) sweep through their usable range of motion. Since the roll arc transmits motion co-planer to the yaw arc and carries the primary weight of the system, we need to verify the maximum loaded torque at the shaft of the roll arc's motor-with the following conditions defined:

1. Materials Properties: the mass of the system
2. Applied Forces: forces on the hand controls
3. Model Properties: mates, friction forces

To do so, we would need to account for, define, and apply appropriate friction conditions to all active components in the model. This means the simulation must include and accurately display both the theoretical and experimental friction coefficient(s) (see Table 5.4) for bearings, bushings, and applied contact materials. To validate our motor selection, we can then compare the torque values to the known torque quantities for the spherical motors.

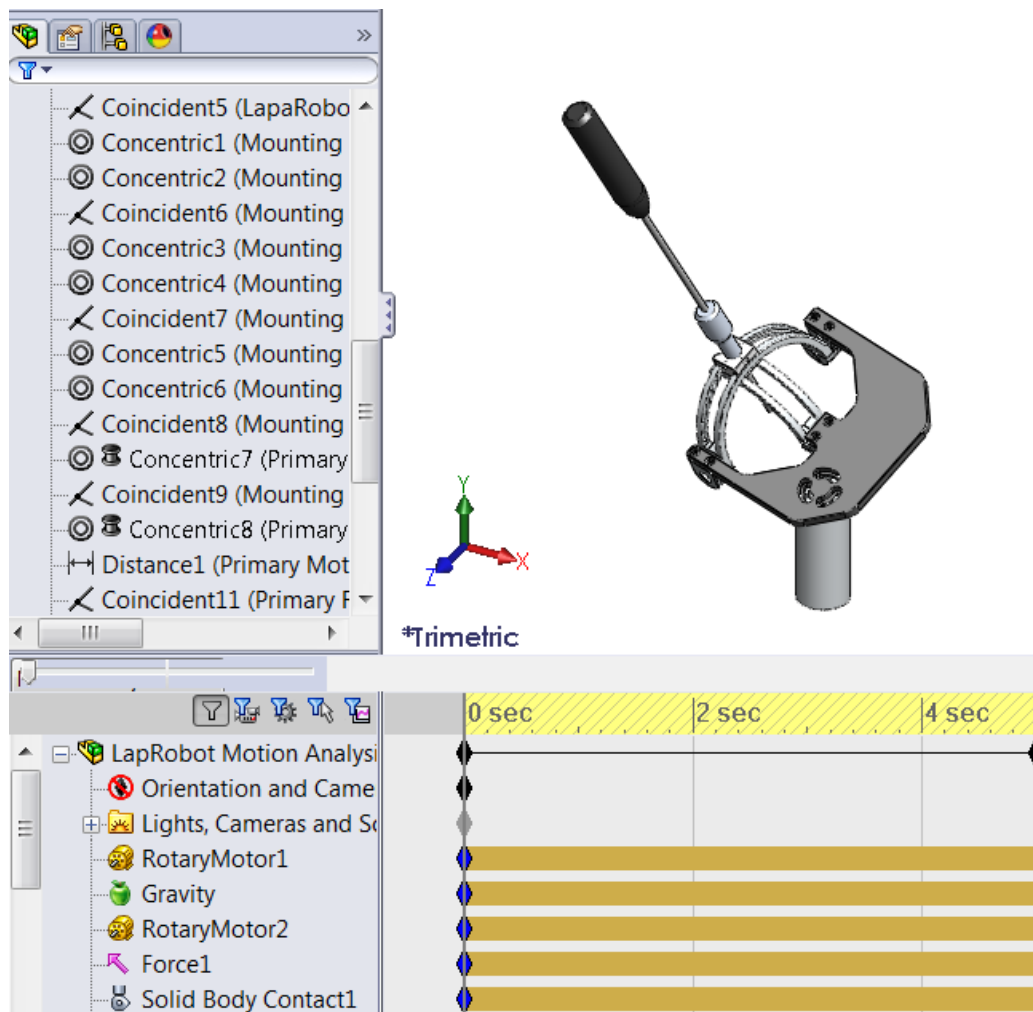


Figure 5.17: Motion Study Simulation Setup

Table 5.4: Friction Coefficients for Different Surface-Contact Materials Affected by Dry and Greasy Surface Conditions

Material 1	Material 2	Coefficient of Friction			
		<i>Dry</i>		<i>Greasy</i>	
		Static (μ_s)	Sliding (μ_k)	Static (μ_s)	Sliding (μ_k)
Aluminum	Aluminum	1.05 – 1.45	1.4	0.3	-
Aluminum	Brass	0.60	0.45	-	-
Aluminum	Delrin	0.13	0.09	0.05	0.03
Steel	Delrin	0.13	0.09	0.04	0.04

Using the information in Table 5.4, we can define (assembly mates or model properties) for each interacting component in the simulation model; namely, the friction in the motor mount bearings and the drag or bushing surfaces in the motors. The Motion Study elements that are required for the study are: Rotary Motors (yaw and roll arc motors), Gravity, Applied Forces (instrument handles), and Solid Body Contacts (contact surfaces between the pitch (ψ) arc and castor slider). Note: Motor elements only apply motion to components and mass and inertia are not considered. After implementing all of the above, the following torque output plot of the roll arc motor is obtained.

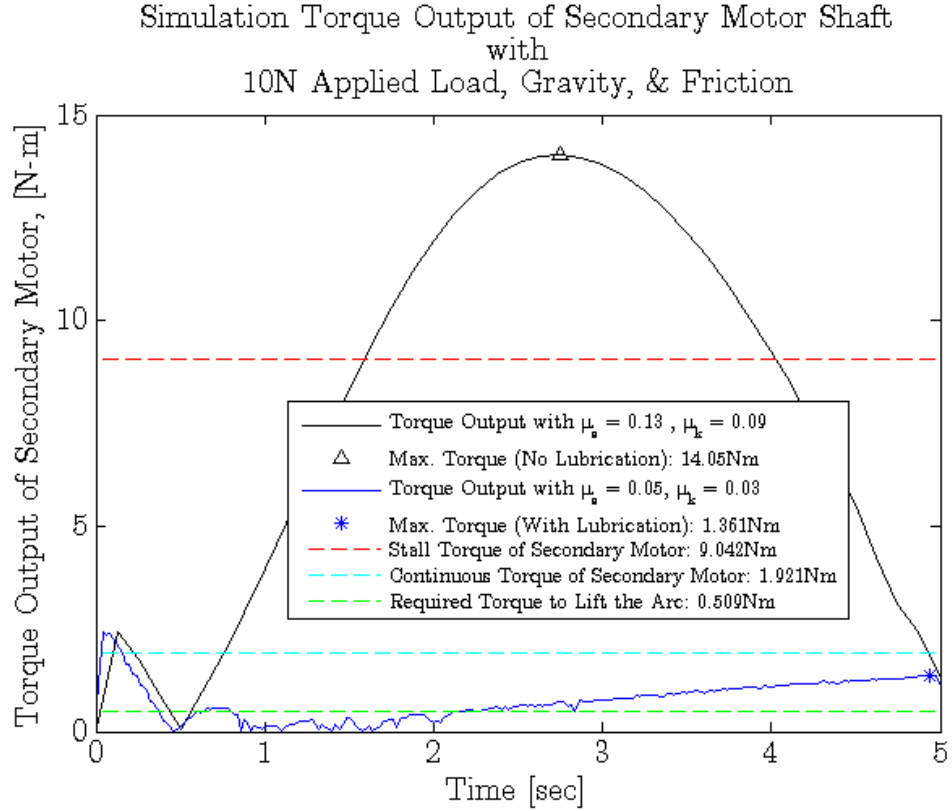


Figure 5.18: Simulation Torque Output of Roll (ϕ) Motor Shaft with a 10N Applied Load, Gravity, and Friction

The results show that if no grease or lube is applied to the arc surfaces, the roll (ϕ) motor would not have sufficient torque to lift the LapaRobot arm. These findings were further validated experimentally, as the motors do in fact, stall in the absence of lubrication. To decrease the coefficient of friction between the aluminum arc and the plastic slider components, we used DuPont's™ Teflon® dry, wax lubricant. From Chapter 4, we recall that the torque required to lift the arc is roughly $0.5Nm$; we also recall that the shaft output torque, or continuous torque for the pitch (ψ) and roll (ϕ) motors is $2Nm$ with a stall torque of $9Nm$. Comparing given motor torque values to the calculated minimum required torque

in Figure 5.18, we can clearly see that the motion analysis correctly predicted the experimental findings and furthermore, the use of Motion Analysis tools is shown to be very instrumental to estimate realistic minimum motor torque values.

CHAPTER 6

Manufacture of the LapaRobot

6.1 Introduction

The LapaRobot system requires precision components for its motion mechanisms to function properly. In order to obtain these tight tolerance bands, the manufacturing process required high precision CNC machines coupled with knowledgeable operators and CAM programmers. Our laboratory utilizes a Mori Seiki SV-50 milling center as well as a Mori Seiki SL-150 lathe center. A variety of machining fixtures were also designed to supplement and aid in machining multiple components of the same type. That is, achieving repeatable tolerance for the master-slave components is a directly consequence of the machine setup.

Although the LapaRobot is a prototype, we made conscientious efforts to present it as much as a commercial product as possible-by constructing enclosures for all the electronics, concealing all wiring, and machining all parts with surface finish and aesthetics in mind. We also prepared manufacture drawings for all of the components and assemblies to facilitate future development and commercialization (See Appendix A). This chapter will discuss the challenges associated with the abovementioned and attempt to clarify the subtleties of the manufacture process.

6.2 Manufacture Case Studies

Using the *roll (ϕ) rotation arc* and the *sliding castor* components for machining examples, we can define the quality control for the material, dimensions, finish, and tolerance for a set of machining operations. To do so, we must recall the component parts and there corresponding engineering drawings.

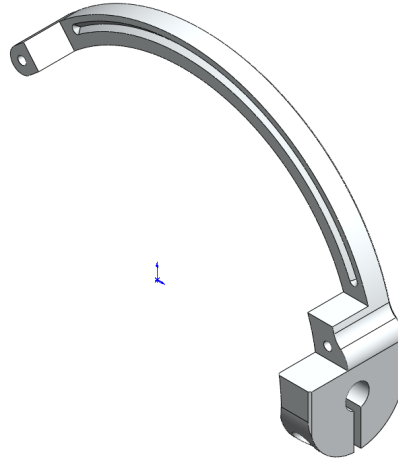


Figure 6.1: Roll (ϕ) Rotation Arc CAD Model

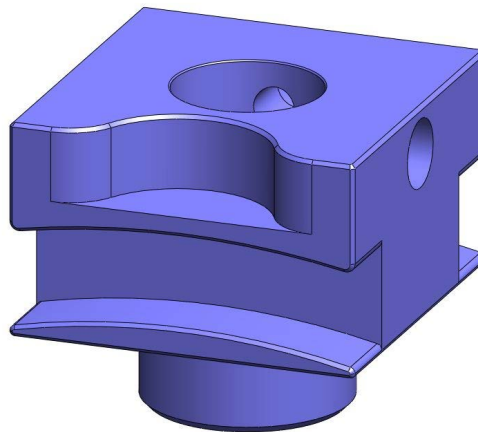


Figure 6.2: Sliding Castor CAD Model

The manufacture drawings for the *sliding rotation arc*, *Roll* (ϕ) are seen in Figures A.26a, A.26b, A.26c, A.26b on pages 207 - 210; whereas the the manufacture drawings for the *sliding castor* are seen in Figures A.28a, A.28b, on pages 213 and 214.

6.2.1 Roll (ϕ) Rotation Arc

In order to insure the laparoscopic tool is in the plane of each arc, the tolerance between the inner faces of the arcs must be within $+0.0000in$ to $-0.0025in$. This will allow for a running-fit (*slip-fit*) for the *slider castor* to move and transmit motion. Also important are the I.D and O.D's concentricity to the perpendicular AoR for both arcs. In other words, the pitch (ψ) rotation arc must be concentric to the AoR of the roll (ϕ) arc, and vise versa. The reason for this is that the remote center for each AoR must be in the same plane, thus allowing the tool to pass through the RCM. This means that the pitch (ψ) and roll (ϕ) motor mounts must also be aligned perpendicularly to one another. To achieve this accuracy, the following gross machining procedure was implemented:

1. Machine the face perpendicular to the AoR and parallel to the sliding face (Square face and defines part zero).
2. Drill/Ream hole for AoR
3. Machine contour profiles and drill/tap AoR pinch hole and arc insert bolting pattern
4. Flip part and face work-holding material.

The following display-state depicts the machining processes and the corresponding computer aided machining (CAM) programs that were implemented

for this part. We see that there are 5 breakdowns-setups that are required to machine the roll (ϕ) arc components.

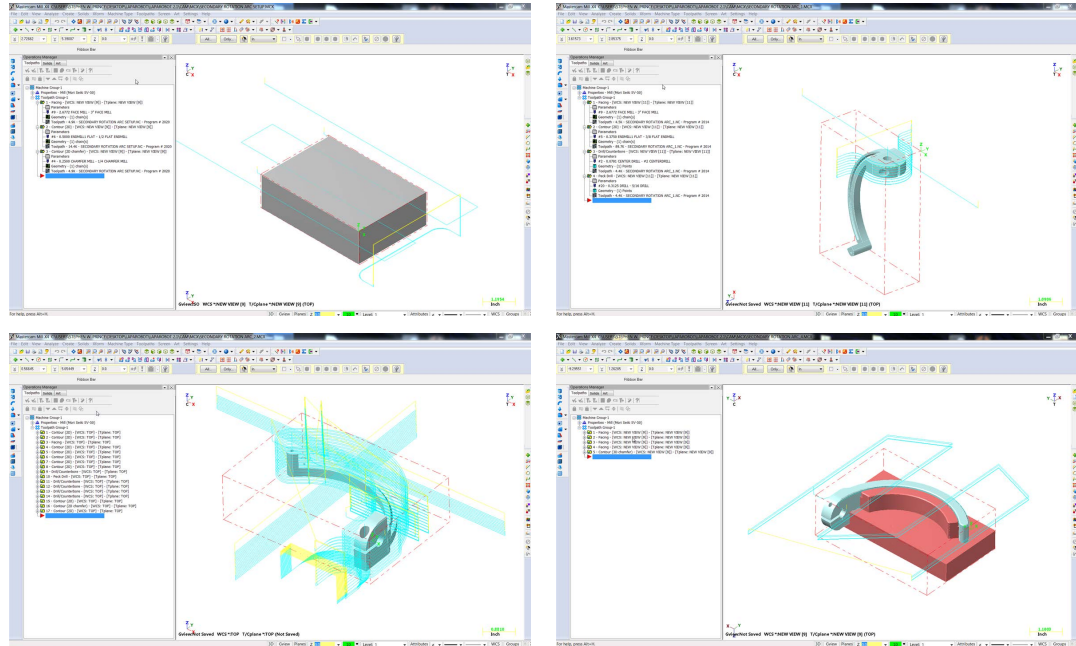


Figure 6.3: Machining Procedures for the Roll (ϕ) Rotation Arc: Top Left: facing and squaring procedure to create parallel edges; Top Right: facing/drilling/reaming to create AoR; Bottom Left: contour operations to create arc profiles; Bottom Right: facing operation to take away work-holding material

Taking a closer look at each machining procedure and their corresponding pre-processing procedures, we have the following:

1. Facing and squaring procedure to create parallel edges
2. Facing/drilling/reaming to create AoR
3. Contour operations to create arc profiles

- Fixture development and implementation

4. Facing operation to take away work-holding material

Step 1: Create Parallel and Perpendicular Edges for Reference Coordinate System

The first step in fabricating any part, regardless of its tolerance level(s), is to define a set of surface(s) that can be reference for every step (part breakdown) of the machining process. In other words, the referenced surface(s) must be known and controlled for each defined manufacture process or CAM program. For example, in Figure 6.4, we see that four coordinate systems exist; namely, the graphics origin (defined from the CAD model orientation and can not be changed), the cutting and tool origins (relative coordinates), and the part origin which is defined by the user). The user defined origin is seen in green and it is on the front face of the x-axis. One should notice that there are three operations that used to create part origin: facing operation, which creates a perpendicular face with respect to the cutting tool plane and work holding edge; side-cut operation: establishes an edge also perpendicular to the cutting tool plane and the work holding edge. The difference being is that the side-operation is performed so that a perpendicular z-coordinate is established for subsequent machining step (i.e. to create tangent surface for the tool).

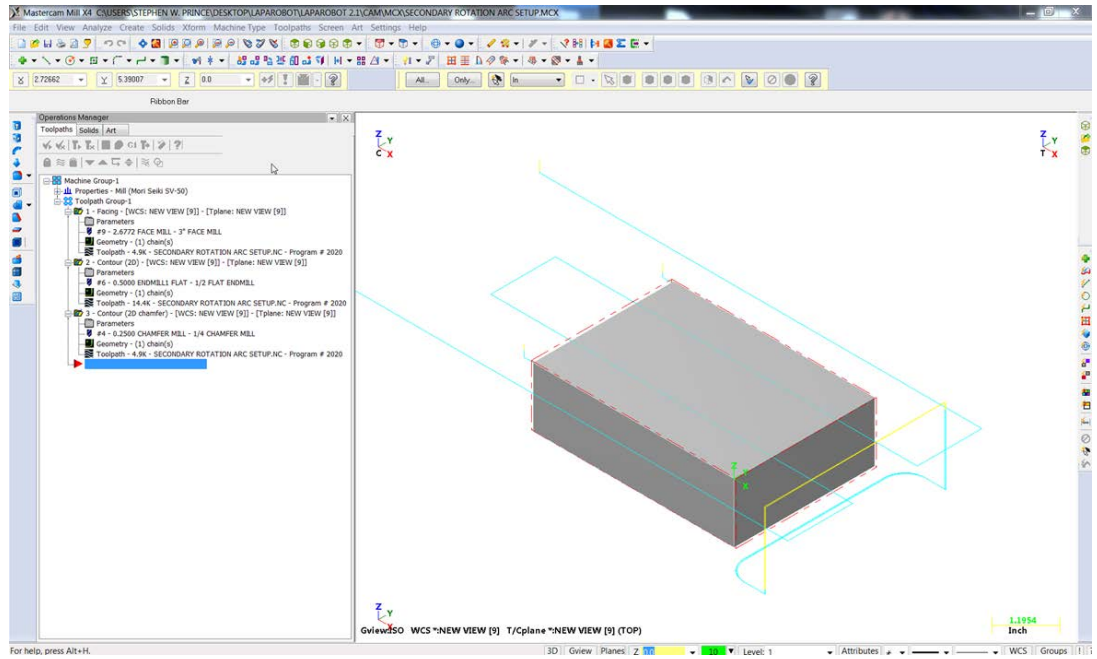


Figure 6.4: Step 1: Machining Procedure for the Roll (ϕ) Rotation Arc

By rotating the part 90° around the positive y-axis and the positive z-axis, we can use the machined faces (z-x edges) created in Step 1 for our y-z origins in the next step. The orientation for this setup is seen below:

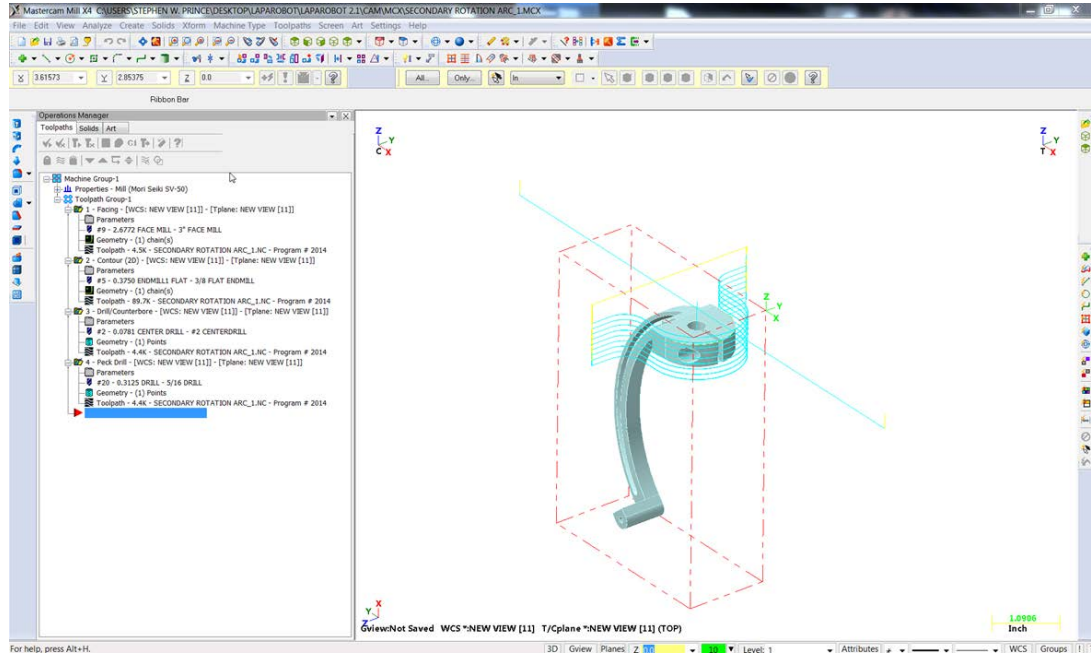


Figure 6.5: Step 2: Machining Procedure for the Roll (ϕ) Rotation Arc

Step 2: Create the Roll (ϕ) Arc Axis of Rotation (AoR)

In this step we are to create a face that is perpendicular to the AoR; create the AoR, and a contour that surrounds the AoR. To do this, we are to face the top surface [which is now parallel to the bottom work holding surface created in Step 1) and then commence with center drilling, pilot drilling, reaming of the AOR. A reamer is chosen because the I.D. hole call-out needs to have at least a 30μ in *RA* [surface finish] so that the motor shaft coupler is able to slide on easily and fit within the tolerance specification(s). The contour for the AoR—along with a chamfer call-out are machined last for this setup.

Step 3: Create the Surface Profile for the Roll (ϕ) Arc

For the third step, we will again use the machined surfaces in Step 2 to establish coordinates zeroes for our next set of operations. The part zero for this setup is

defined using the right-hand coordinate system again: rotate the part 90° around the negative x-axis and then the positive z-axis. The next eight operations belong to a category of machining called roughing; in that, in order to obtain good circularity for the arc (ϕ) profile contour, sufficient material must be removed prior to making a final finish pass. Roughing and finish pass quantities (depth of cut and spring pass amount) are dictated by the machine tool and the machine being used. Typically, larger diameter cutters are used for roughing, while smaller diameter cutters are used in finish work. The quality of the surface finish is a factor of the machine tool, as well as the spindle speed (plus spindle power) and the axes feed rate. For the Mori Sieki SV-50 milling center, we are able to run at a max spindle speed of $8,000rpm$ at power close to $6.5HP$. Using appropriate cutters, while increasing the spindle speed and lowering the feed rate, we are able to obtain surface finishes in the range of $20 - -35\mu$ in *RA* and tolerances bands around *H9/H10*. The rest of the machining procedures are for the pinch clamp that secures the motor coupler to the arc are omitted for brevity. The most important stage for this setup is the z-height offset definition; that is, the machine tool that cuts the contour finish pass needs to be the same machine tool that machines the final depth dimensions. This method produces less error compared to using separate tools (The actual error produced will be covered in the Chapter 7).

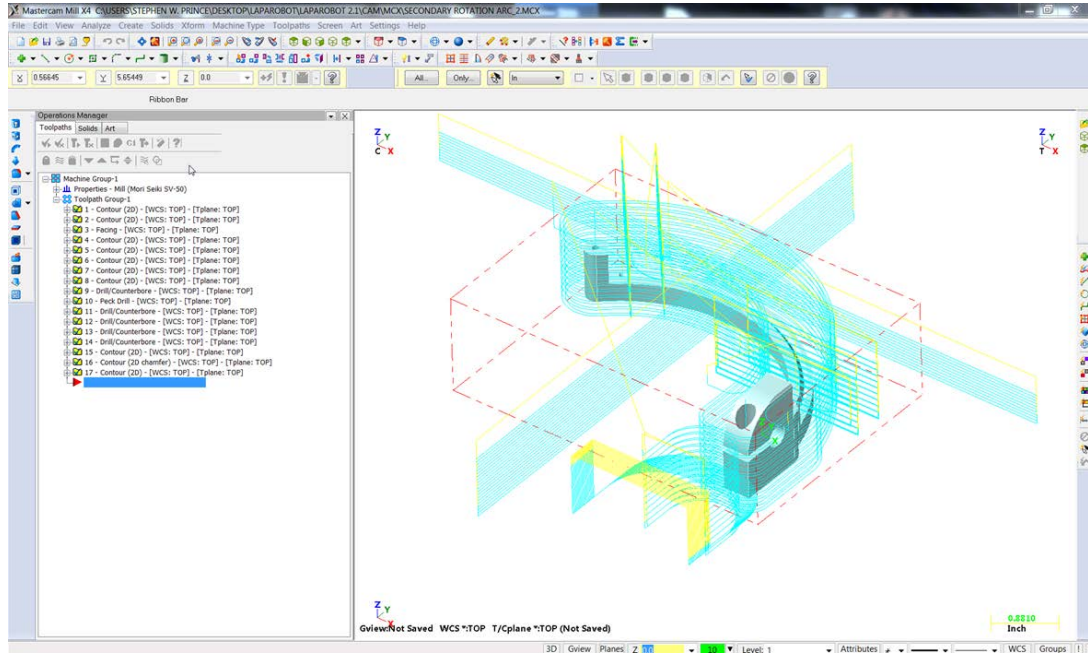


Figure 6.6: Step 3: Machining Procedure for the Roll (ϕ) Rotation Arc

Step 3.5: Create a Work-Holding Fixture (Jig)

To complete the last step (removal of the working holding fixture), fixtures were fabricated so that the parts could be indicated to a known coordinate system; while providing a holding solution for the arc. Simply put, there not a sufficient way of clamping the arc(s) in the machine vise, as their geometric shapes prohibit doing so. It is also important to note that fixture was not removed from the vise until all of the arcs were completed; this insures repeatability in position accuracy for the remaining three arcs. Similar procedures were implemented for the sliding castors and the majority of the components that make up the LapaRobot system. The orientation of the fixture setup can be seen in the figure below.

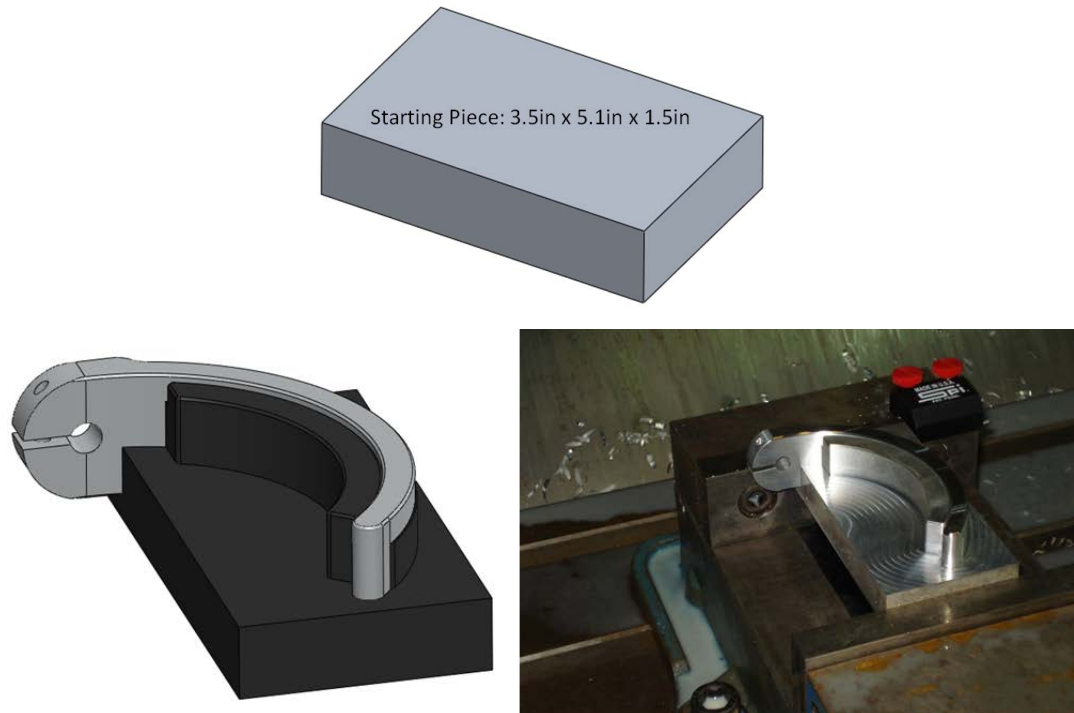


Figure 6.7: Fixture Setup for Machining the (ϕ) Rotation Arc: Top: Starting Stock Piece); Bottom Left: Machining-Fixture; Bottom Right: Vise-Machining Setup

Step 4: Remove the Work-Holding Material

The last step for the realization of the roll (ϕ) arc is a facing operation that removes the material that was used to hold the part in the previous setups.

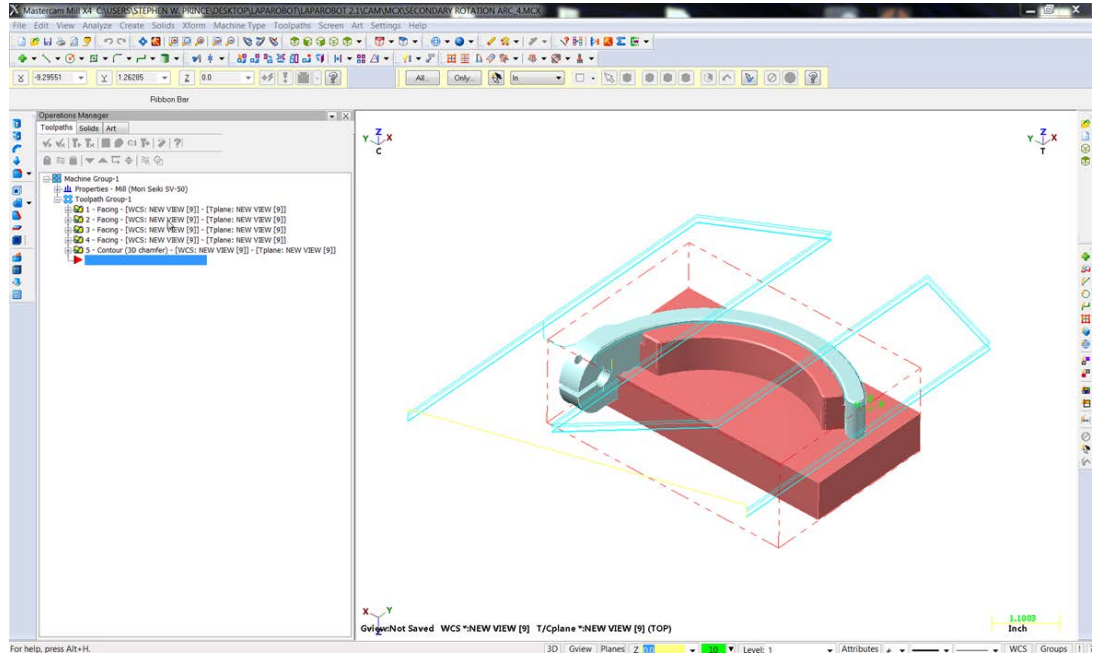


Figure 6.8: Step 4: Machining Procedure for the Roll (ϕ) Rotation Arc

6.2.2 Sliding Castor Component

The sliding castor component mates with the pitch (ψ) rotation arc I.D. and O.D. surfaces—allowing for a radial surface slip fit. This means the concentricity of the sliding castor needs to be within $+0.0015$ and -0.0000 tolerance band. Since the sliding castor component is to be made out of Delrin, we need to consider the machine tools used and the corresponding feeds and speeds. Contrary to traditional methods in machining, using a two-flute endmill instead of four-flute [with the airblow on (no coolant) and moderate spindle speeds and feedrates], will produce the best possible milled surface finish for Delrin plastics. Implementing the machining processes described above, we have the following machining procedures for the sliding castor components.

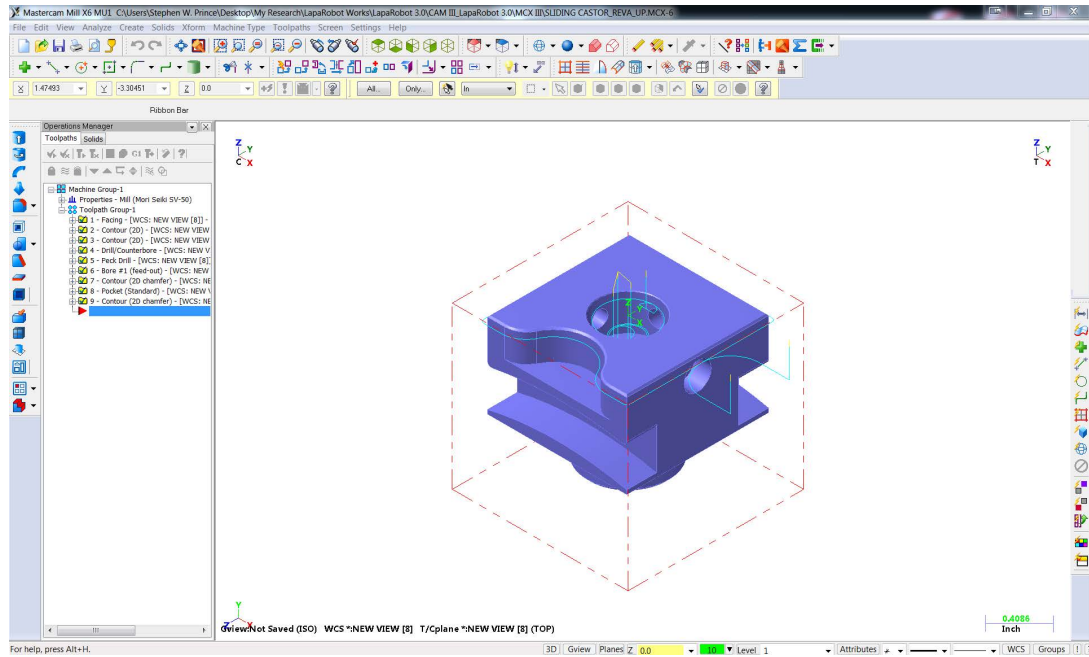


Figure 6.9: Machining Procedure the Sliding Castor: Top: facing and squaring procedure to create parallel edges and the AoR for laparoscopic tool

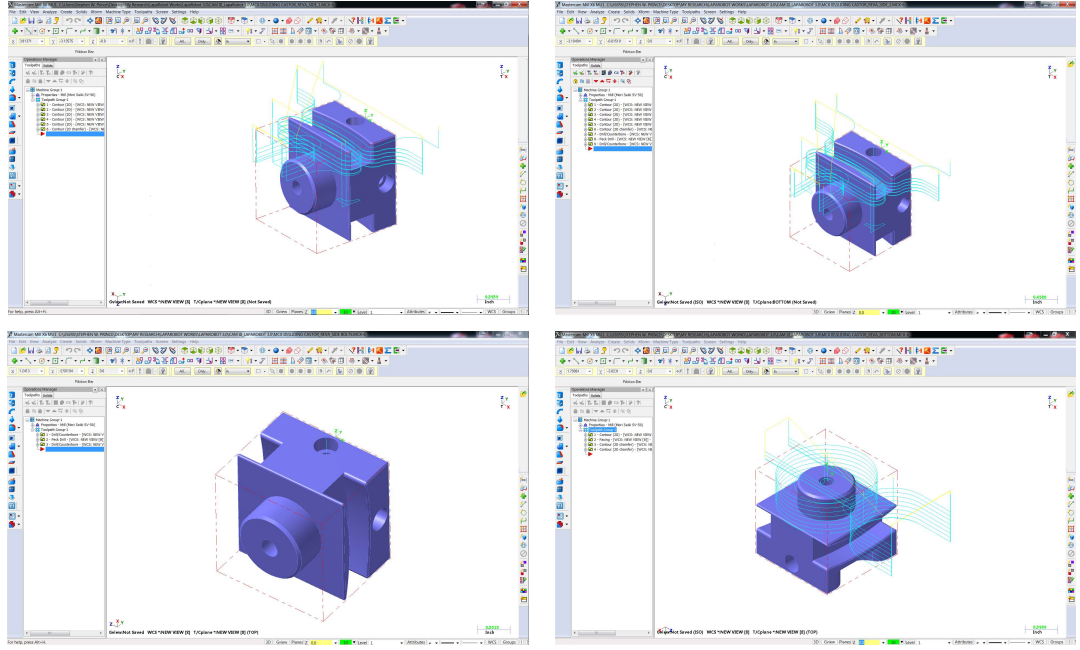


Figure 6.10: Machining Procedure the Sliding Castor: Left and Right: contour profile for the pitch (ψ) rotation arc surface contact and drilling operations; Bottom Left: drilling and counterbore operations; Bottom Right: contour profile for the roll (ϕ) rotation arc tangent sliding contact

The manufacture case studies given in this chapter include a gross overview of the machining practices used to realize the LapaRobot system. The fine details, including the dimensions, tolerances, geometric fit, surface finishes, revisions, etc. should be referenced from the engineering drawings seen in Appendix A of this dissertation. The CAM g-code is omitted for brevity, but all of the CAM programs should be referenced as needed. A tolerance Error classification is included in next separate chapter; in this chapter, an overview of error classification, along with some object lessons showing the propagated error and tolerance stack-up of a few components is given.

CHAPTER 7

Manufacture Process Error Classification

7.1 Introduction

In this chapter, the link between manufacture machining errors and the associated tolerance stack-up or error propagation in assembled components for the LapaRobot design is discussed. A standard for precision manufacture techniques and methods that control tolerance in production planning is also presented. The reason for this investigation is that most machining processes involve many machining operations containing various locating datum features that control the part manufacture quality. For simplicity, these systems will be referred to as multi-setup or multi-breakdown component/parts. Furthermore, errors in machining could originate from a variety of factors, which include, but are not limited to, the geometric and kinematic errors of machining equipment, thermal errors, static and dynamic errors, machine tool wear, and most significantly, the operational error of the part setup [39]. It becomes apparent that a complex non-linear relationships exist between the computational geometry formed by the CAM software and the end-user. This however does not preclude this research from recognizing that a skilled technician is required to realize accurate parts.

7.2 Propagation of Errors

7.2.1 Significant Figures

Whenever a measurement is made, there is a corresponding number of significant digits or [meaningful] digits that correspond to the error in the measurement. This principle is best made clear through an example. For example, if one is to measure the length of a component and the length of that measurement is called out to be $0.627in$, the implied uncertainty would be $0.001in$. On the other hand, if the measurement was recorded as $0.6in$ or even $0.6275500in$, the corresponding uncertainties would be $0.1in$ and $0.000001in$, respectively; however, the estimated error for both cases are significantly different. Even though the hypothetical measurement $0.627in$ has three decimal places, its three significant figures are not related. Furthermore, if one was to convert $0.627in$ into SI units, that value would translate to $15.9mm$ and not $15.9258mm$. Traditionally, only one uncertain digit is reported for a given measurement, but we will see that this is not always the case. In the example above, if we were to take the implied uncertainty as the estimated error, we would report the measured quantity as $0.627 \pm 0.001in$.

7.2.1.1 Absolute and Relative Errors

In manufacturing, absolute error is the amount of error in a physical measured quantity. In other words, the absolute error is the uncertainty in the quantity being measured and it always has the same units as the quantity. An example is drawn from the following pair of digital calipers: Mitutoyo ABSOLUTE Caliper Series 500



Figure 7.1: Mitutoyo ABSOLUTE Caliper Series 500 [40]

Range: $0 - 0.8in \mid 0 - 200mm$

Resolution: $0.0005in \mid 0.01mm$

Repeatability: $0.0005in \mid 0.01mm$

Accuracy: $\pm 0.001in \mid \pm 0.02mm$

For the caliper above, the absolute error is the accuracy for the measuring device, namely $\pm 0.001in \mid \pm 0.02mm$. In terms of the error propagation, the absolute error for the caliper is equal to Δx .

$$Absolute\ Error = \Delta x \quad (7.1)$$

where x is linear distance.

The relative error is a dimensionless reading of how good a measurement is *relative* to the quantity of the measured object. The relative error is determined by dividing the absolute error of the measured quantity by the measured quantity.

$$Relative\ Error = \delta = \frac{\Delta x}{x} \cdot 100 \quad (7.2)$$

Returning to the example above, the relative error would be:

$$\delta_{ex} = \frac{0.001in}{0.627in} \cdot 100 = 0.159\%$$

7.2.1.2 Systematic Errors

By making the same incorrect measurement over-and-over again, the measurement will diverge systematically, or diverge from the correct measurement in the same direction. In other words, systematic errors always push results away in the same direction-as there is a flaw in the measurement strategy, and this error repeats each time a measurement is taken [41]. Examples of systematic errors include:

- The measuring equipment has not been calibrated or has fallen out of calibration specification(s)
- An incorrect measurement technique is being employed
- Experimental Drift: systematic errors which drift over time or between setup(s)
- Bias or Offset Error: A measurement error that remains constant in magnitude for all observations
 - Calipers have $+0.005in$ bias

7.2.1.3 Random Errors

Random errors are the [observed] changes or fluctuations in repeated experiments or measurements [41]. These uncertainties arise from a number of reasons, but most all of these uncontrollable fluctuations are from the process of the experiment, or in the case at hand, the manufacture setup. Some common sources of random errors include:

- Variations in Initial Conditions: Environmental (Temperature), Tool Wear, etc.

- Limitations in the Precision of the Measuring Equipment: Using a caliper when the measurement requires a micrometer
- Intrinsic characteristics of the measured quantity: Electrical noise

Estimating Errors: Supposing we have identified all sources of systematic errors and reasonably accounted for the random error of the configuration, we can now measure some unknown quantity x that we desire. Take for example, the yaw (θ) rotation motor mount, previously conceived, designed, and fabricated. This mount has multiple purposes and many important dimensions that are crucial for other *stacked* subassemblies to function properly. To name a few functions, the yaw (θ) rotation motor mount locates the insertion motor mount to the AoR and it also sets the offset between the insertion motor pinion and the insertion motor's rack. The yaw θ motor mount's geometric specifications and tolerances can be seen in its CAD engineering drawings found in Figures 7.3a, 7.3a on pages 111 - 112. From the drawings, we can take a series of measurements for important quantities and calculate the mean(s), $\bar{x}$ and the standard deviation(s), σ_x ; which are defined as,

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (7.3)$$

Where x_i is the i^{th} measurement and n is the number of measurements taken.

$$\sigma_x = \left(\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2 \right)^{1/2} \quad (7.4)$$

Combining equations 7.3 and 7.4, the measured value(s) can be expressed as

$$\bar{x} \pm \sigma_x \quad (7.5)$$

Equation 7.5 becomes a more exact representation of the true quantity of x [42, 43]. Also important to note is the standard deviation of the mean or the uncertainty in $\bar{x}$ [43].

$$\sigma_{\bar{x}} = \frac{\sigma_x}{\sqrt{n}} \quad (7.6)$$

We notice that as the number of measurements increases, the overall precision of the measurement also increases in proportion to $\sqrt{n}$ [42]. It should also be noted that there are theoretical arguments to be made for replacing the number of measurements n in Equation 7.4 with $n - 1$ and defining the standard deviation as seen in Equation 7.7, but for this research, the customary form of the standard deviation will be used [41, 44].

$$\sigma_x = \left(\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2 \right)^{1/2} \quad (7.7)$$

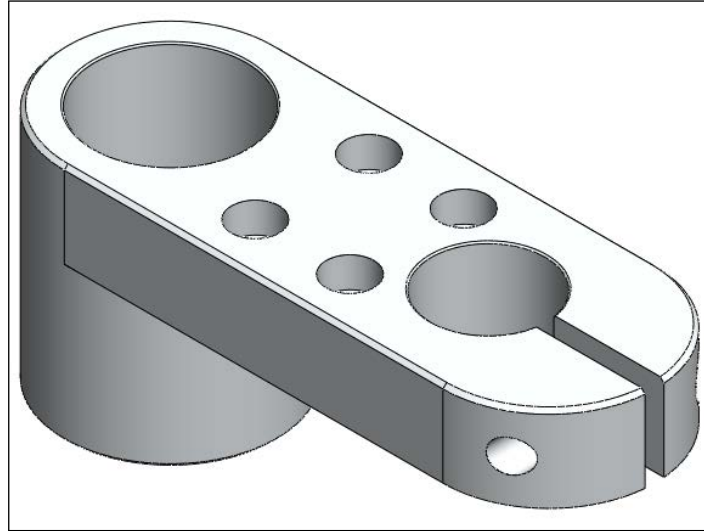


Figure 7.2: Yaw (θ) Rotation Motor Mount

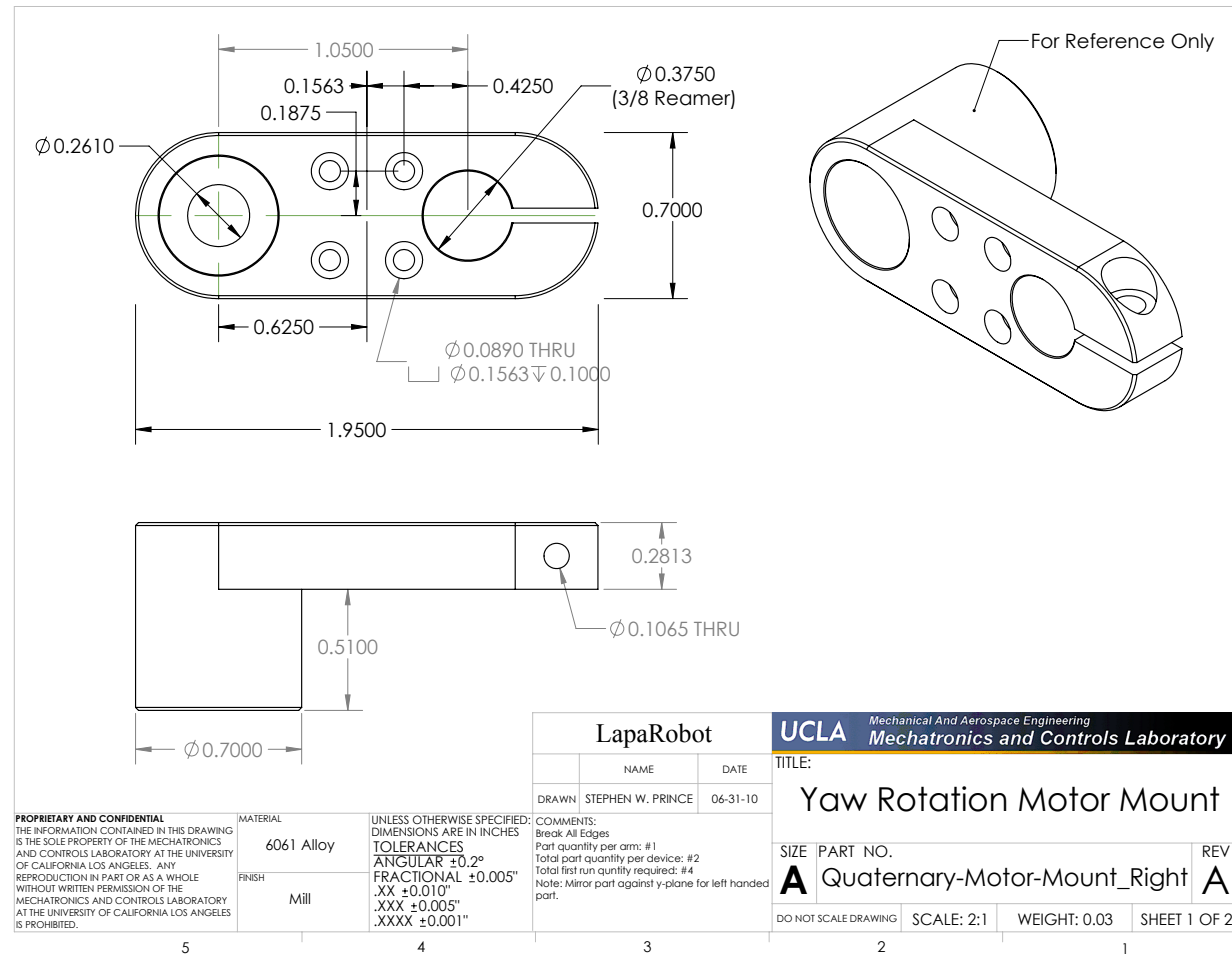


Figure 7.3a: Cutting Diaphragm CAD Drawing

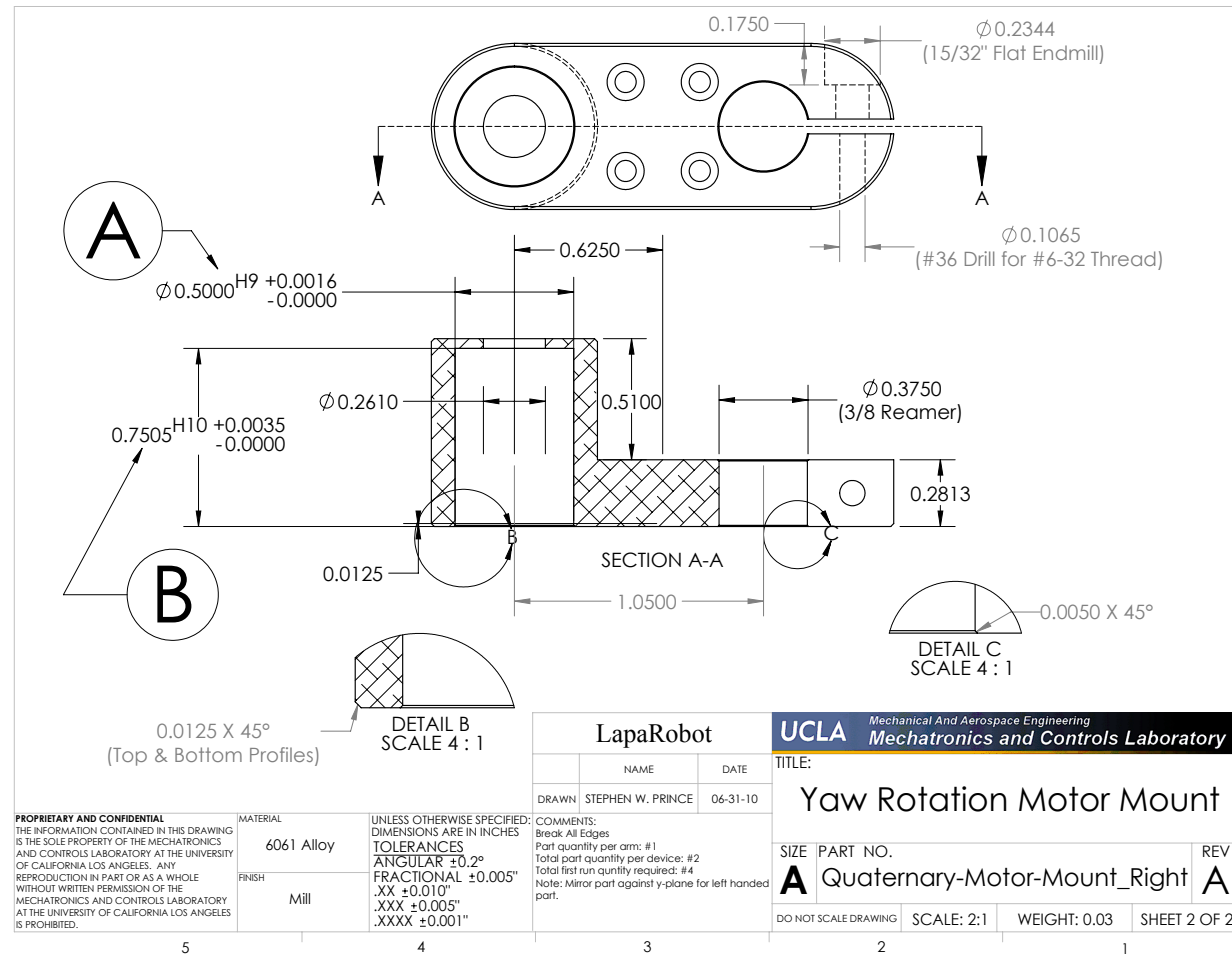


Figure 7.3b: Inner Diaphragm CAD Drawing

Table 7.1: Press-Fit Hole Measurements

<i>Dimension</i>	<i>Measurements with Measuring Equipment Uncertainty (Accuracy)</i>				
Type	Setup	Part #1	Part #2	Part #3	Part #4
Dim A [in]:	0.5012 ± 0.0002	0.5008 ± 0.0002	0.5002 ± 0.0002	0.5001 ± 0.0002	0.5011 ± 0.0002
Dim B [in]:	0.75055 ± 0.00012	0.75065 ± 0.00012	0.75065 ± 0.00012	0.75075 ± 0.00012	0.75075 ± 0.00012

Table 7.2: Averaged Measurements with Measuring Equipment Uncertainty
(Accuracy)

<i>Dimension</i>	<i>Averaged Measurements with Uncertainty</i>
Type	Measurements
Dim A (in):	0.5007 ± 0.0002
Dim B (in):	0.75067 ± 0.00012

Once the manufacture process was verified, 4 yaw (θ) motor mounts were machined and measurements were taken using a Mitutoyo micrometer depth gage ($\pm 0.00005in$ accuracy) for the depth measurements and Mitutoyo micrometer ($\pm 0.00012in$ accuracy) for the diameter measurements; these results can be seen in Table 7.1. A telescoping gage was planned to be used in conjunction with the above micrometer to measure the inner diameter. Note: This type of gage is spring loaded and touches the inner wall with two single point contacts. Once extracted, an inner diameter measurement can be taken by measuring the telescoped distance using the micrometer. However, since the tolerance band of the feature tolerance is very tight-coupled with the fact that the accuracy of the of telescoped gauge is 10 *times* ($\pm 0.001in$) less accurate than the measuring tool itself, a Mitutoyo bore gage with $\pm 0.0002in$ accuracy was utilized. All of these measuring devices have been calibrated and are seen below:



Figure 7.4a: Mitutoyo Micrometer Series 293 [40]

Range: $0 - 1in$ | $0 - 25mm$

Resolution: $0.00005in$ | $0.001mm$

Repeatability: with Ratchet Stop

Accuracy: $\pm 0.00005in$ | $\pm 0.001mm$



Figure 7.4b: Mitutoyo Micrometer Depth Gage Series 329 [40]

Range: $0 - 1in$ | $0 - 25mm$

- Rod length can be adjusted in $1in$ increments

Resolution: $0.00005in$ | $0.001mm$

Repeatability: with Ratchet Stop

Accuracy: $\pm 0.00012in$ | $\pm 0.003mm$

- $\pm[0.00008 + (0.00004 \cdot R/3)]in$ $R = max.$ measuring length (inch)
 $\pm(2 + L/75)\mu m$ for interchangeable rod, $L = max.$ measuring length
(mm)



Figure 7.4c: Mitutoyo Micrometer Bore Gauge Series 511 [40]

Range: $0.4 - 0.75in$ | $10 - 20mm$

Resolution: Dial Gage

- Graduation: $0.0001in$ | $0.001mm$

Repeatability: User Dependent

- Indication Stability: $0.00008in$ | $0.002mm$

Accuracy: $\pm 0.0002in$ | $\pm 0.005mm$

Propagation of Errors: The linear bearing is designed to have a slight radial pre-load on the outer housing—so that the linear rod (rack) running through its inner cylinder is in constant contact with the ball bearings housed within the cylinder wall. To create such a fit, the yaw (θ) motor mount and linear bearing need to have an interference fit between them. An interference fit, or better known as a press fit, implies that the O.D./I.D.’s surfaces need to be in contact as per the function of the design intent. The *class of tolerance* chosen for the inner/outer [shaft/bore] diameters’ tolerance fit is $h9/H9 + 0.0016in$, respectively; whereas the depth tolerance specification for the linear bearing is $\pm 0.0005in$.

The general form for propagating errors consists of using the exact differential for a given function. For example, suppose we have the function $z = f(w, x, y, \dots)$, where the variables x, y, z are independent; then the total exact differential using averaged errors is [45],

$$\delta z = \left| \frac{\partial f}{\partial w} \right| \delta w + \left| \frac{\partial f}{\partial x} \right| \delta x + \left| \frac{\partial f}{\partial y} \right| \delta y + \dots \quad (7.8)$$

$$\delta f(x_i) = \sum_{i=1}^n \left| \frac{\partial f}{\partial x_i} \right| \delta x_i \quad (7.9)$$

Where δf is equal to the random error in the function f and δx is equal to the random error in some measurement x .

Using the formula above we would be adding the errors of the inputs, which is an overestimation of the uncertainty in the measurement; that is, if the errors in the inputs are random, statically speaking, they are likely to cancel one another out over time [46]. Consequently, the more accurate method to determine the absolute error in a result is to use the standard deviation approach; namely, we are to take the square root of the sum of the squares of the absolute errors of the

input value [42]. The general form for the error propagation then takes the form,

$$(\delta z)^2 = \left(\frac{\partial f}{\partial w}\right)^2 (\delta w)^2 + \left(\frac{\partial f}{\partial x}\right)^2 (\delta x)^2 + \left(\frac{\partial f}{\partial y}\right)^2 (\delta y)^2 + \dots \quad (7.10)$$

$$(\delta f(x_i))^2 = \sum_{i=1}^n \left(\frac{\partial f}{\partial x_i}\right)^2 (\delta x_i)^2 \quad (7.11)$$

Applying Equation 7.11 to the function, $f(a, b) = a \pm b$, the propagated errors in z due to the errors in a and b .

$$\begin{aligned} (\delta f(z))^2 &= (\delta f(a, b))^2 = \left(\frac{\partial f(a, b)}{\partial a}\right)^2 (\delta a)^2 \pm \left(\frac{\partial f(a, b)}{\partial b}\right)^2 (\delta b)^2 \quad (7.12) \\ &\Rightarrow (\delta(a \pm b))^2 = \left(\frac{\partial(a \pm b)}{\partial a}\right)^2 (\delta a)^2 \pm \left(\frac{\partial f(a, b)}{\partial b}\right)^2 (\delta b)^2 \\ &\Rightarrow (\delta(a \pm b))^2 = (\delta a)^2 \pm (\delta b)^2 \\ &\Rightarrow \delta(a \pm b) = [(\delta a)^2 \pm (\delta b)^2]^{1/2} \end{aligned}$$

Using Equation 7.12, we can determine and account for the propagated error through the accumulation of combined measurements. In other words, since certain dimensions cannot be measured directly, the use of multiple measuring devices is required to realize a single desired dimension. The precision in the measurement then becomes the largest value of the absolute error from the least accurate measuring tool. Since the LapaRobot design has many important dimensions—coupled with the fact that we were not always able to measure these dimensions directly, we employ the method above to verify that our measurements are within the tolerance specification(s) called out in the engineering drawing(s).

7.3 Geometric Tolerance

Geometric tolerance specifies the zone or total amount that a dimension of a manufacture feature (coordinate, line, axis, plane, surface, medium, surface finish, etc.) can fluctuate for given component or assembly [47]. Put another way, geometric feature tolerance is a well defined method for indicating the geometric requirements on technical schematics and engineering drawings. With the advent of computer aided design, often times these tolerance features are embedded in the CAD model itself-thus directly translating important design information into the generated engineering drawing [47]. The symbols that represent some of the tolerance features are internationally standardized and accepted within the engineering world; such criteria include ASME, ANSI, ASTM, and ISO codes and standards [48, 49]. Typical tolerance features are measured or referenced from a datum or datum feature. A datum is standard position [either a plane or axis] from which measurements are taken from [47, 50]. These engineering standards give the engineer the necessary guidelines to correctly dimension and tolerance their designs. Nevertheless, there is cost associated with geometric tolerance. Simply put, the more precise or accurate a feature becomes, the more cost intensive the machinery and labor required to fabricate the part become. For example, for a given manufacture processes there is a corresponding accuracy range for the process. The following figure shows various dimensional tolerances for different manufacturing processes.

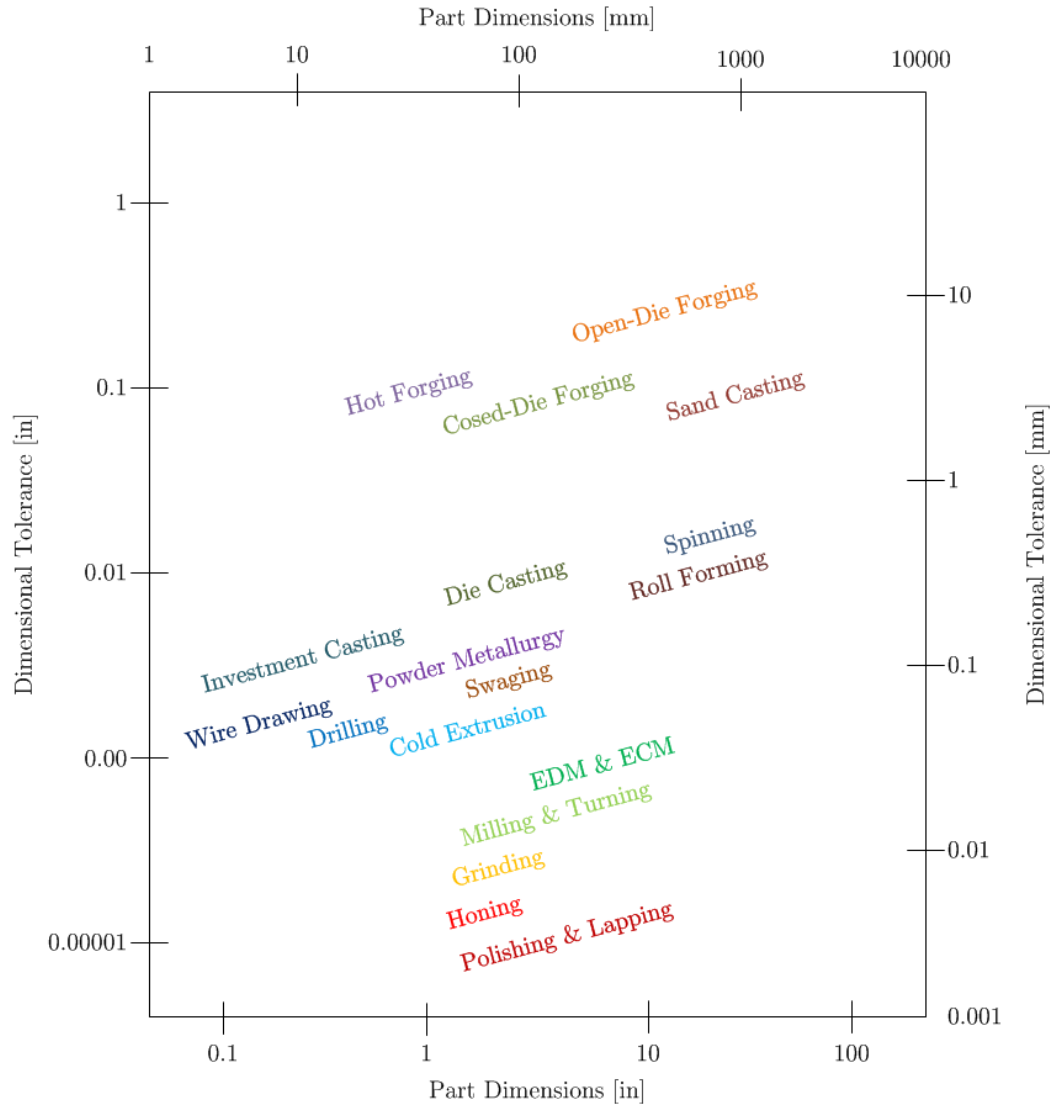


Figure 7.5: Manufacture Tolerance from Specified Processes [49]

7.3.1 Tolerance Fits

Machined components are characterized by fundamental dimensions. These permissible deviations or variances from some nominal value of a part are an important part of each design-as it is a key factor in validating the accuracy of machined components. In the example above, if either of the measurements would

have fallen outside of the tolerance specifications, the components would not assemble or function as designed. Consequently, special attention was exercised when machining tolerance A and B. To insure that these tolerance specifications were met, a setup part/fixture was made to verify both the generated G-code and any corresponding tool offsets from the CNC mill and lathe. The quality of the fit between A and B is categorized by an allowance value; this allowance value is specified in the manufacture drawing and is determined by design intent.

7.3.2 Tolerance Classification

Tolerance classification aids in the defining manufacture machining errors that pertain to the feature tolerance specifications of the final measured product [51]. The tolerance stack-up analysis includes evaluation of the machining errors for a given toolpath operation as well as the error propagation through the accumulation of these stages. The types of tolerance features and their corresponding symbols are explained in detail below [47, 50, 52, 53].

—	Straightness
▭	Flatness
⤿	Line Profile
○	Circularity
⊘	Cylindricity
⌒	Surface Profile
⊕	Position
◎	Concentricity
≡	Symmetry
//	Parallelism
⊥	Perpendicularity
∠	Angularity
↗↘	Total Runout
↗	Circular Runout
Ⓜ	Maximum Material Condition
√ ³²	Surface Finish

Figure 7.6: Tolerance Feature Type

Straightness: *Shortest distance between two points.*

- Straightness Tolerance: Specified distance or zone between two parallel straight lines.

Flatness: *State of a surface containing all elements in one plane.*

- Flatness Tolerance: Deviation from a real plane (where a surface must lie) between two defined parallel planes.

Line Profile: *Two-dimensional line segments or element profiles.*

- Line Profile Tolerance: Two-dimensional (profile) zone that controls line elements along a profile or feature.

Circularity or Roundness *Proximity of being round or circular.*

- Circularity Tolerance: Controls the roundness of circular features and components.

Cylindricity: *The measure of circularity and straightness between two cylinders and common axis.*

- Cylindricity Tolerance: The cylindricity tolerance is the radial distance-measured between two coaxial cylinders.

Surface Profile: *Three-dimensional line segments or element profiles.*

- Surface Profile Tolerance: Three-dimensional (profile) zone that controls line elements along a profile or feature.

Position: *Spatial location of an entity.*

- Position Tolerance: The spatial location (position) between two features or between a feature and a datum.

Concentricity: *Two circular features that have a common center, or the quality or relationship of having the same center*

- Concentricity Tolerance: The Deviation of two circles or cylinders from a common central axis.

Symmetry: *The characterization or correspondence in size, profile, and arrangement of components divided into equal parts by a common point, line, or plane*

- Symmetry Tolerance: The distance between two parallel lines or planes and parallel datum or feature.

Parallelism: *An equilibrium or uniform distance of two or more lines, planes, or surfaces*

- Parallelism Tolerance: The parallelism between two or more lines, planes, or surfaces and controlled tolerance feature.

Perpendicularity: *Being at a right angle to a horizontal or vertical line or plane. A line or plane is perpendicular to another line or plane if all of the angles created by their intersection create right angles*

- Perpendicularity Tolerance: The angular degree to which two or more right-angled lines or planes may vary.

Angularity: *The character of being angular or having an angle.*

- Angularity Tolerance: The angular degree to which two or more angled lines or planes may vary.

Total Runout: *The circular deviation from roundness along the length of a cylindrical part.*

- Total Runout Tolerance: The circular deviation from roundness along the length of a cylindrical part-as it is rotating 360 degrees about its own central axis.

Circular Runout: *The circular deviation from roundness of one cross section of a cylindrical part.*

- Circular Runout Tolerance: The circular deviation from roundness of one cross section of a cylindrical part as it is rotated 360 degrees about its own central axis.

Maximum Material Condition: *Feature-of-size that contains the greatest amount of material*

- Material Condition Tolerance: Feature-of-size that contains the greatest amount of material, but stays within the tolerance specification.

Surface Finish: *Surface Finish or Surface Texture or Surface Roughness is the measure of the characteristics of a surface; namely, roughness, waviness, and form or lay.*

- Surface Finish Tolerance: Deviation from surface roughness average (Ra).

An important point to make surrounding product manufacturing/realization comes through an understanding that every successful production outcome is a direct result of a well-planned production cycle. This means that understanding and identifying important design information, and determining the correct sequence of manufacturing toolpath operations is necessary and essential for producing accurate parts. In order to streamline the iterated components that makeup the LapaRobot manipulators, the product realization sequence flowchart, seen on page 128, was developed and implemented. This product realization flowchart,

Table 7.3: Tolerance Quality Classifications [54]

Tolerance Specifications	
<i>Dimension</i>	<i>Measurement</i>
Shape or Form	Straightness
	Flatness
	Circularity
	Cylindricity
Orientation	Parallelism
	Perpendicularity
	Angularity
Runout	Circularity
	Total
Profile or Contour	Line
	Surface

similar to [54] work on computer aided manufacture planing, details and depicts a schematic breakdown of the design process, the manufacture planning process, and the manufacture production process.

In order to classify outcome measures accurately, combined features need to be organized into a hierarchial structure within the machining process used [54]. Using this hierarchial structure allowed us to distinguish between repeatable and random errors when machining components and further classify individual component errors and combined component assembly errors from the LapaRobot. This classification of errors, described by [55], is broken down into the following categories: machining errors, assembly errors, clearance errors, and other hardware related errors.

- **Machining Errors:** Errors resulting from deviation from the tolerance feature type [engineering drawing] of the individual component(s)
- **Assembly Errors:** Errors resulting from deviation from linear or non-linear alignment/assembly of the individual component(s)
- **Clearance Errors:** These types of errors are from the compliance of mechanical components mated within motors, actuators, etc. [e.g. Gear Backlash].
- **Joint Errors:** Runout errors associated with rotating and spherical driven components [e.g. Bearings, Spherical Joints].

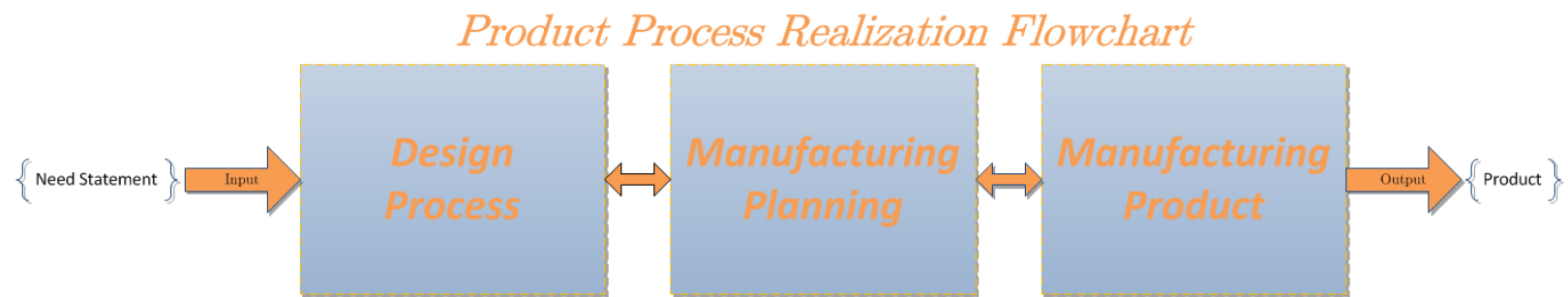


Figure 7.7a: Product Process Realization Flowchart

Figure 7.7b: Design-Process-Flowchart

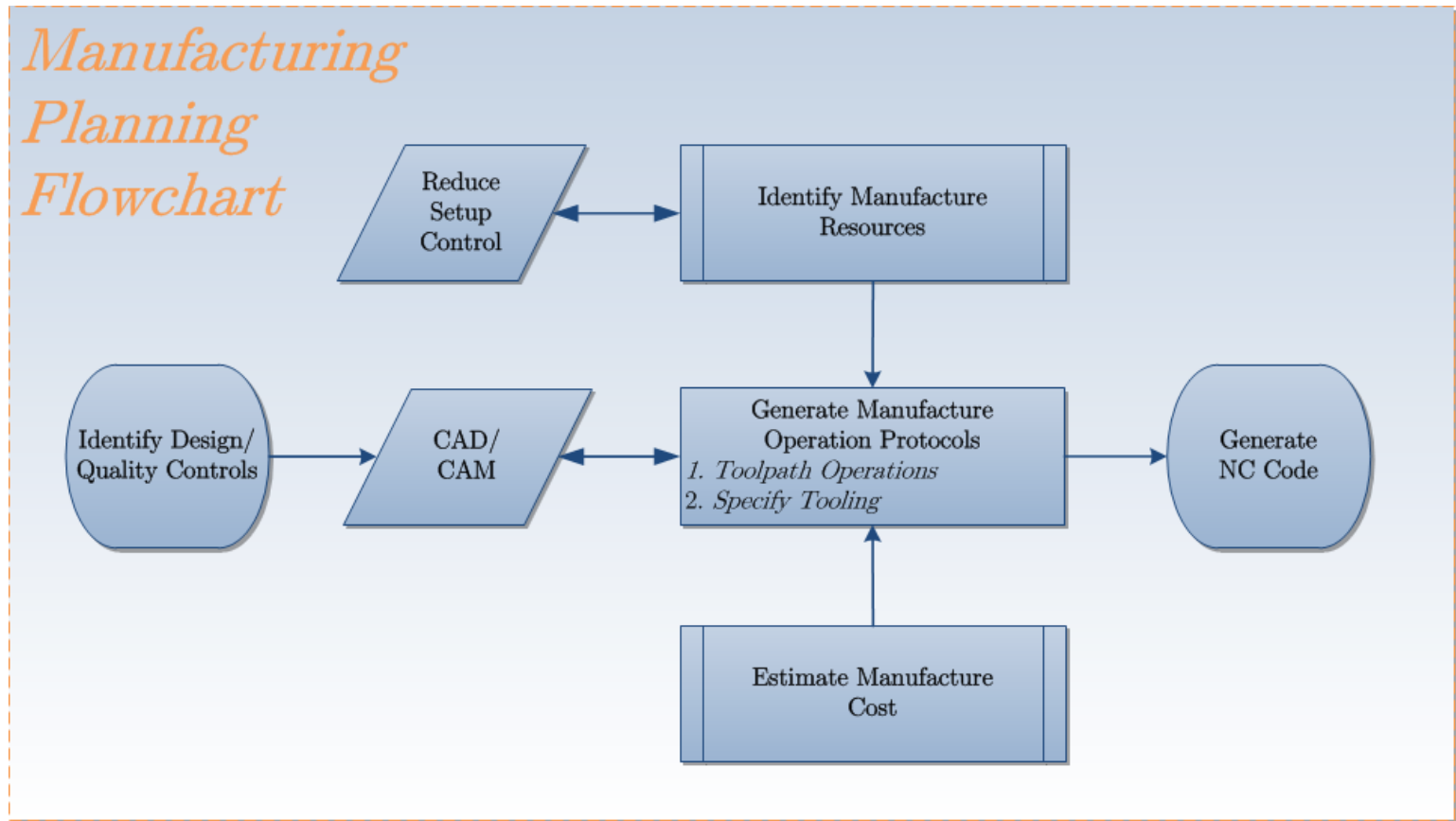


Figure 7.7c: Manufacturing-Planning-Flowchart

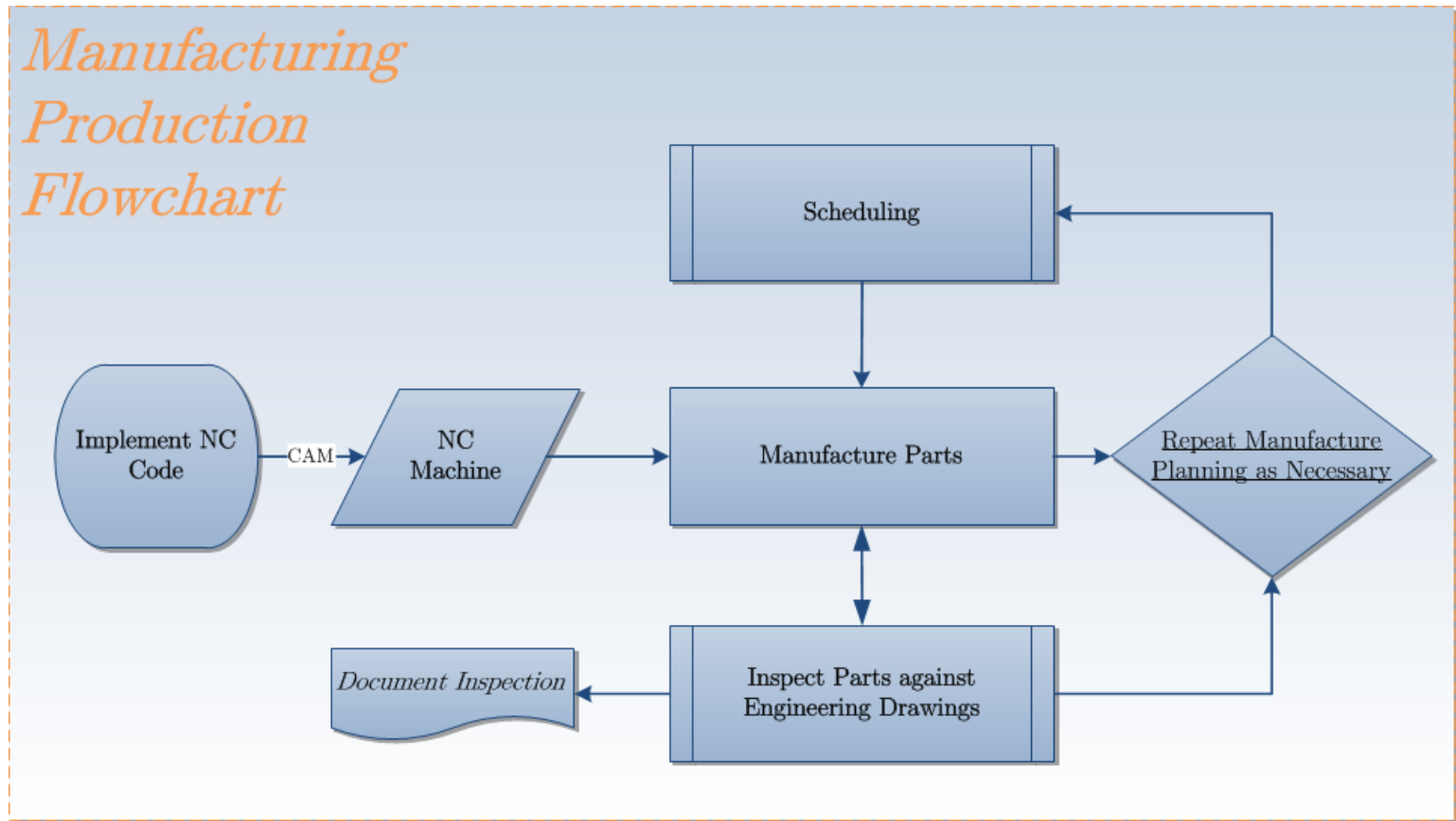


Figure 7.7d: Manufacturing-Production-Flowchart

The manufacture case studies and the design process organization given in this chapter include a gross overview of the manufacture process error classification and machining practices used to realize the LapaRobot system. The fine details, including the dimensions, tolerances, geometric fit, surface finishes, revisions, etc. that reference the engineering drawing tolerance specification(s) can be found in Appendix A of this dissertation. The CAM g-code is omitted for brevity, but all of the CAM programs are a vital component to manufacturing planning and product realization.

CHAPTER 8

Teleoperated/Telementoring Laparoscopic Surgery

8.1 Introduction

The figures below illustrate the devices and systems conceived for telesurgical and telementoring laparoscopic robots.

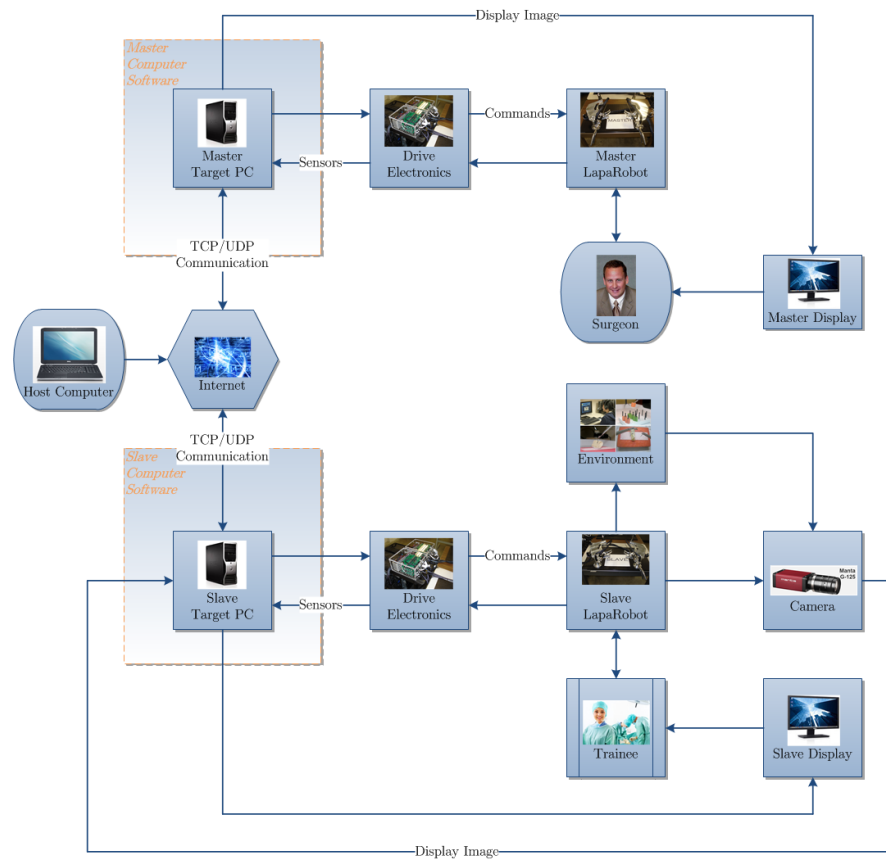


Figure 8.1a: LapaRobot System Overview

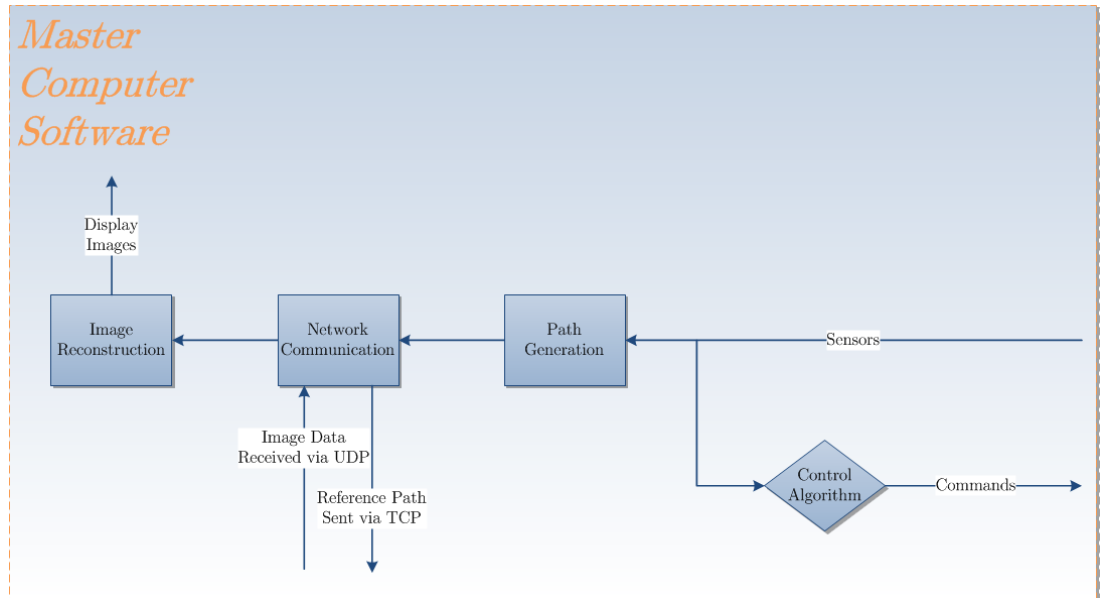


Figure 8.1b: LapaRobot Master Computer Software

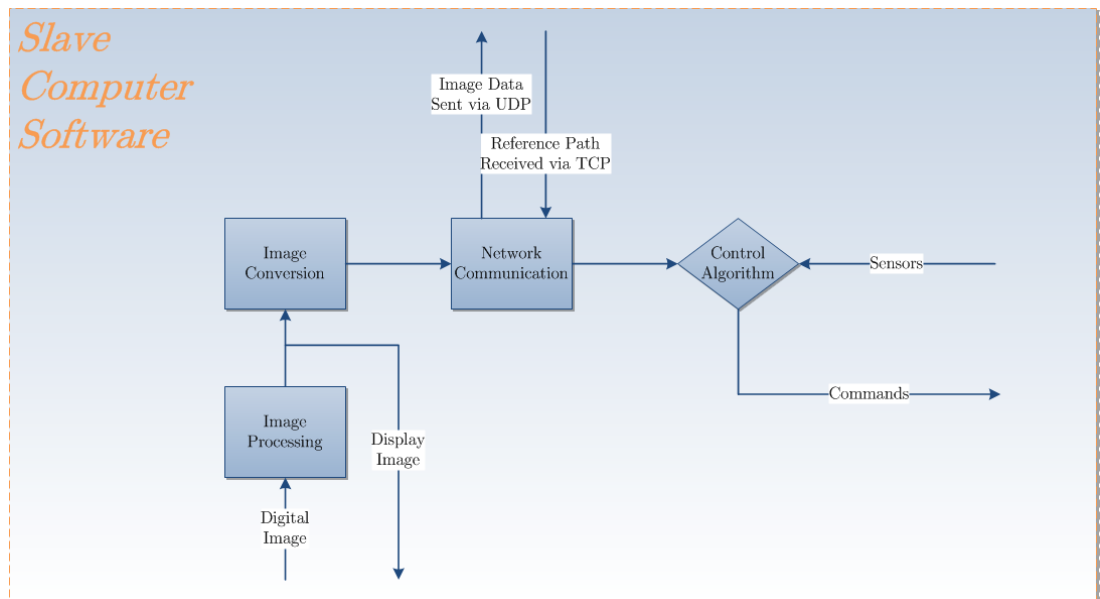


Figure 8.1c: LapaRobot Slave Computer Software

8.2 System Integration

8.2.1 Teleoperated/Telementoring Laparoscopic Surgery

In order to perform laparoscopic procedures from beginning to end, the master surgeon has to use a variety of instruments for differing surgical tasks. Consequently, teleoperated surgery requires the mechanism to have an extended range of motion as well as the ability accept various instrument tools. To accomplish these challenging tasks, the robotic system and its subsystems require more advanced engineering and control software to translate information from the surgeon at the *master* controls to the end-effectors, or Slave station that carries out the surgical instructions. This design consists of two circular arcs that rotate on independent axes. The laparoscopic tool is held between the arcs, thereby constraining the tool motion at the holding point to a spherical surface. This design inherently guarantees a remote center at the geometric center of this spherical surface. The improved range of motion will cover a half-cone region with 60 degree inclination measured from vertical.

For telementoring, the mentoring surgeon must be able to see the laparoscopic robot and its environment at the remote site. To do this, we are using a gigabit ethernet camera-connected to a LabVIEW real-time target, to stream images from the remote site over the Internet to another target computer separated at a distance. Here challenges include transferring images with minimal latency and satisfactory image quality. Since the gigabit cameras are intended to mount directly to a standard tripod and they require a certain working distance from the lens interface to the target scene, we had to design a rigid but adjustable mounting solution to accommodate for these needs. This adjustable camera mounting subsystem, as seen in Figure 8.2, allows for spatial adjustment on the mounting

platform as well as height, angle, and spherical adjustability on the camera side.

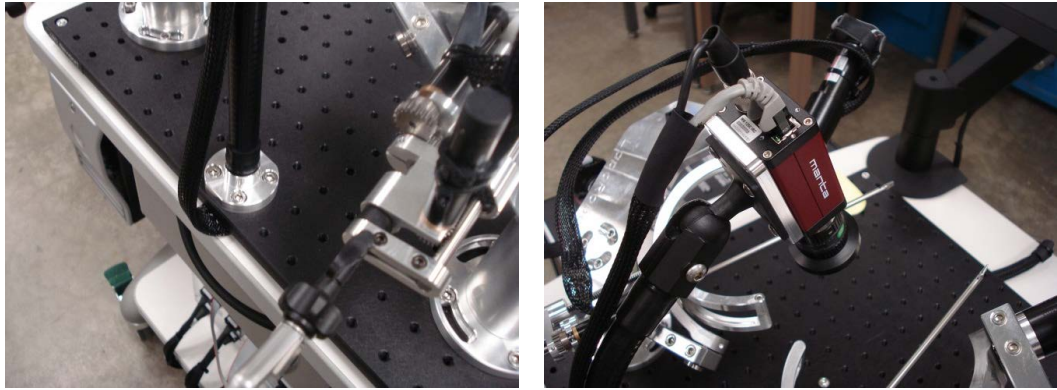


Figure 8.2: Adjustable Gigabit Camera System

During evaluation, it is important to record and save continuous images of the students as they take their FLS evaluation exam. Later this recorded video will be evaluated using custom software to rate the students on their performance. Here challenges included saving images at a sufficient frame rate with maximum image quality and without dropped frames. This is achieved using LabVIEW's IMAQ vision module and programming a sufficiently large memory buffer for the images to be written quickly to disk, while keeping up with the rate of acquisition.

8.2.1.1 Modes of Operation

1. In this mode, the remote slave device replicates the motion of the master device. The user on the master can freely manipulate the laparoscopic tools on the master device in all degrees of freedom. Encoders measure the position of the tool in each degree of freedom and this reference trajectory is transmitted to the remote slave device via TCP or UDP communication over any network including the Internet. A computer feedback controller, located at the slave site, commands the slave motors to track the received

trajectory with minimal position error. In order for the master user to be aware of how the slave tools are affecting the slave-side environment, a video stream is transmitted back to the master station. The captured video must be resampled to a low enough resolution to facilitate low latency transmission. In addition, compression is required to reduce the data size of the video and reduce the data transfer rate. The frame rate must also be sufficiently low, as to not over burden the network with packet transfer. These restrictions must be balanced with the need for decent video quality and refresh rate on the master display, which depends on the teleoperated task being performed. The key challenge in this mode is minimizing the two-way latency so that the master user can comfortably perform the desired tasks. The telesurgery mode can also be used to telementor a student on the slave-side. The student can be trained on laparoscopic task by holding onto the tools and feeling the motions directed by the master user. In addition, the student sees the same video stream. In this way, the student is taught tasks through visual feedback and virtual [cognitive] hand holding. A key advantage to this is that the teacher and student do not need to be at the same location saving on the time and cost of travel.

2. In this mode, the master or slave device is used as a stand-alone device. The user manipulates either device to perform box trainer tasks including peg transfers, suturing, or circle cuts. These tasks have been defined by the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) as part of the Fundamentals of Laparoscopic Surgery (FLS) program. Surgeons must perform these tasks with sufficient competency to become FLS certified. However, the proposed device has a significant benefit over the traditional box trainer in that the user motions can be recorded along with

video of the task performance in real-time. The recorded data can be used in two ways. The first proposed use is using the recorded video to automatically assess the performance of the trainee using machine vision based software. The second use is playing back the video and motion trajectory so that the trainee can observe his or her mistakes and learn how he or she can improve. This has the added benefit of being able to see how the tools were moving during your performance, which can be difficult to observe in video. Another benefit of this mode is that a certified surgeon can record his or her task performance and replay it for training students. In this way, students can hold the tools and get a feel of how the tools should be held and moved around. The surgeon can share his recordings with students which are at a remote location and they can learn from the surgeon without ever meeting.

3. In this mode, the master and slave users can interact with one another through position-position based control. A computer controller on the master and one on the slave control their respective devices using position based feedback. The master device follows the reference trajectory generated by the slave and the slave device follows the reference trajectory generated by the master. By tuning the dominance of the controllers, we can adjust the dominance of the master-slave cooperation. A resulting benefit of this system is two-way force feedback between the master and slave users. However, the master will feel the additional weight of the slave and slave will feel the additional weight of the master. To overcome this, gravity compensation on both devices is required. This is achieved by experimentally mapping the static force required to hold the tool up against gravity. Cooperative mode is useful for both cooperative surgery and telementoring with force feedback. However, since the master and slave are operating in a

closed loop, the network latency between the two devices must be minimal in order to produce a stable system.

Since the systems are being used at great distances, portable carts were integrated with the LapaRobot sub-systems- thus allowing the entire surgical platform to be mobile. Furthermore, adjustable laboratory jacks, camera extensions, laptop mounts, monitor-display mounts, and LED lights were also designed and incorporated with the mobile platform. These enhancements accommodate a wide array of demographics and stature criteria for the test subjects. Figure 8.3 shows the completed *master* robot.

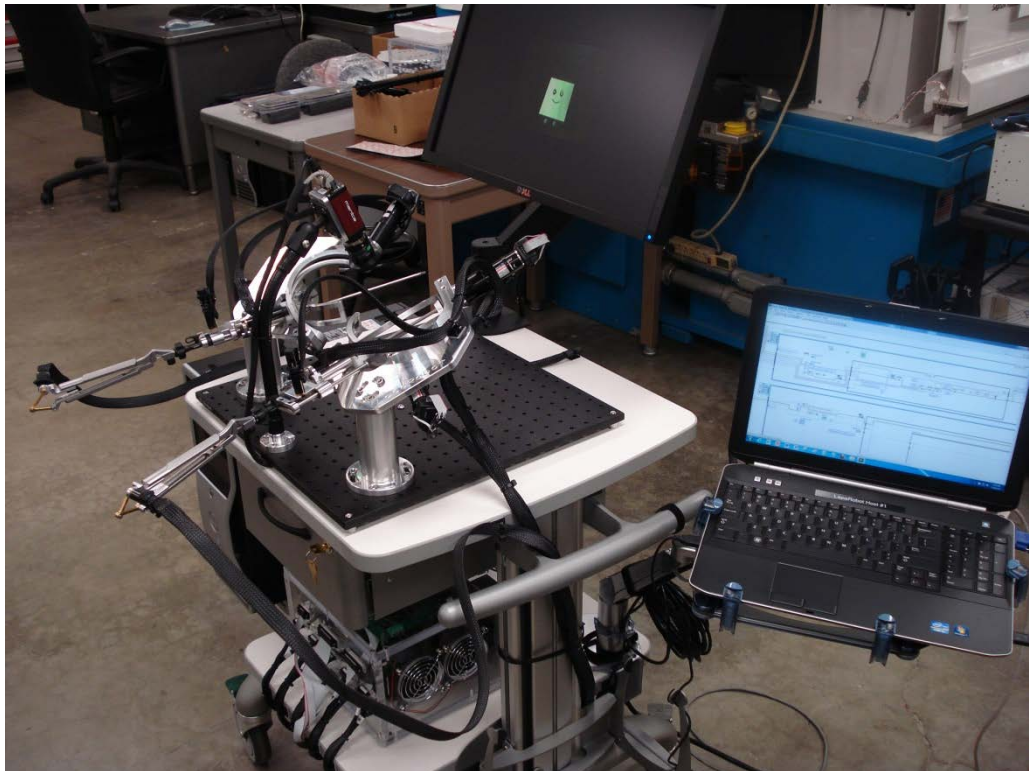


Figure 8.3: LapaRobot Prototype Surgical System

8.3 Clinical Demonstration & Evaluation

8.4 Design Study

8.4.1 Protocols

The telementoring demonstration from the University of California, Los Angeles (UCLA) to/from the Eisenhower Medical Center (EMC) in Rancho Mirage, CA, is approximately 130 miles away. Implementation protocols for both the telementoring sessions of the FLS tasks and FLS evaluation sessions for mentored participants is required for proper data collection. The FLS tasks for this study include the triangle peg transfers, suture/knot tying, and precision circle cutting. These sessions require the use of cameras for capturing video streams as well as time stamping the data with subsequent motor encoder positions. The figures below illustrate the clinical demonstration format used for evaluation of the LapaRobot telesurgical and telementoring laparoscopic robot(s).

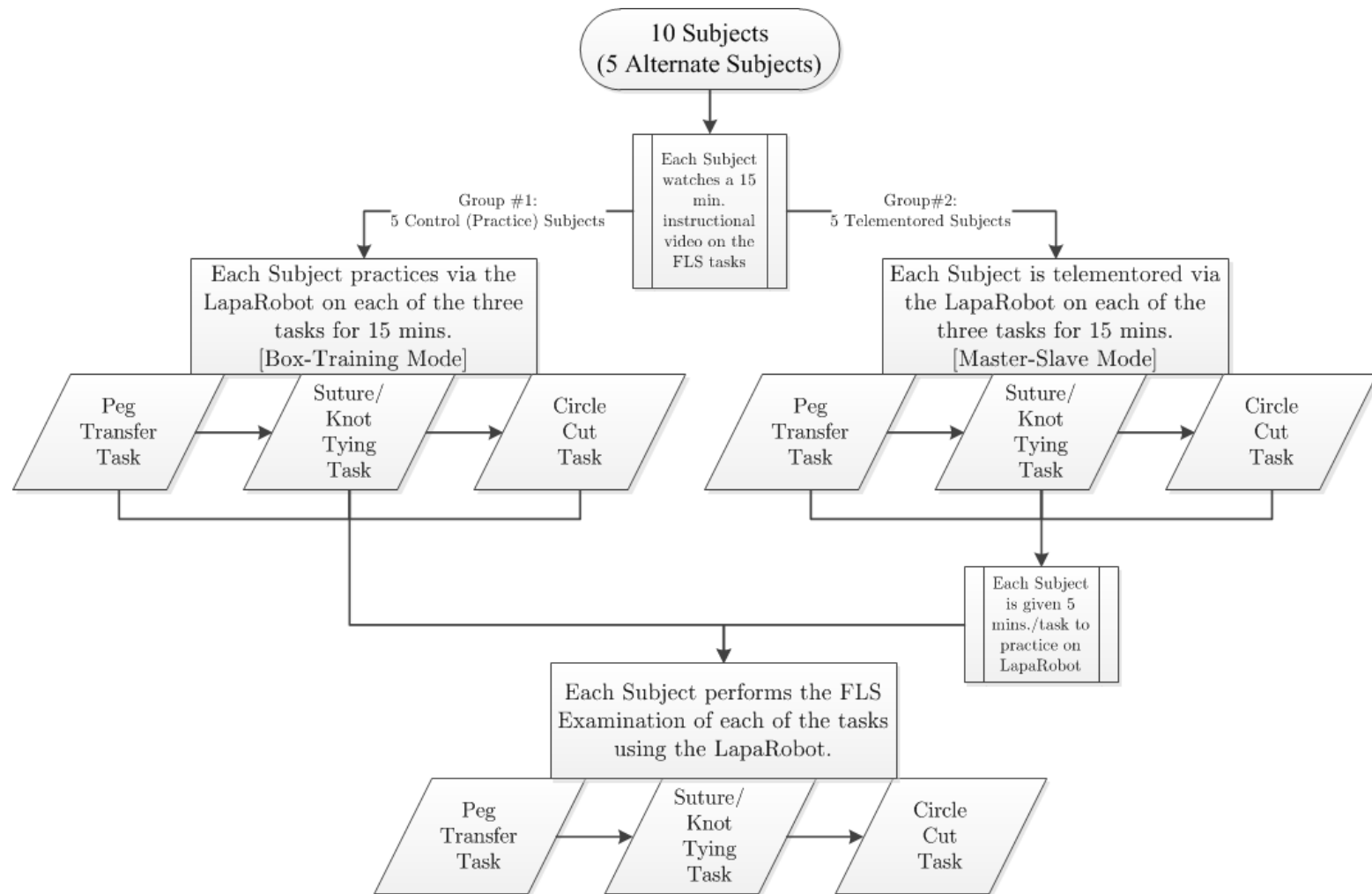


Figure 8.4: Clinical Demonstration Format Overview

The protocols for the Subject Testing/Evaluation are as follows:

- Acting Principle Investigator escorts subject to testing area
 - Ensure Eligibility (Screening Script)
 - * Consent Form
 - FLS Training Video
 - * Training video calls for 5 FLS Tasks, but there are only 3 tasks employed
 - De-Identify Subject using "Subject #1, Subject #2, etc."
 - * Randomly place Subject into Group 1 or Group 2
- Escort Subject to LapaRobot Testing Room

Subject Training/Practice (60min Total)

- If the Subject is in Group 1, the Subject will be telementored by the Master Surgeon (15min per task)
- If the subject is in Group 2, the subject will practice independently (15 minutes per task)
- Groups given safe-handling instructions; remind subjects to look at display and not on the actual objects

Subject Testing (30min Total)

- FLS proctor reads testing script, times each task, and scores the Subjects (All data tabulated on FLS score sheet)

- Penrose drain and circle gauze are categorized with the subject's number and group number and sent out to graded by the FLS committee

8.4.2 Fundamentals of Laparoscopic Surgery Tasks

$$FLS\ Tasks(t) = \begin{cases} Triangle\ Peg\ Transfer, & \text{for } t \leq 300\text{sec (5 min)} \\ Suture\ Knot\ Tying, & \text{for } t \leq 600\text{sec (10 min)} \\ Precision\ Circle\ Cut, & \text{for } t \leq 600\text{sec (10 min)} \end{cases} \quad (8.1)$$

1. Triangle Peg Transfer

Subject is given 6 triangles and a pegboard located on his or hers opposite-dominant side hand: the subject is to pick the triangle up off a given peg and transfer each peg from tool-to-tool in mid-air, and place the triangle down on an adjacent peg. Once all the pegs are transferred from one side to the other, the subject repeats the process from the other hand. Time stops when the process is completed.

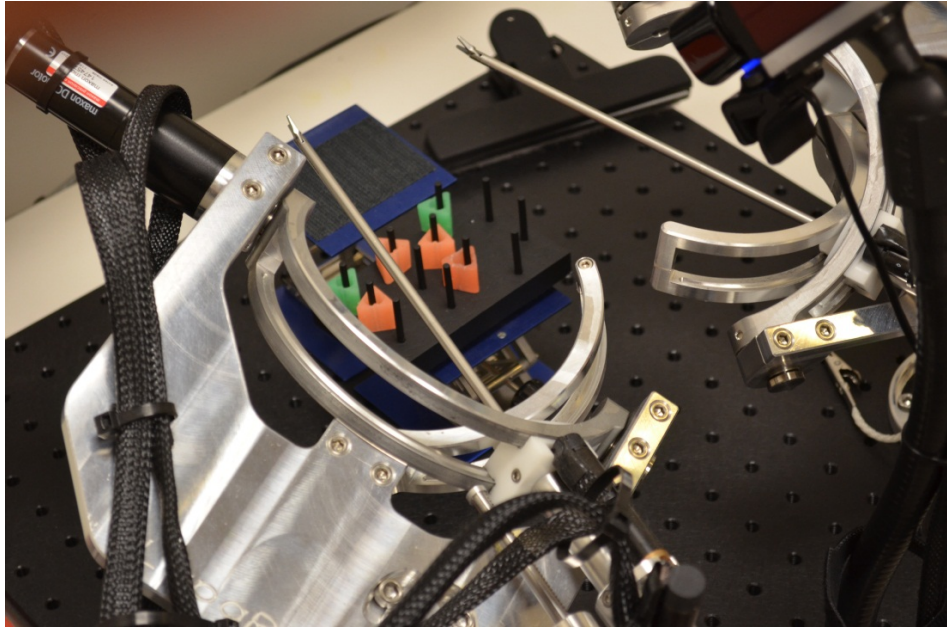


Figure 8.5: Triangle Peg Transfer Task

2. Suture Knot Tying

Subject is given a needle and thread within the field of view-along with a suture board and a penrose drain. They are to start and hold the needle with their non-dominant hand and navigate the needle tip through the black dots on both sides of the penrose drain. From there, the subject is to tie and secure a single knot and then hold the needle with his or hers opposite hand and tie and secure a double knot. Time stops when the process is completed.

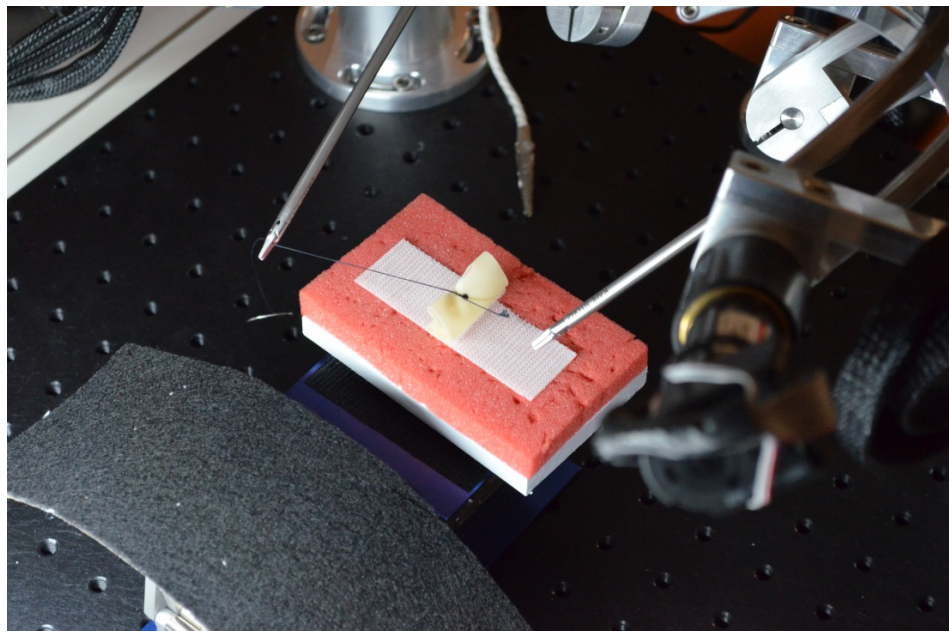


Figure 8.6: Suture Knot Tying Task

3. Precision Circle Cut

Subject is given a gauze strip that has a black circle outline within its perimeter. The subject is to cut the circle out-while staying on the black outline. Time stops when the process is completed.

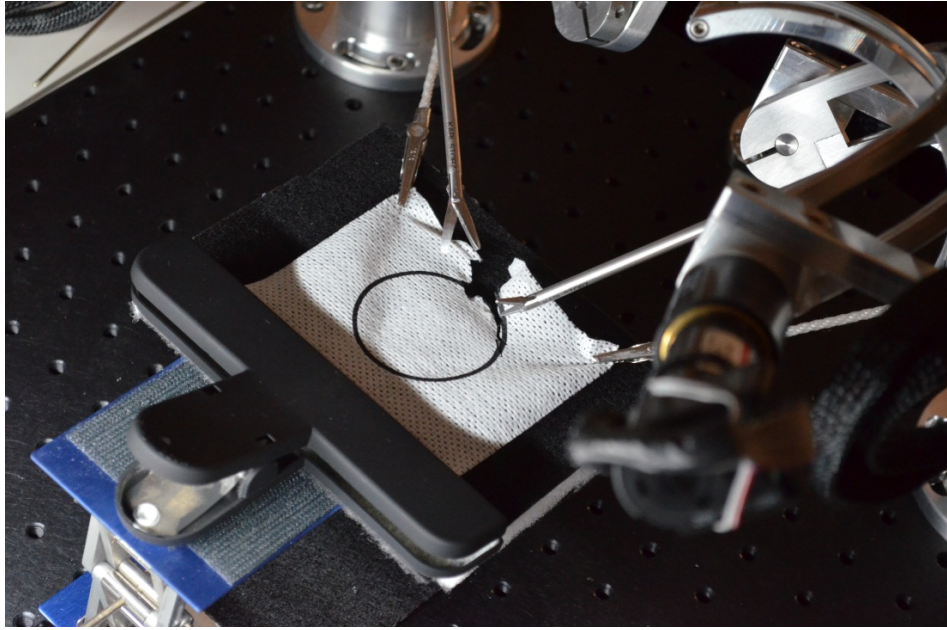


Figure 8.7: Circle Cut Task

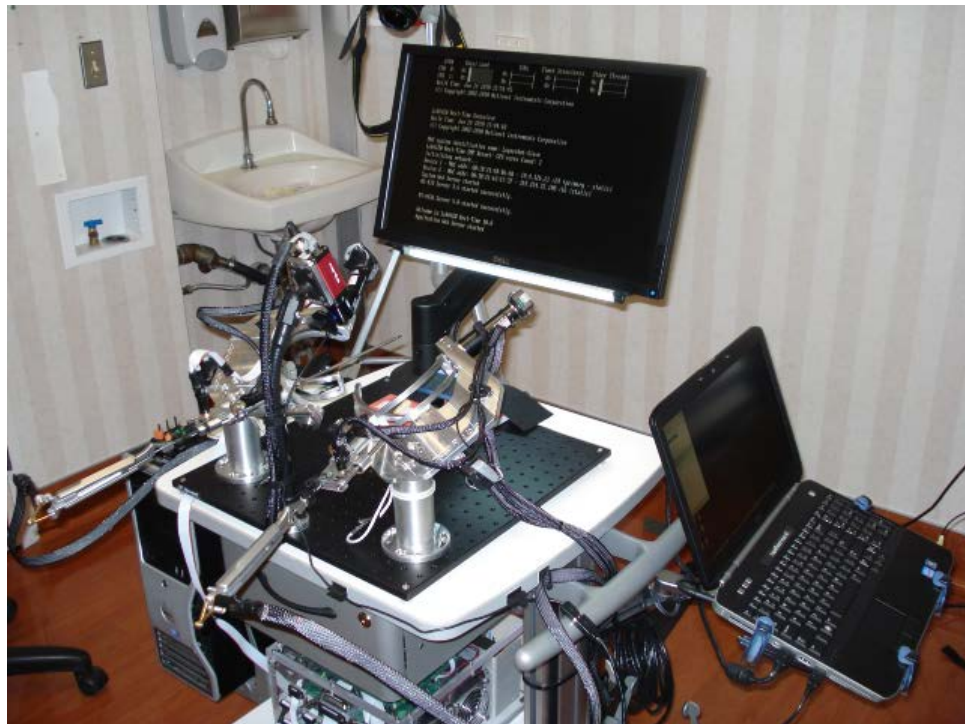


Figure 8.8: The LapaRobot Master at the *University of California, Los Angeles* (Left) and the LapaRobot Slave at the *Eisenhower Medical Center in Rancho Mirage, CA* (Right)



Figure 8.9: The LapaRobot Slave at the *Eisenhower Medical Center* in *Rancho Mirage, CA*

CHAPTER 9

Conclusions

9.1 Conclusions

The primary objectives of this research to design and manufacture a minimally invasive laparoscopic robot with telesurgical and telementoring capabilities were met. The *LapaRobot Surgical Manipulators* are a pair of master and slave surgical manipulators, designed as portable robotic solutions for training and quickly developing laparoscopic surgical skill-sets for surgeons seeking FLS certification. Each LapaRobot station provides five DoF motion-control over two standard MIS instruments. The master station will allow a training surgeon to teleoperate the remote-slave robot, while mentoring a novice or less-experienced surgeon; such that, the less-experienced user can autonomously perform these tasks without the aid of the robot or teaching surgeon.

In order to perform laparoscopic procedures from beginning to end, the master surgeon has to use a variety of instruments for differing surgical tasks. Consequently, teleoperated surgery requires the mechanism to have an extended range of motion as well as the ability to accept various instruments. In order to accomplish these challenging tasks, the LapaRobot required more advanced mechanisms and control software to translate information from the surgeon at the master controls to the end-effectors, or Slave station that carries out the surgical instructions. The LapaRobot Surgical System's novel design consists of two circular arcs

that rotate on independent axes. The laparoscopic tool is held between the arcs, thereby constraining the tool motion at the holding point to a spherical surface. This design inherently guarantees a remote center at the geometric center of this spherical surface. The spherical mechanism, insertion mechanism, and rotation mechanisms provide precise and repeatable reliability motions. In our work with the LapaRobot, we have demonstrated sophisticated design and manufacturing capabilities-all of which are developed and manufactured in-house.

- Functions as a Fundamentals of Laparoscopic Surgery (FLS) Evaluation Platform
- Added Degrees-of-Freedom
 - Workspace/Range of Motion: Able to Work in Much Smaller Work Areas with Increased Range of Motion (Remote Center of Motion)
 - Uses Commercially available Laparoscopic Tools that accepts Multiple End-Effectors
- Scaled Motion Control: Scale Instrument Tool Motion
 - Accuracy: Stabilizes the Surgeons Hand Motions and Hand Tremors
- Remote Operation for Telesurgery/Telementoring
 - Telesurgery: Provide Surgery at a Distance
 - Teleoperation: Virtual Classroom for Novice Surgeons
- Automation: Tasks can be Performed Autonomously and/or Recorded for Playback
- Master-Slave Position Tracking, Force Estimation, Feedback, and Gravity Compensation

- Ability to Function as a Joystick for other Surgical Manipulators and Robots
- Ergonomic and Mobile
- Reliability: The LapaRobot is Reliable, Robust and Saves Time and Money

For this research, we have developed and manufactured a novel laparoscopic surgery teaching system. As such, we have completed the high level design requirements set forth, and further validated our design through extensive engineering analysis. With the *master* LapaRobot Station at the University of California, Los Angeles, and the *slave* LapaRobot Station at the Eisenhower Medical Center in Rancho Mirage, CA, we successfully demonstrated the LapaRobot's uniqueness, by teaching ten nurses at a distance of over a 130 miles. Simply put, there is a need for better surgical training in all hospitals; and through instruction from a master surgeon controlling the LapaRobot, one is able to efficiently and effectively enhance his or hers FLS skill-sets. Robotic surgery has the potential of enabling complex procedures with a high level of precision with reduced risk to the patient all of which improve clinical outcomes. The LapaRobot is a robotic surgical system that will lead the way for widespread acceptance to clinical implementation of FLS telementoring.

CHAPTER 10

Other Research

10.1 Other Research

10.1.1 Mouse Tail Vein Injections, Vascular Access System (VAS), Mouse Tail Surgery (MTS)

The main purpose for Tail Vein Injections in mice and rats is to allow for the study of preclinical molecular imaging that pertains to biomedical applications. In other words, mouse tail vein injections are a critical step in imaging applications as successful injections of near infrared (NIR) agents allow for safe noninvasive biological and molecular imaging that contribute to early disease detection. This research is a collaboration with the Imaging Science Chatziioannou Laboratory at UCLA.

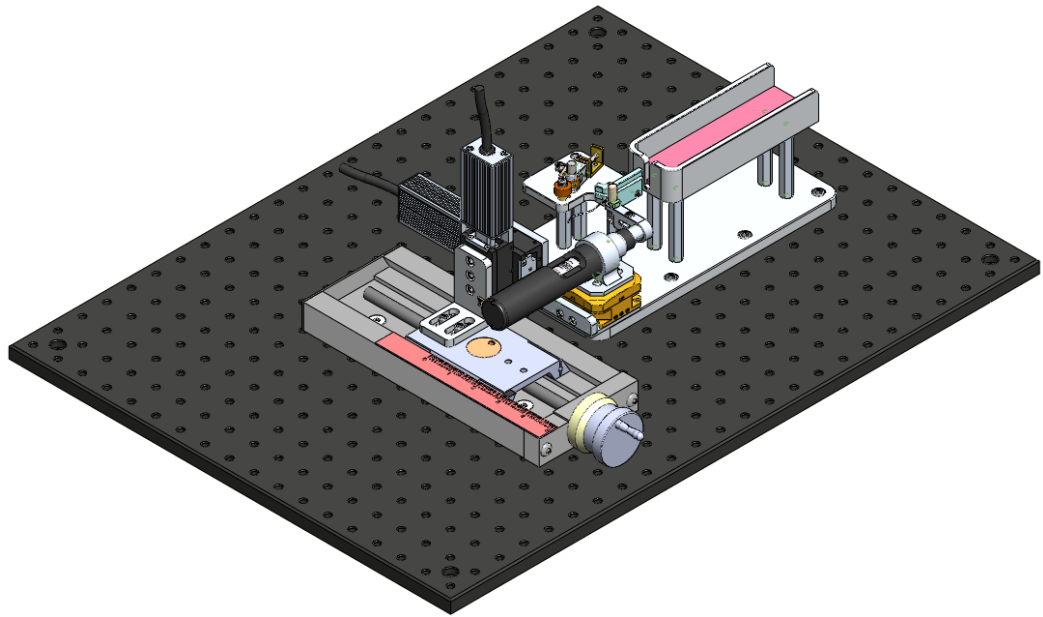


Figure 10.1: Mouse Tail Injection Surgical Station CAD Model, Isometric View

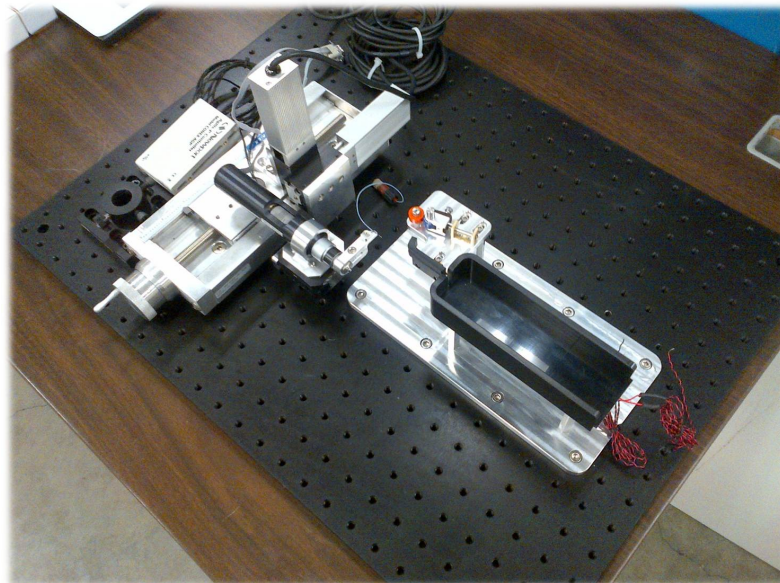


Figure 10.2: Mouse Tail Injection Surgical Station Prototype, Trimetric View

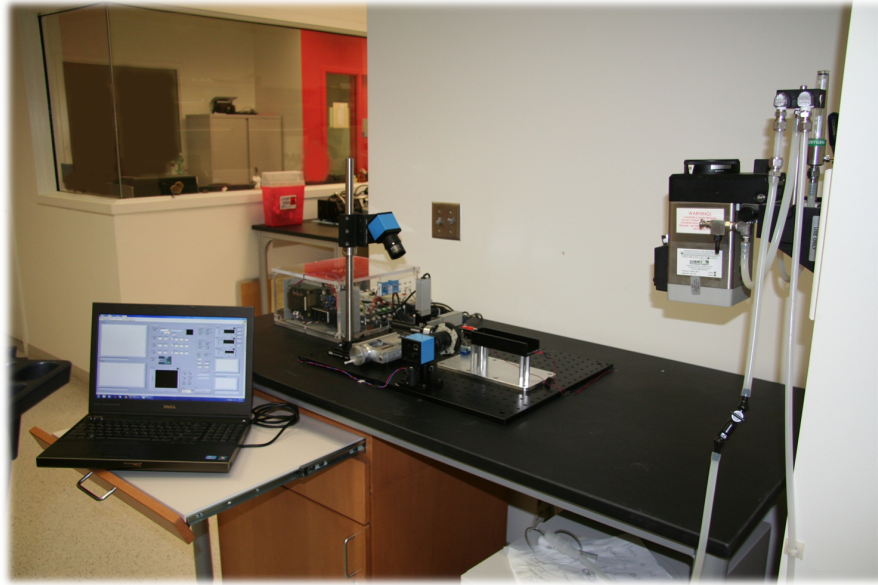


Figure 10.3: Mouse Tail Injection Surgical Station Prototype, Trimetric View

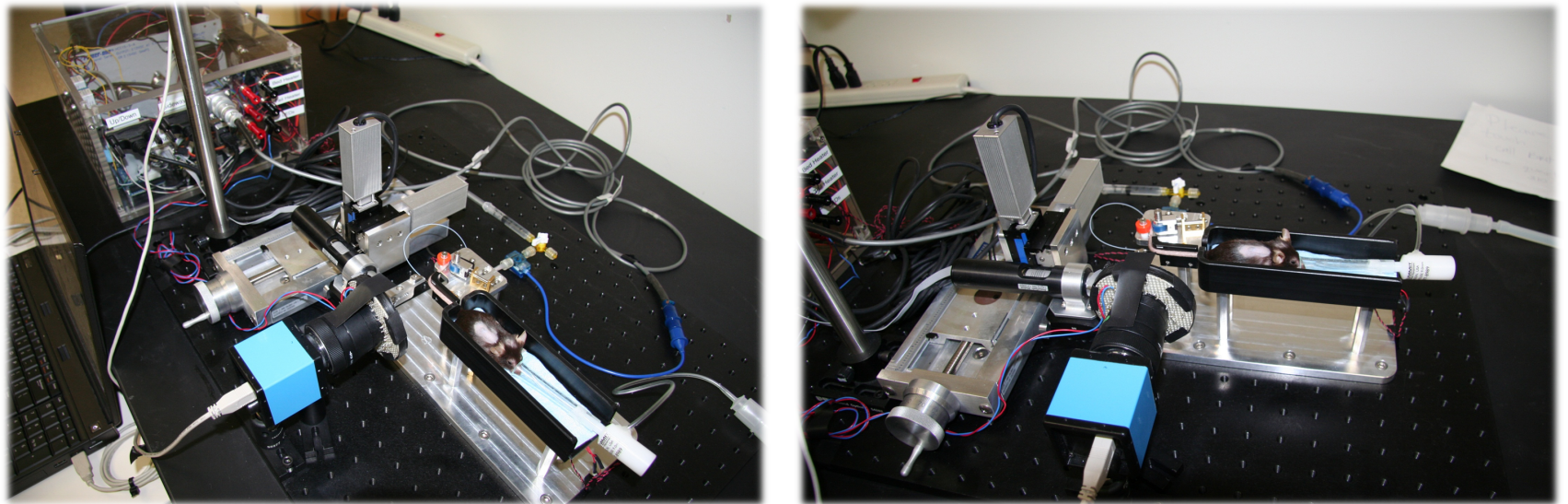


Figure 10.4: Mouse Tail Injection Surgical Station Experimental Setup

10.1.2 Intraocular Robotic Interventional Surgical Station (IRISS)

In Collaboration with the Center for Advanced and Interventional Technology (CASIT) & the Jules Stein Eye Institute (JSEI) at UCLA. We designed, manufacture, and evaluated a stand-alone 6 degree-of-freedom surgical system for robotic ocular surgery. The Intraocular Robotic Interventional Surgical Station (IRISS) is a system conceived for teleoperated and automated ocular surgery. The IRISS surgical platform is capable of performing anterior and posterior surgical procedures via teleoperation and/or automation. The IRISS has the unique capability to manipulate two surgical instruments simultaneously through ocular incisions spaced millimeters apart. The large 6 DoF range of motion of the manipulator allows for both anterior and posterior surgical instrument positioning. To facilitate comprehensive surgical procedures, the IRISS can automatically alternate between multiple surgical instruments on each arm. Dedicated master surgical manipulators and microscope mounted cameras allow for 3-D teloperated surgical visualization based commands. This configuration also lends itself to computer vision based intervention.

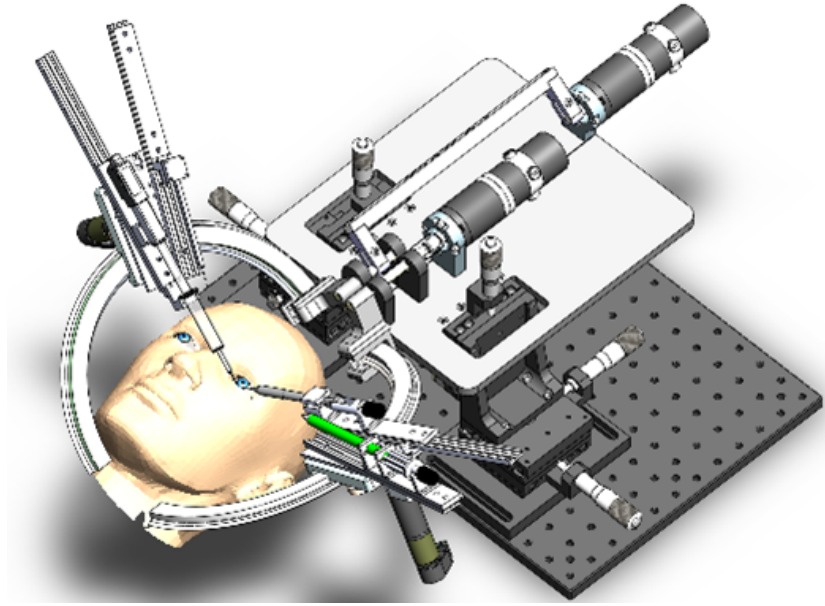


Figure 10.5: Intraocular Robotic Interventional Surgical Station (IRISS)
CAD Model, Trimetric View

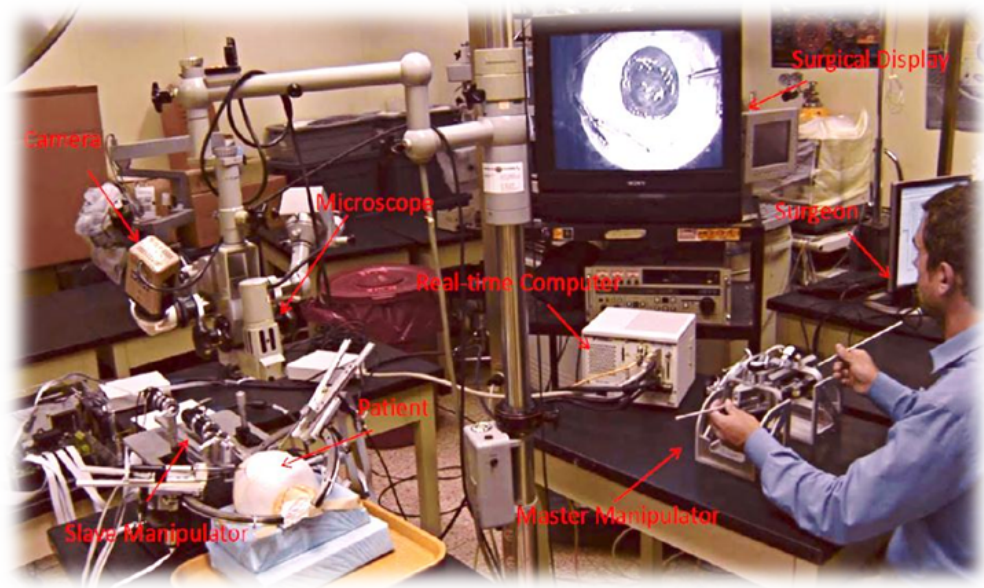


Figure 10.6: Intraocular Robotic Interventional Surgical Station (IRISS)
System Configuration

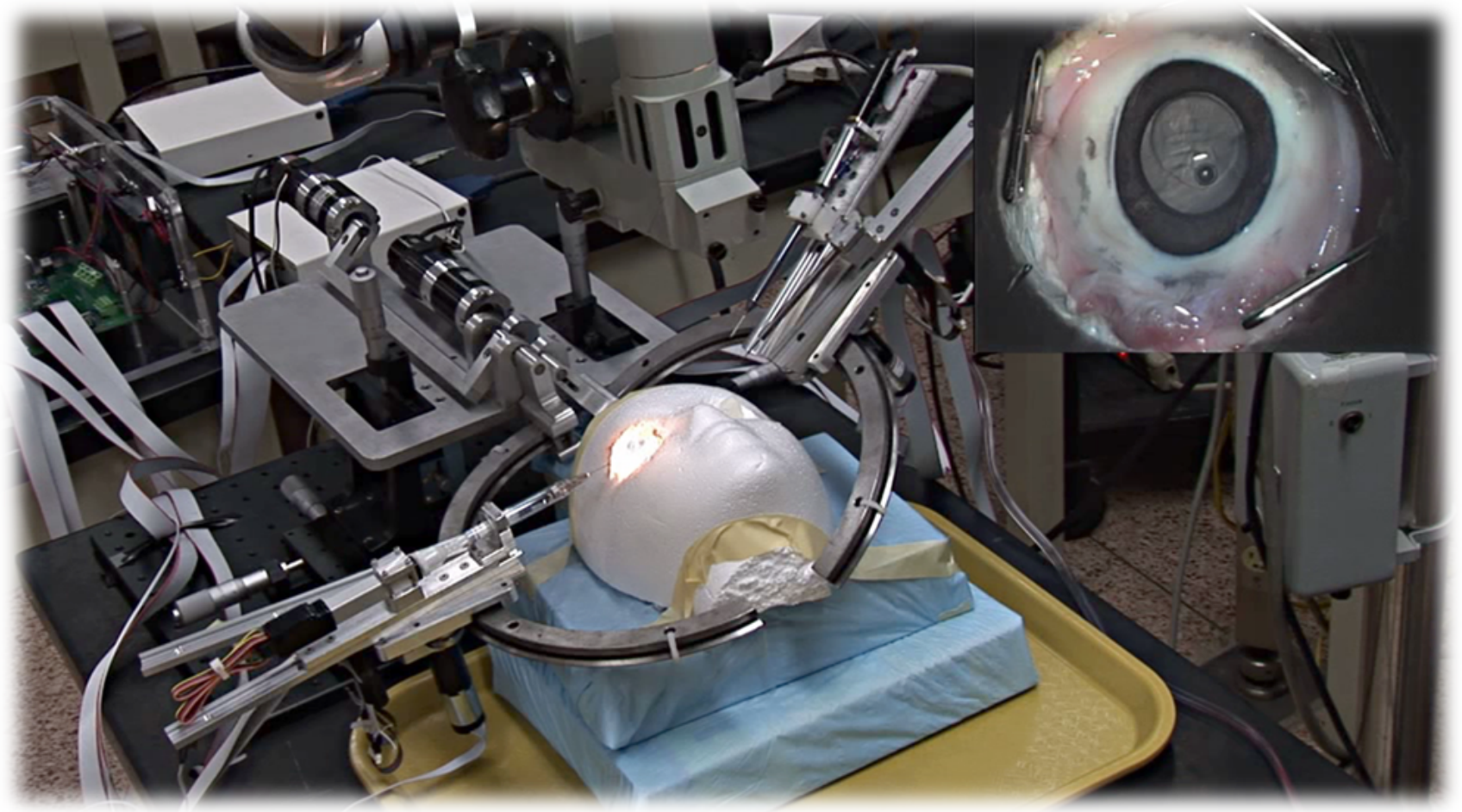


Figure 10.7: Cataract Surgery using the IRISS System

10.1.3 Hexapod Surgical System

Also in collaboration with the Center for Advanced and Interventional Technology (CASIT) & the Jules Stein Eye Institute (JSEI), we designed and manufactured a hexapod surgical system for robotic micro-macro manipulators in ocular surgery. The Hexapod Surgical System (HSS) is a microrobot that can be mounted on other macrorobots [i.e. *daVinci*] for intraocular microsurgery.

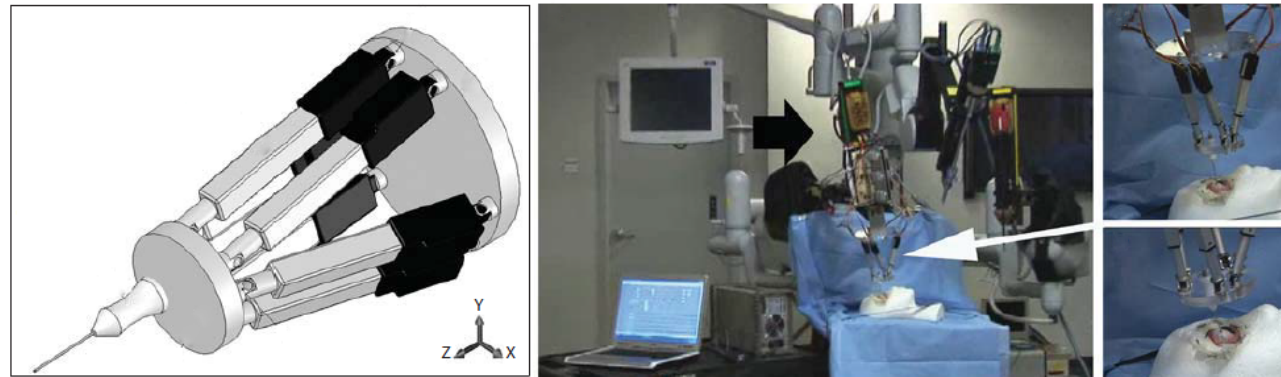


Figure 10.8: The Hexapod Surgical System (HSS): HSS CAD Model (Left), HSS Prototype mounted on the *da Vinci* Robot performing Cataract Surgery (Right)

10.1.4 Dual Stage Fast Tool Servo

We designed, manufactured, and controlled a single-degree of freedom dual stage fast tool servo (FTS). Common areas of use for a FTS using CNC machines include, precise engine piston profiling for non-circular turning, bearing surface texturing, and inner diameter boring. The present dual diaphragm FTS design is based on a previously conceived single diaphragm configuration designed by Lin2008 [56]. As seen in Figure 10.9, the single diaphragm FTS system uses a $20\mu m$ stroke ceramic hollow piezoelectric actuator (PZT) for motion and a $25nm$ peak-to-peak resolution capacitance sensor probe for measuring displacement. The sensor probe uses an adjustable clamp collar coupled to a ball bearing which is in contact with the inner diaphragm; this alignment structure allows for two important design features: one, the piezo's preload can be tuned and adjusted, and two, this mechanism minimizes the transverse forces applied to the piezo stack. A custom set screw is mounted concentrically with the PZT and sensor probe which allows the sensor to be calibrated to the working standoff range.

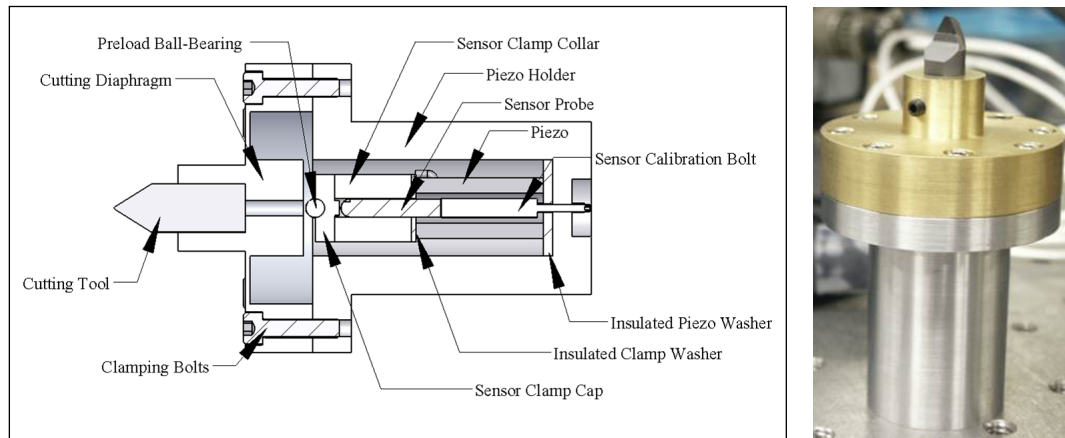


Figure 10.9: Single Diaphragm Fast Tool Servo (FTS) Actuator System
Schematic and Prototype

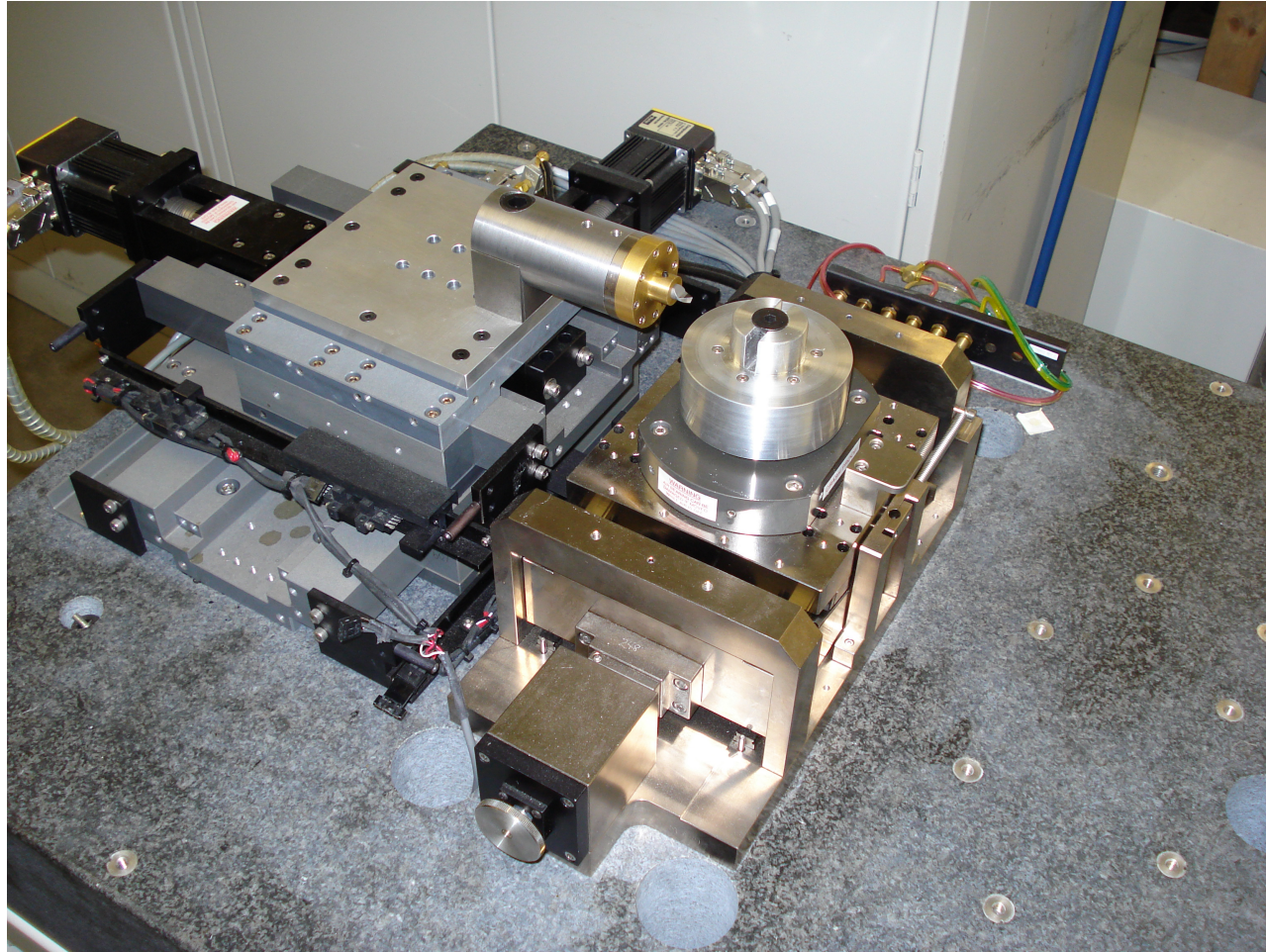


Figure 10.10: Single Diaphragm Fast Tool Servo (FTS) Actuator System mounted on an Air-Bearing Table for Surface Texturing

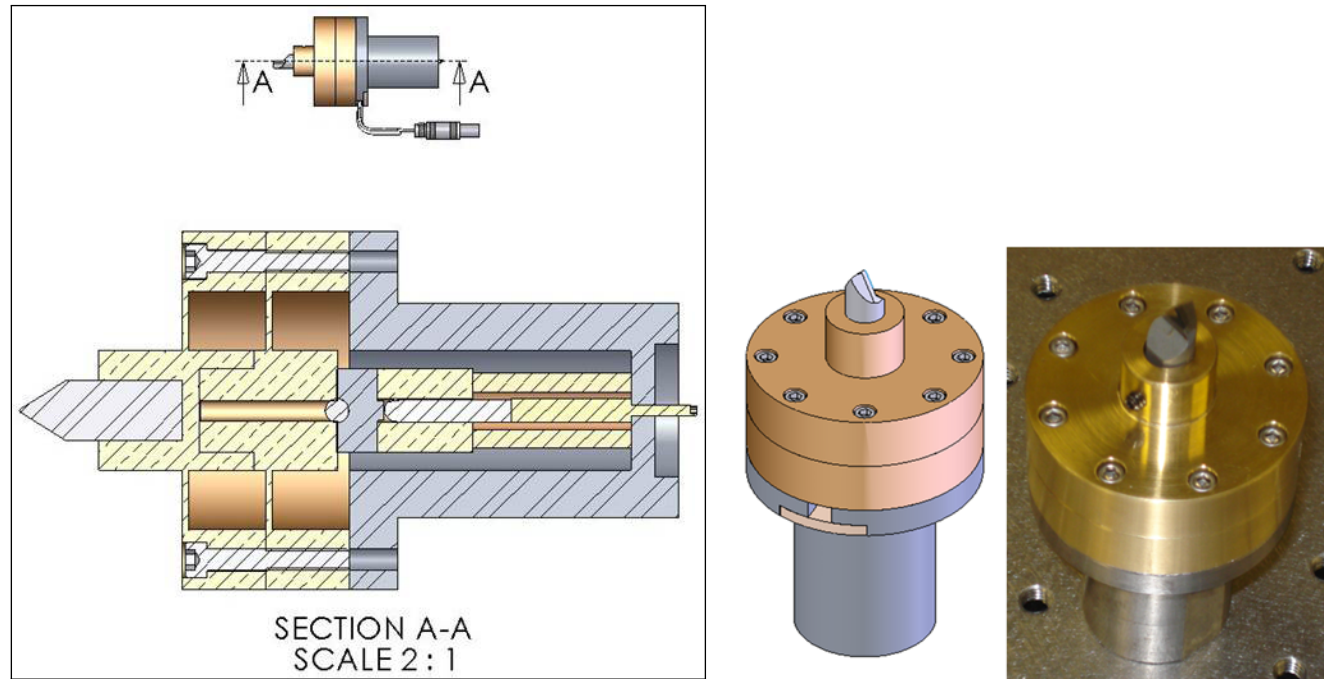


Figure 10.11: Dual Diaphragm FTS Actuator System: (DDFTS CAD Model of Cross-Section (Left), DDFTS CAD Model (Middle), DDFTS Prototype (Right))

The dual diaphragm FTS is a compact system-capable of being intergraded with conventual CNC turning equipment; such that, non-circular turning and surface texturing machining can be performed using a single platform.

10.1.5 Nano-Positioning Stage

In Collaboration with the Center for Scalable and Integrated Nanomanufacturing (SINAM), we designed, manufactured, and controlled a two degree-of-freedom nano-positioning stage. This stage integrates nano-precision with flexural machine design for nano-manufacturing processes.

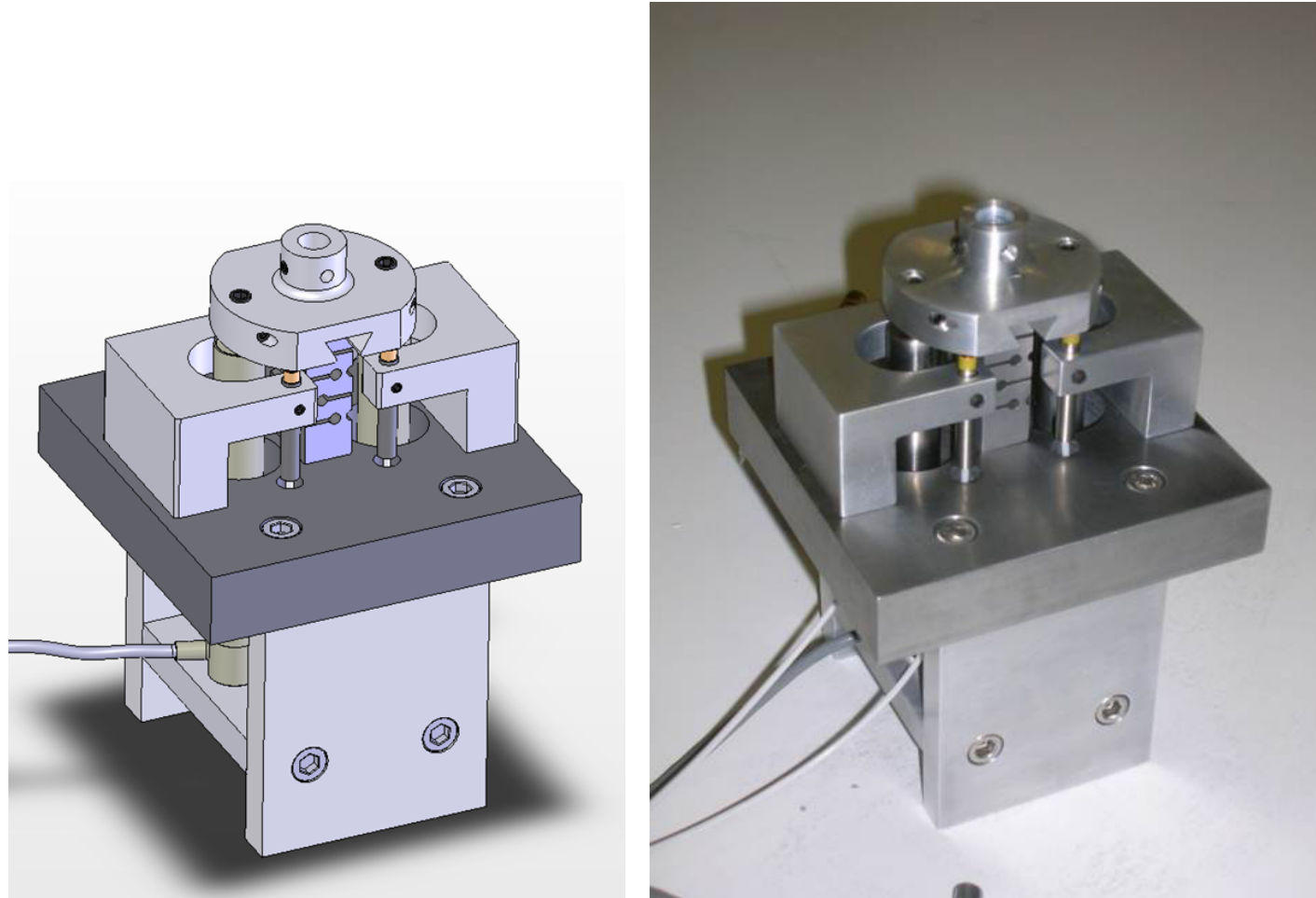


Figure 10.12: Two DoF Nano-Positioning Actuator System CAD Model and Prototype

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APPENDIX A

Manufacture Drawings

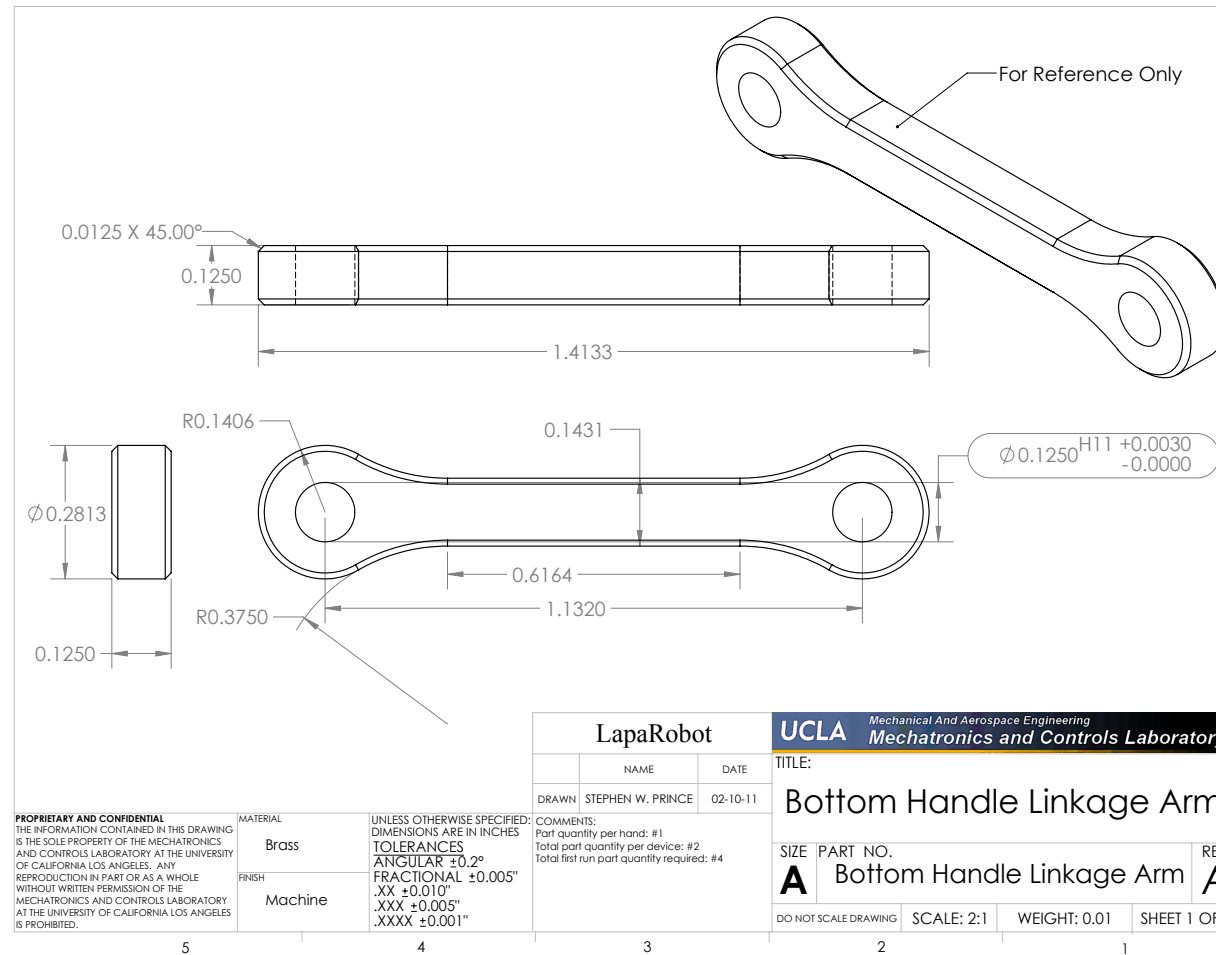


Figure A.1: LapaRobot: Bottom Handle Linkage Arm CAD Drawing

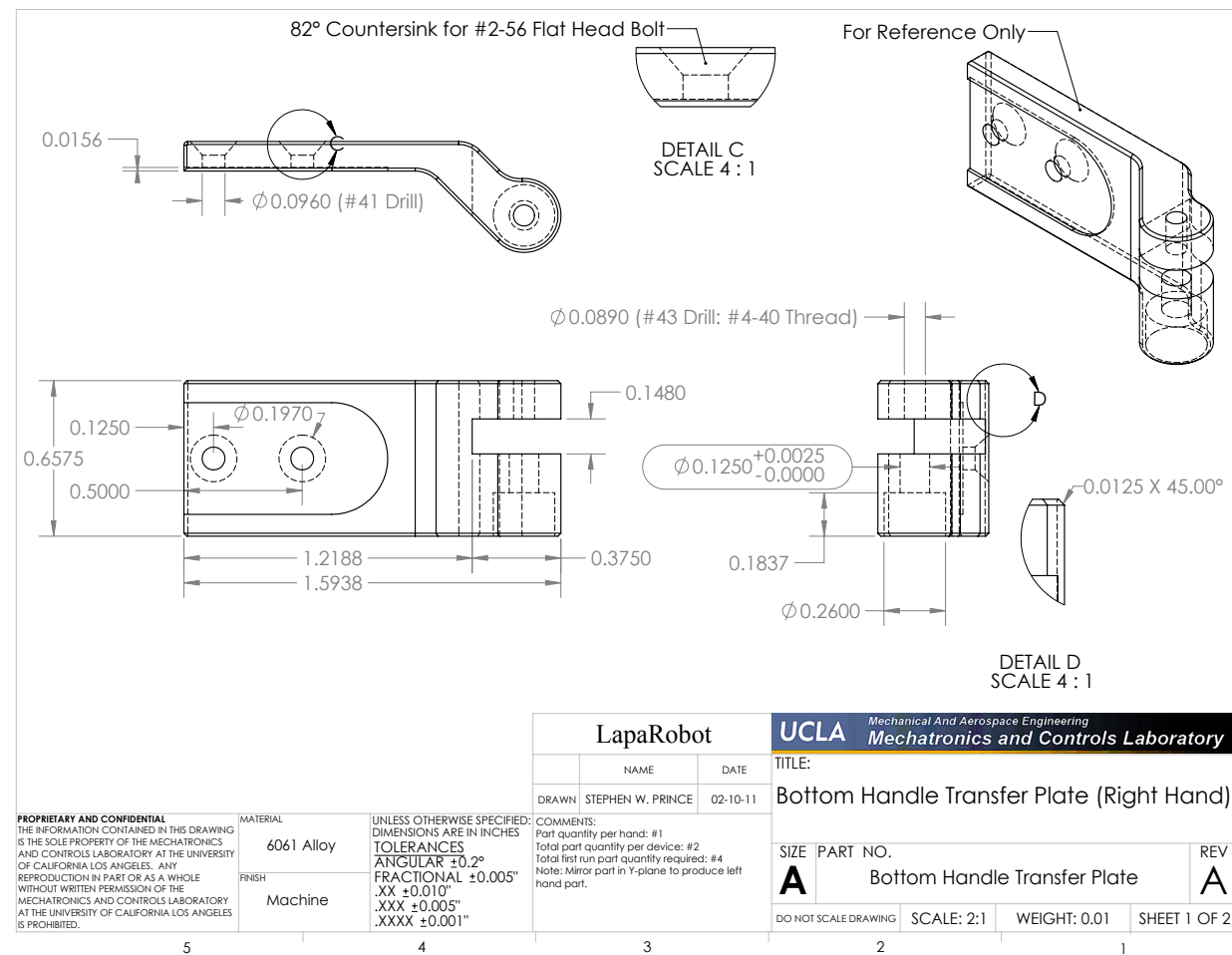


Figure A.2a: LapaRobot: Bottom Handle Transfer Plate CAD Drawing

Figure A.2b: LapaRobot: Bottom Handle Transfer Plate CAD Drawing

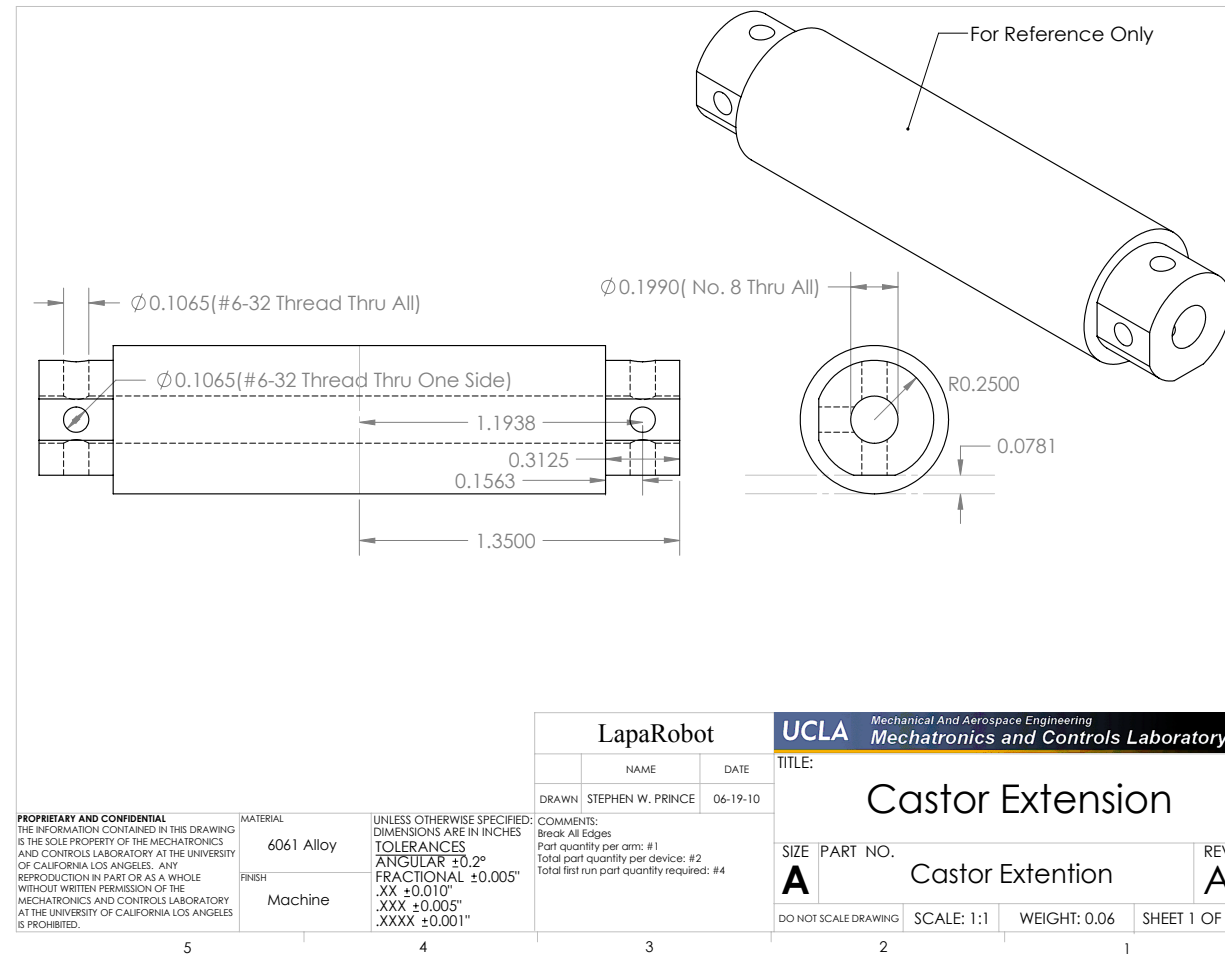


Figure A.3: LapaRobot: Castor Extension CAD Drawing

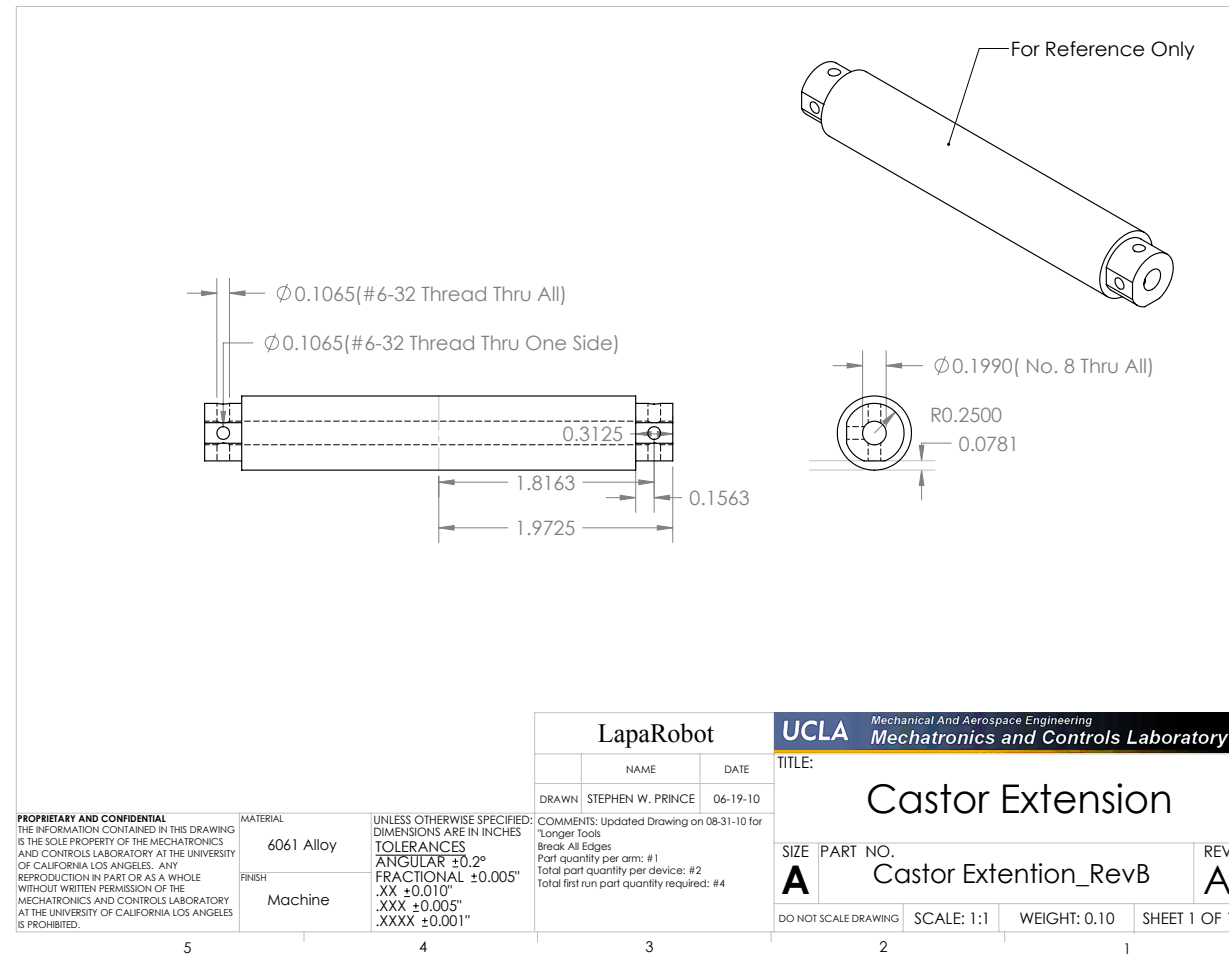


Figure A.4: LapaRobot: Castor Extension RevB CAD Drawing

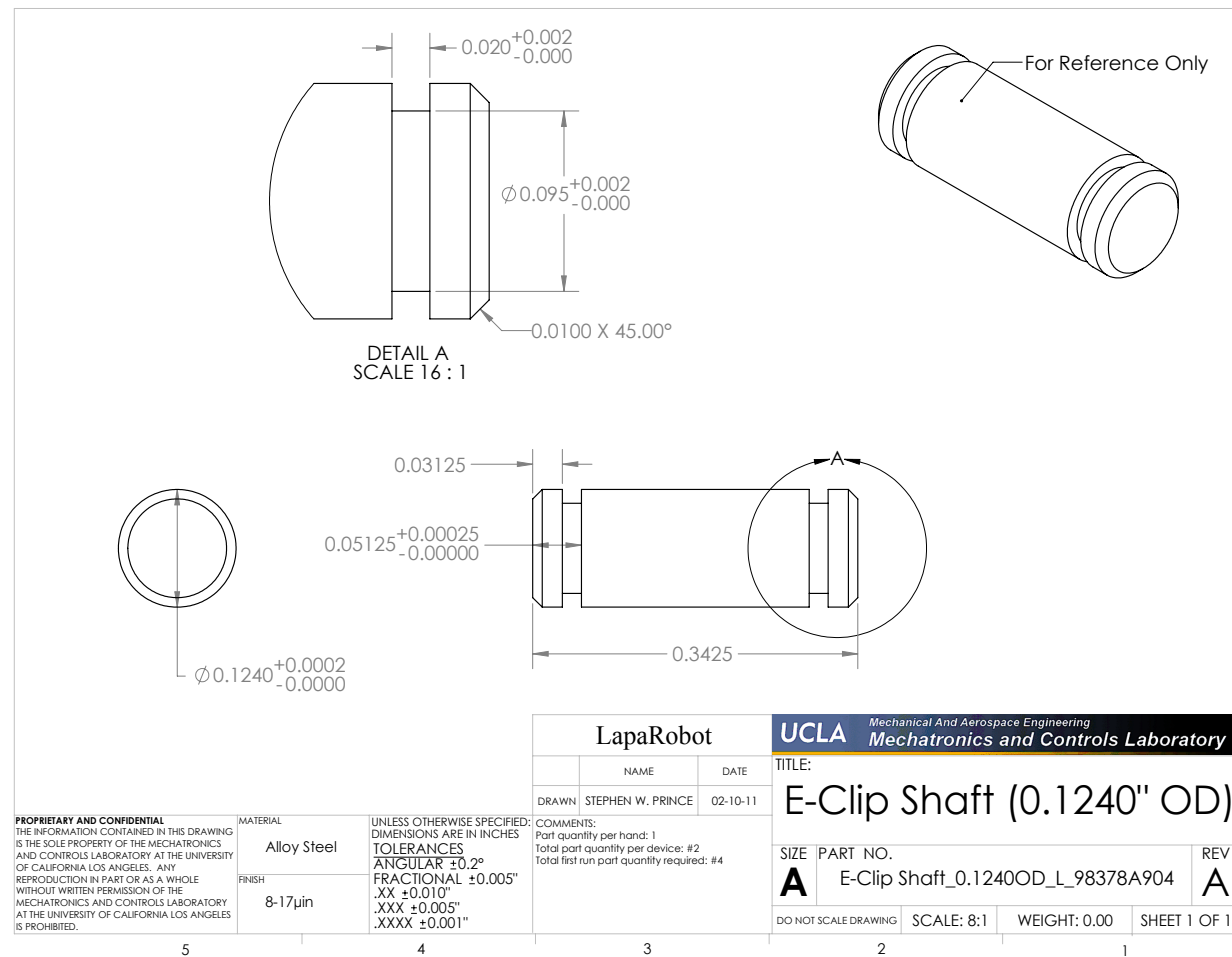


Figure A.5: LapaRobot: E-Clip Shaft CAD Drawing

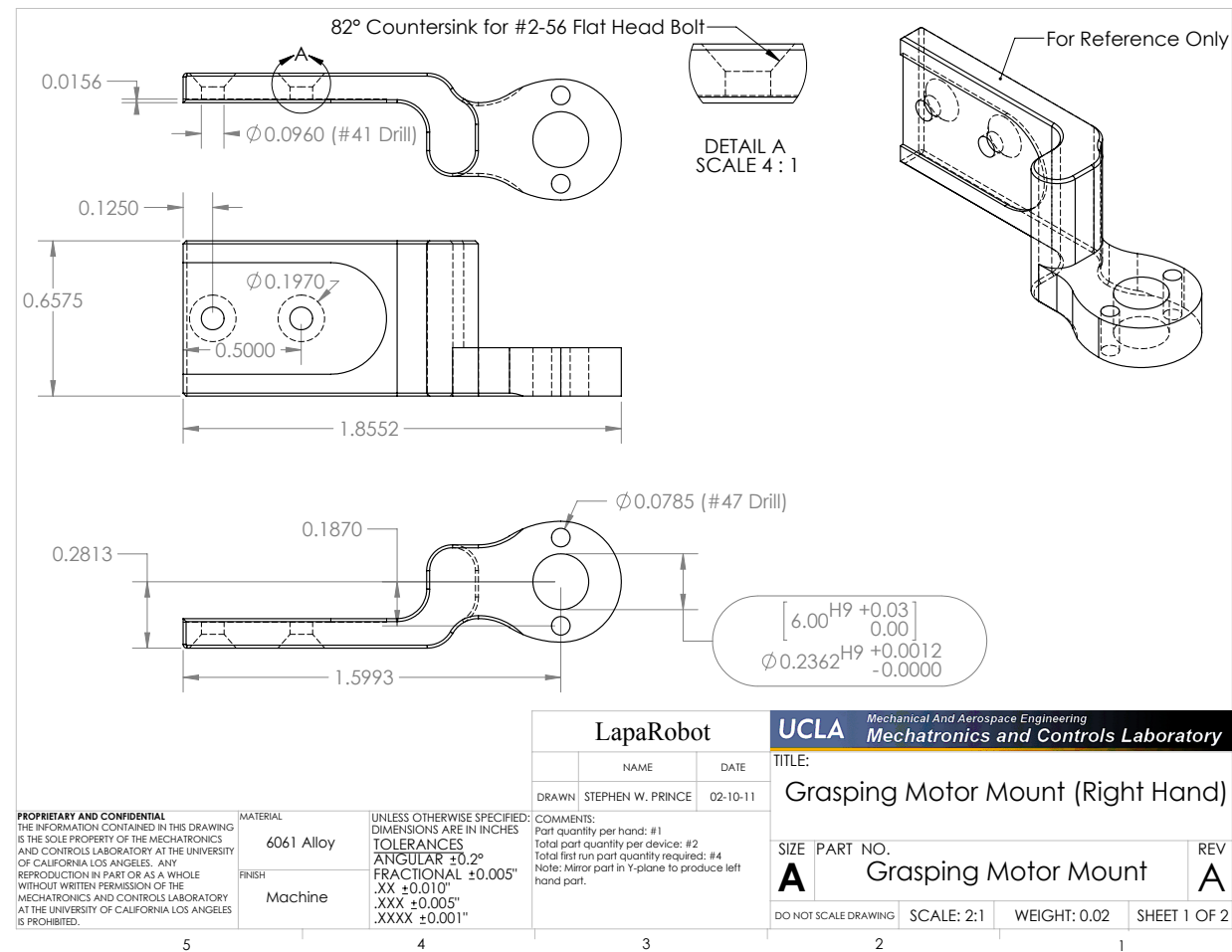


Figure A.6a: LapaRobot: Grasping Motor Mount CAD Drawing

Figure A.6b: LapaRobot: Grasping Motor Mount CAD Drawing

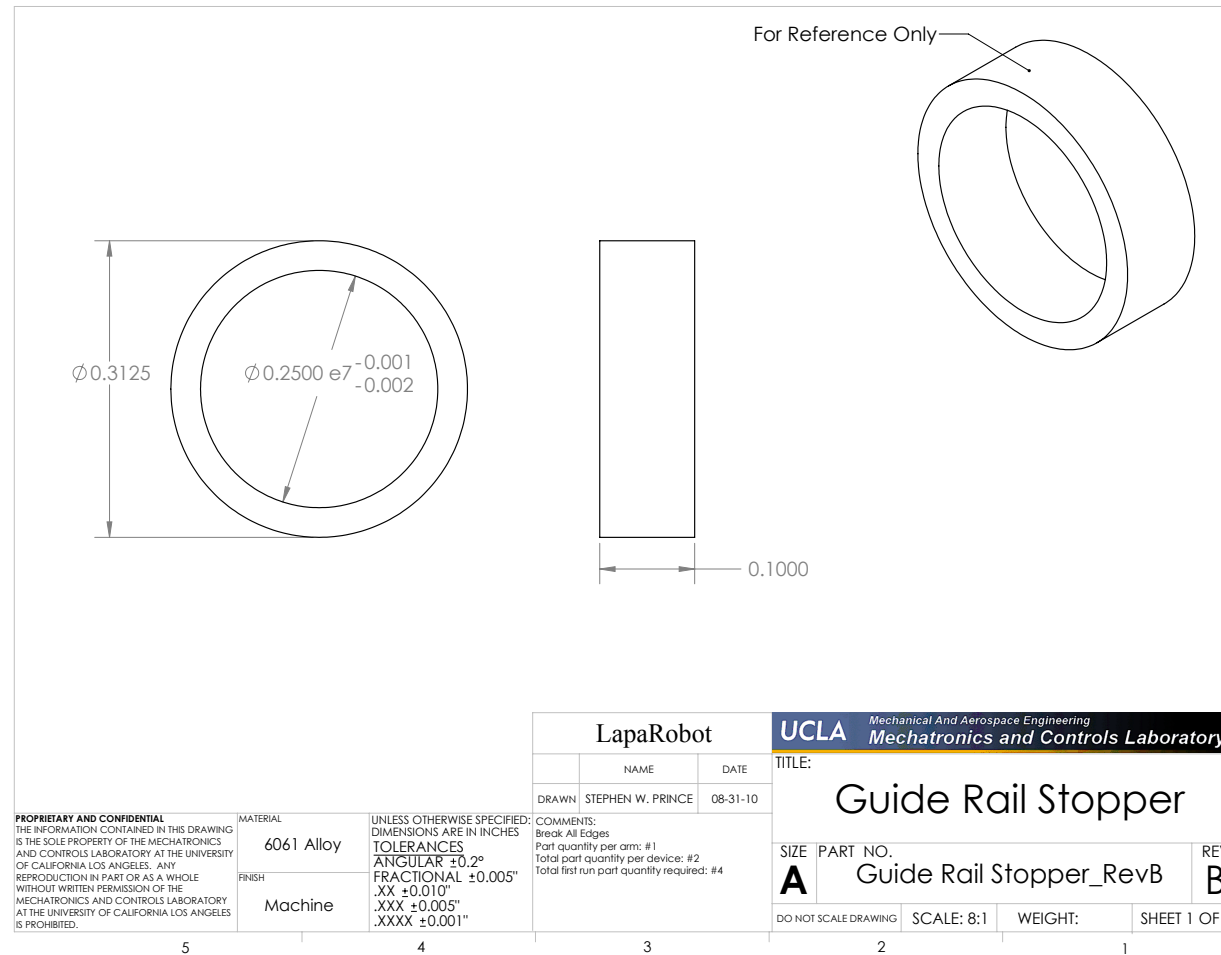


Figure A.7: LapaRobot:Guide Rail Stopper RevB CAD Drawing

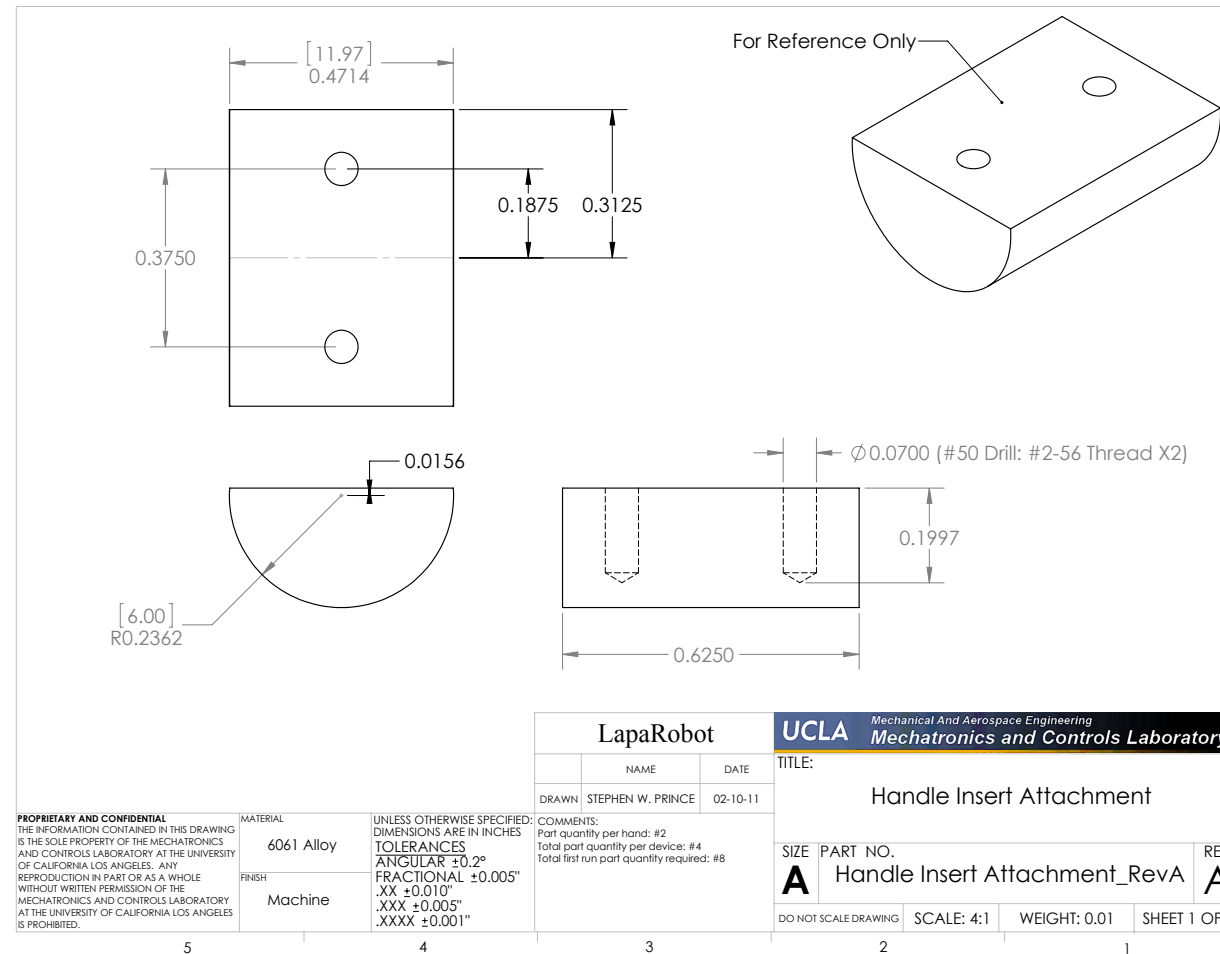


Figure A.8: LapaRobot:Handle Insert Attachment RevA CAD Drawing

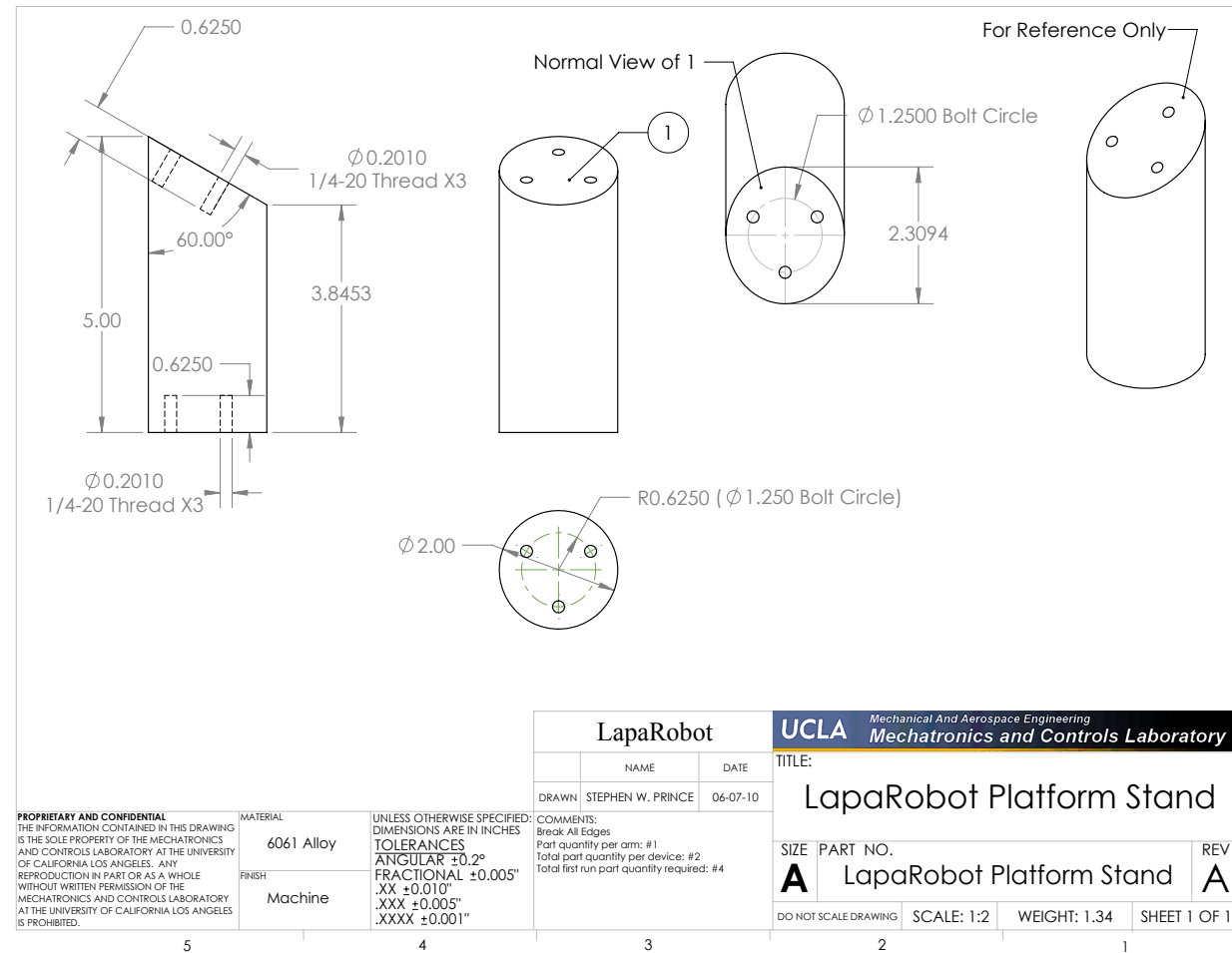


Figure A.9: LapaRobot: Platform Stand CAD Drawing

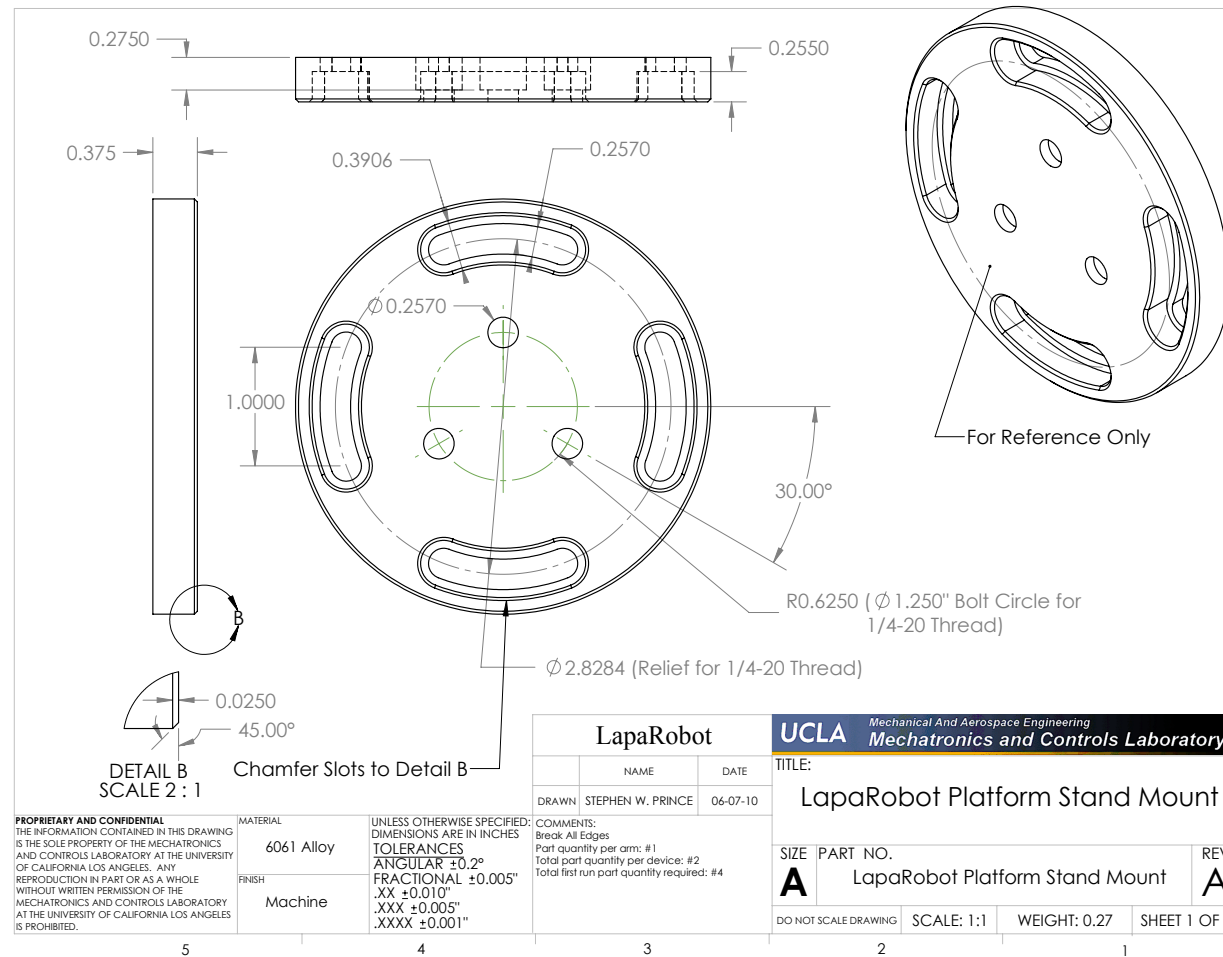


Figure A.10: LapaRobot: Platform Stand Mount CAD Drawing

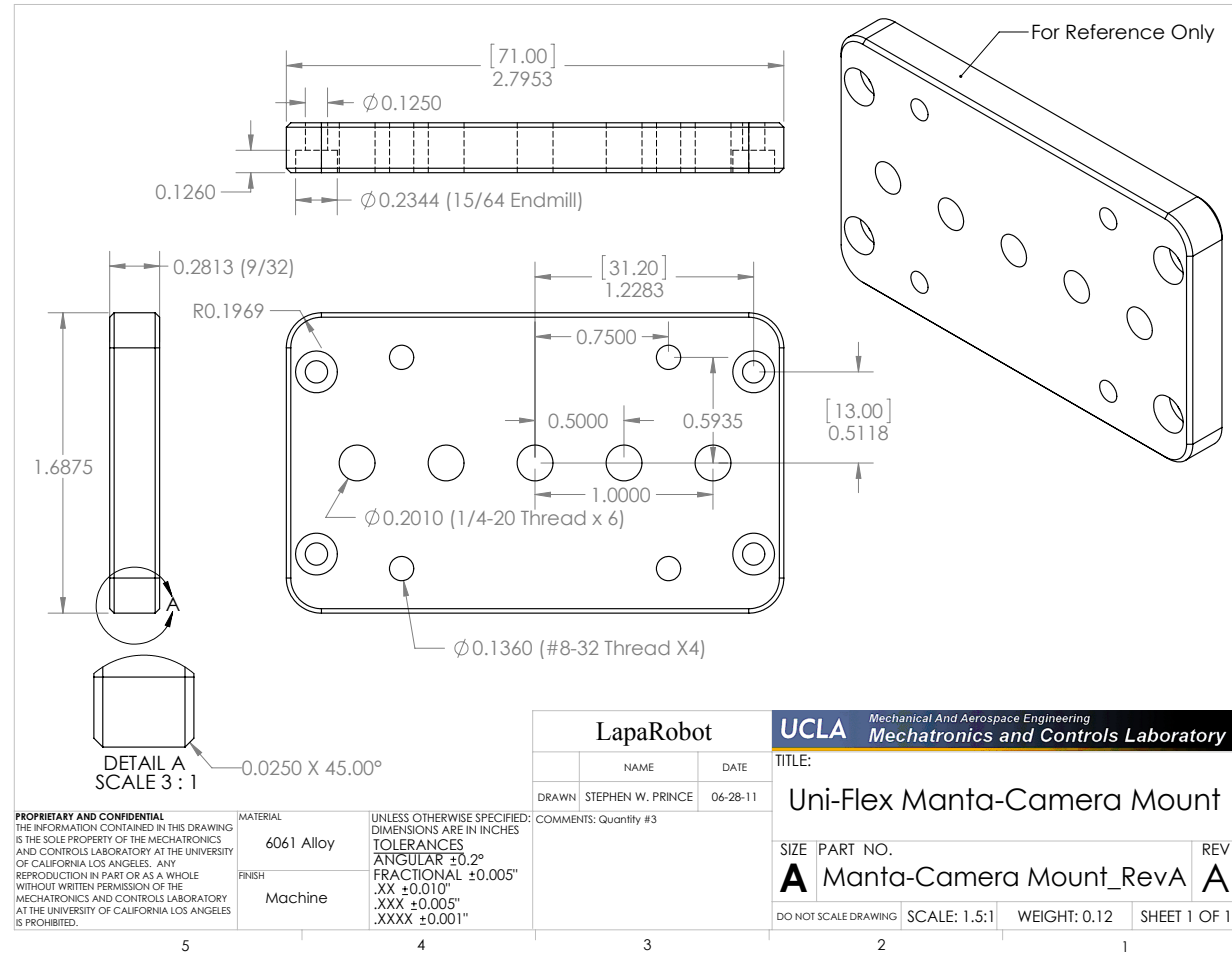


Figure A.11: LapaRobot: Manta Camera Mount RevA CAD Drawing

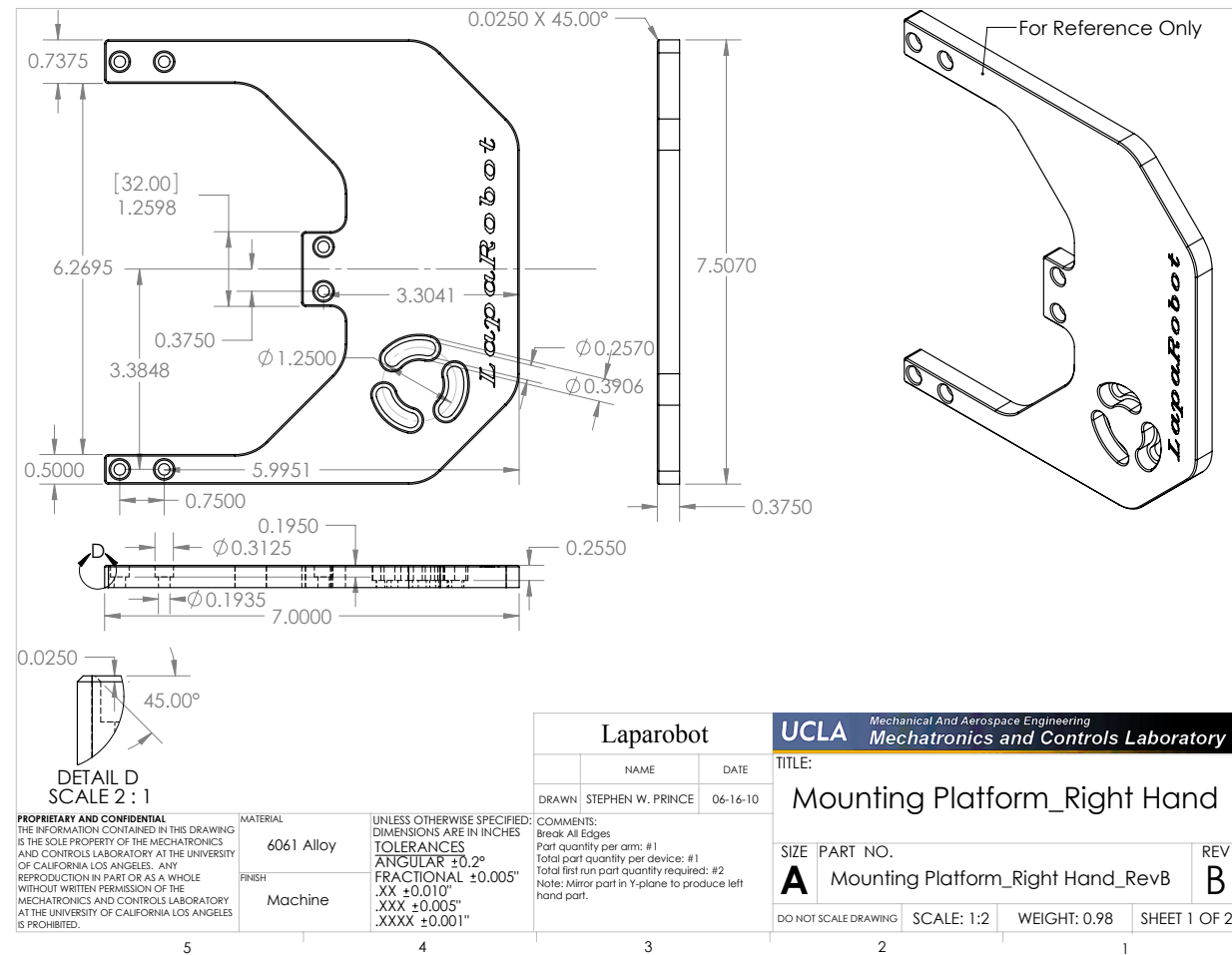


Figure A.12a: Laparobot: Mounting for Platform Right-Hand RevB CAD Drawing

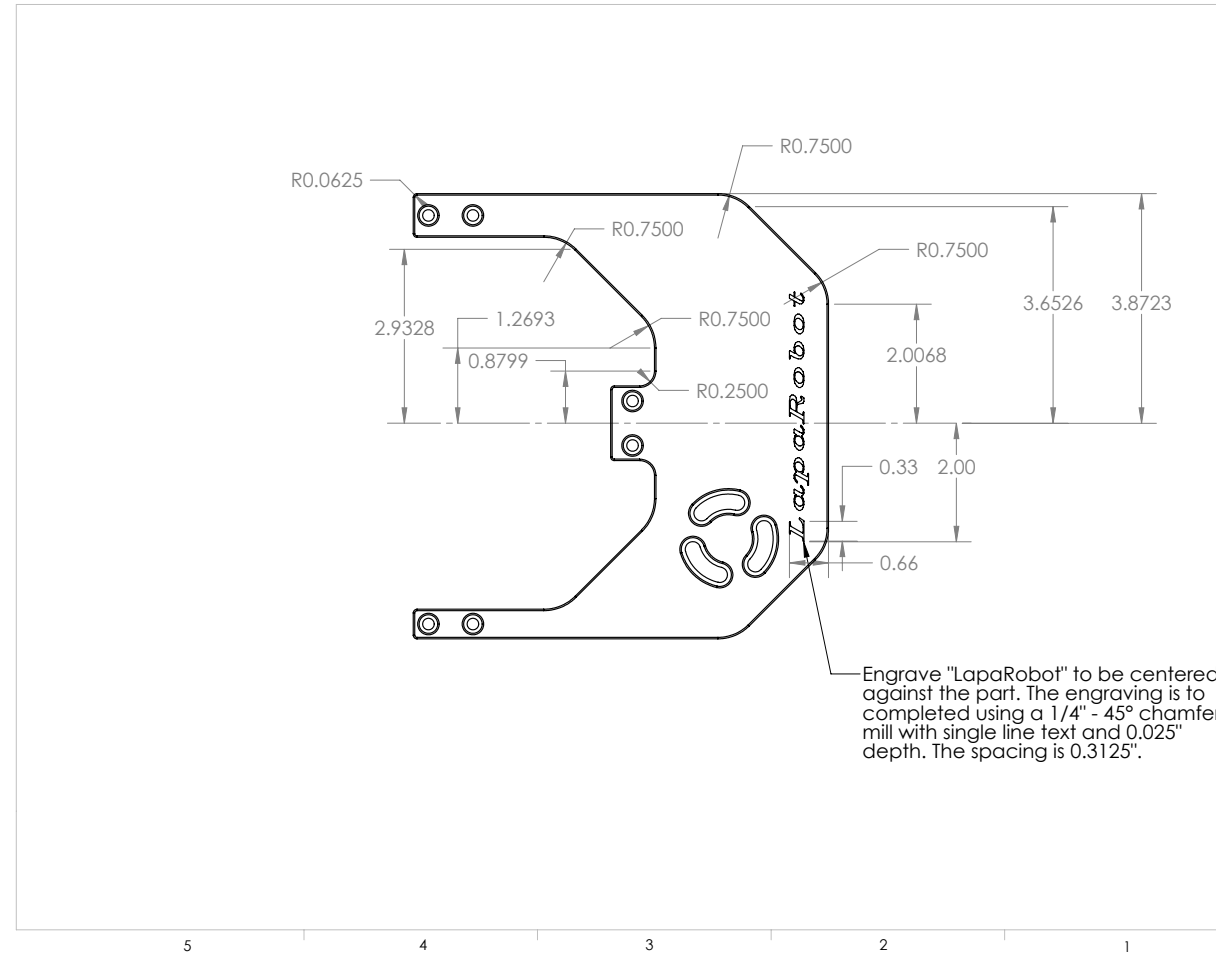


Figure A.12b: LapaRobot: Mounting Platform for Right-Hand RevB CAD Drawing

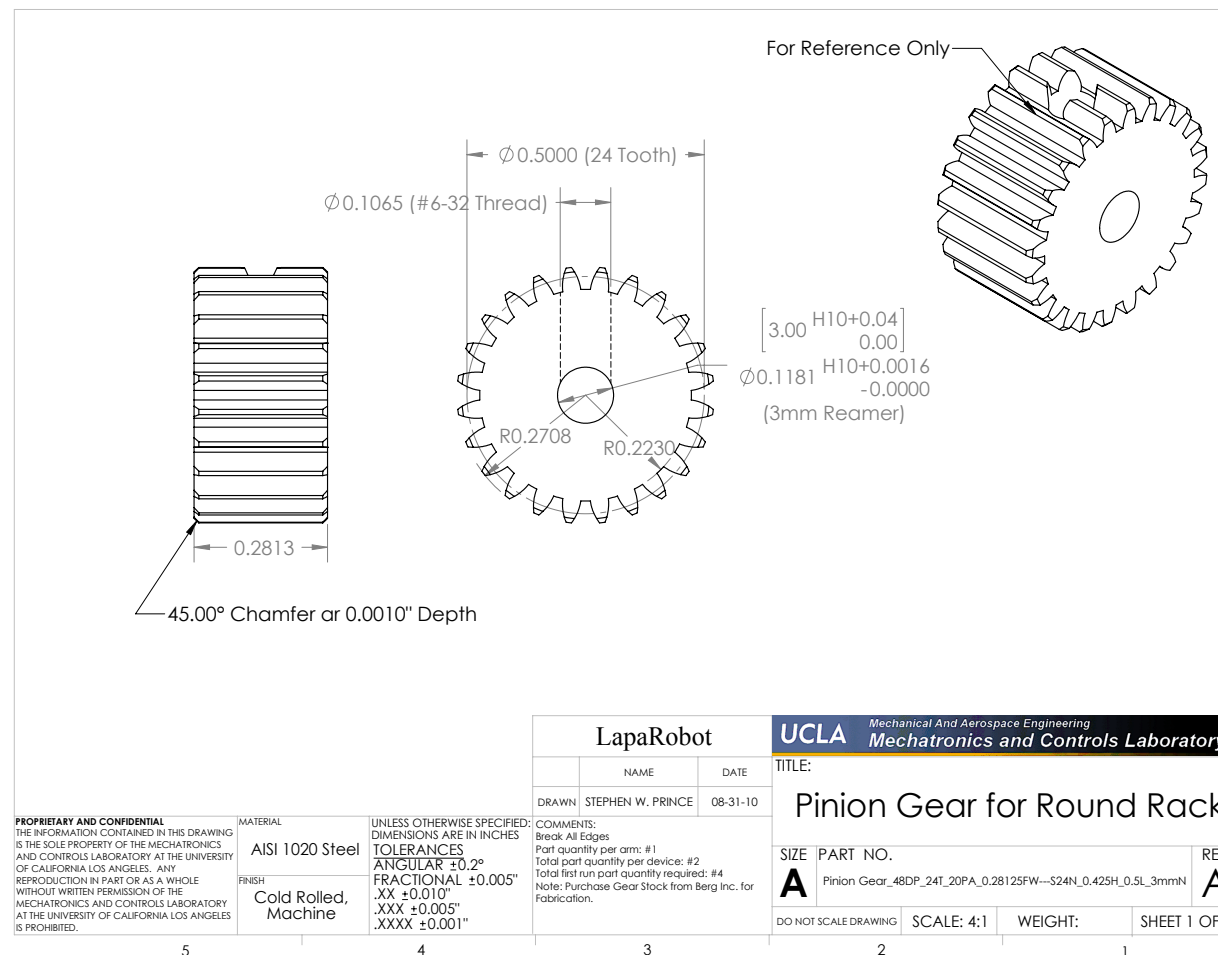


Figure A.13: LapaRobot: Pinion Gear (48DP 24T 20PA) CAD Drawing

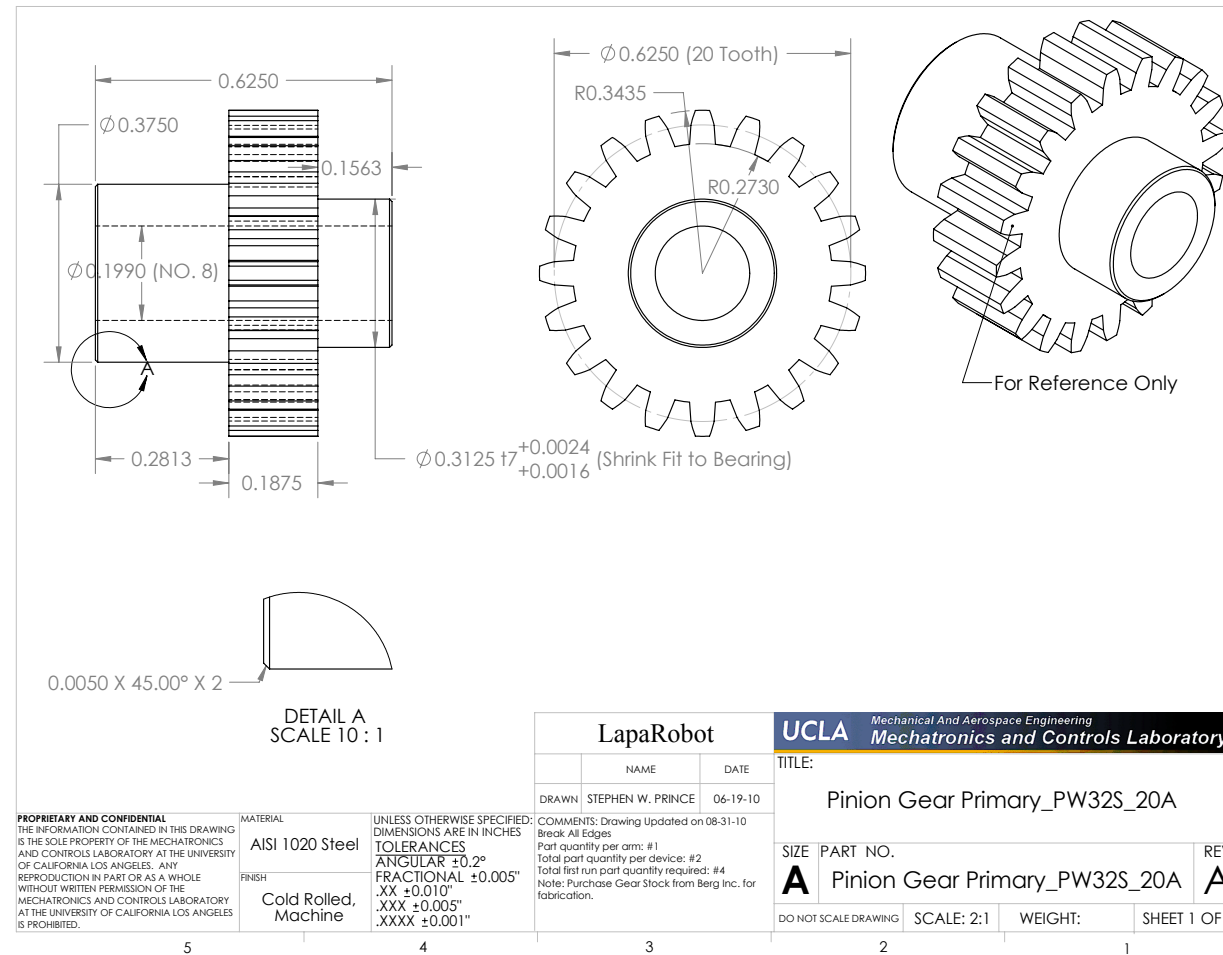


Figure A.14: LapaRobot: Pinion Gear Primary (PW32S 20A) CAD Drawing

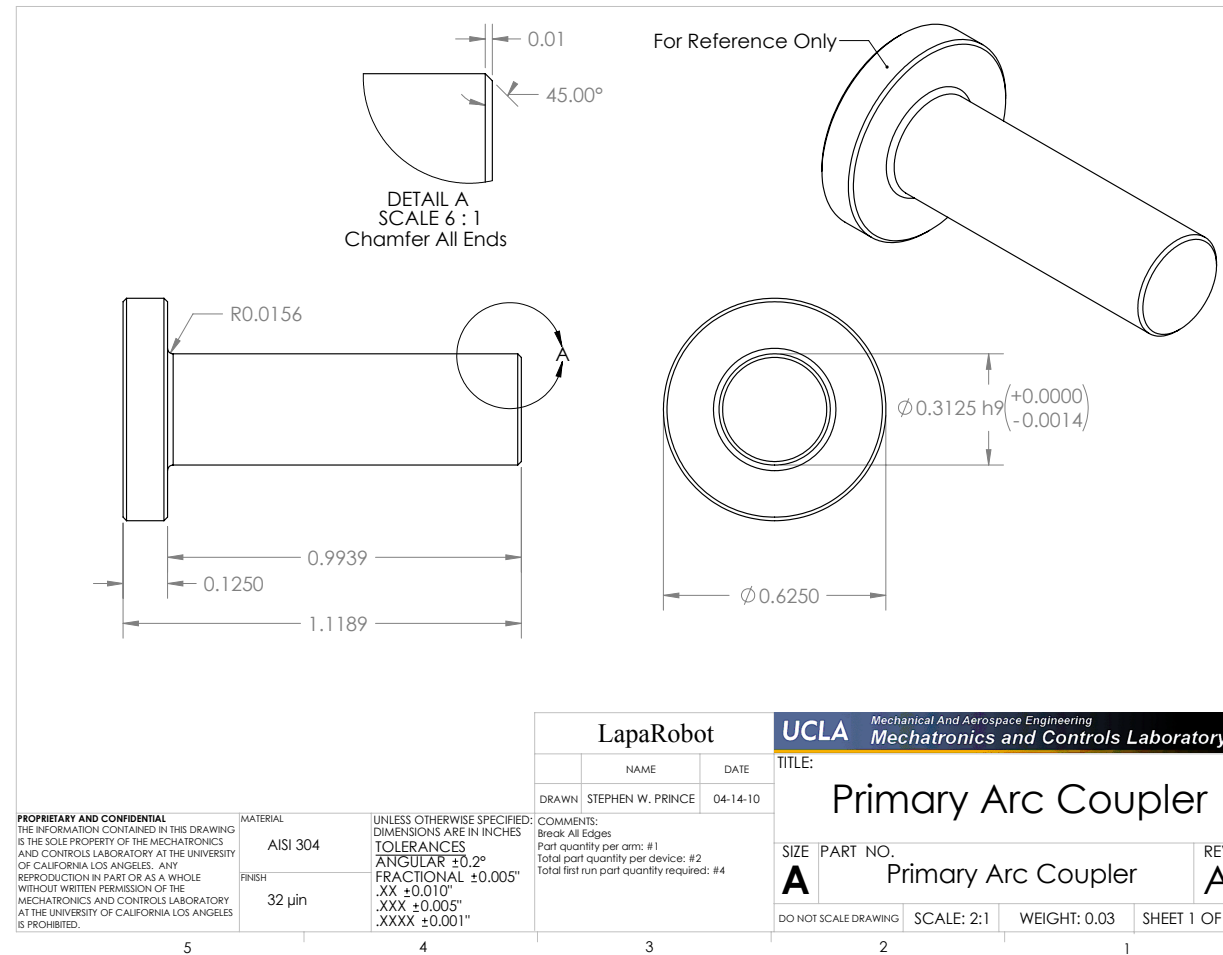


Figure A.15: LapaRobot: Primary Arc Coupler CAD Drawing

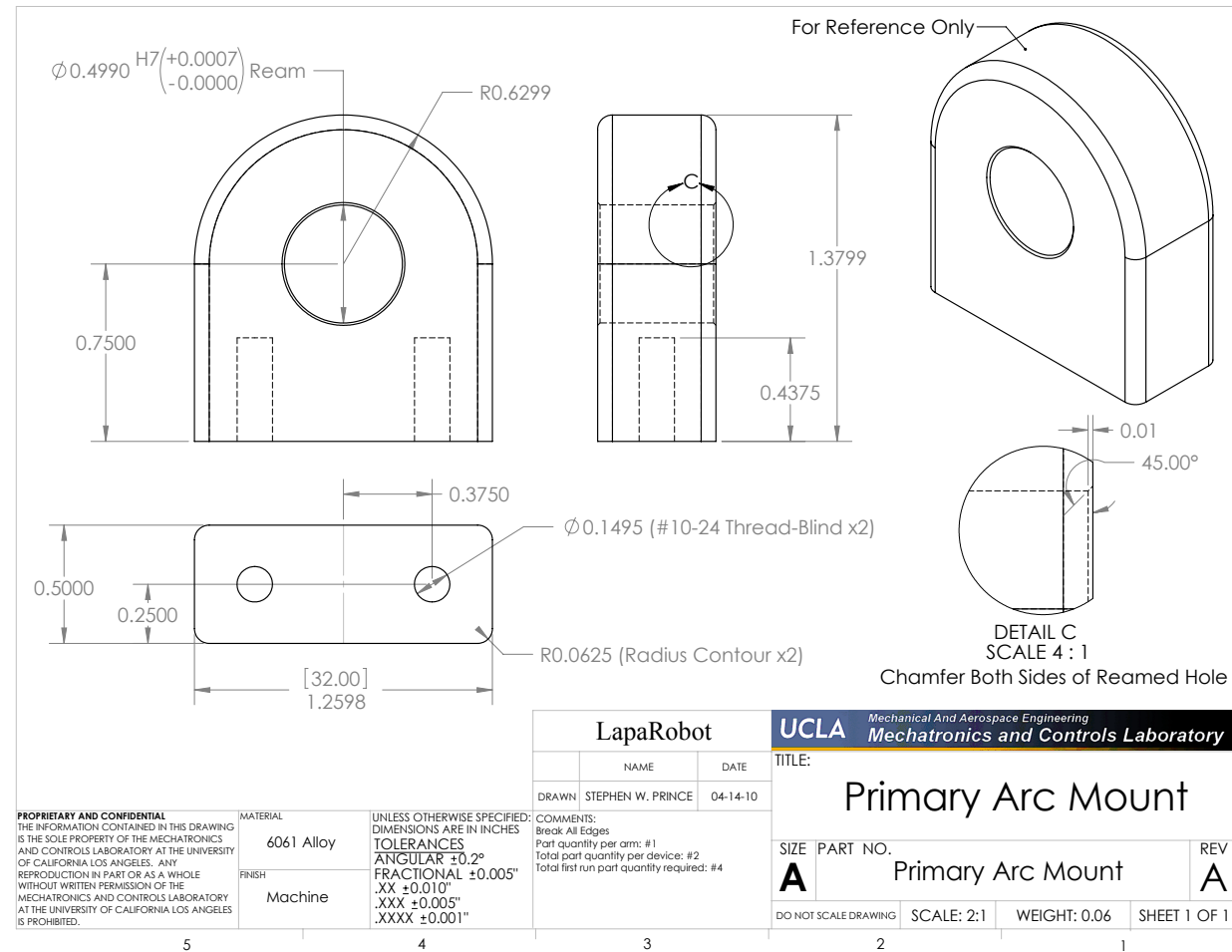


Figure A.16: LapaRobot: Primary Arc Mount CAD Drawing

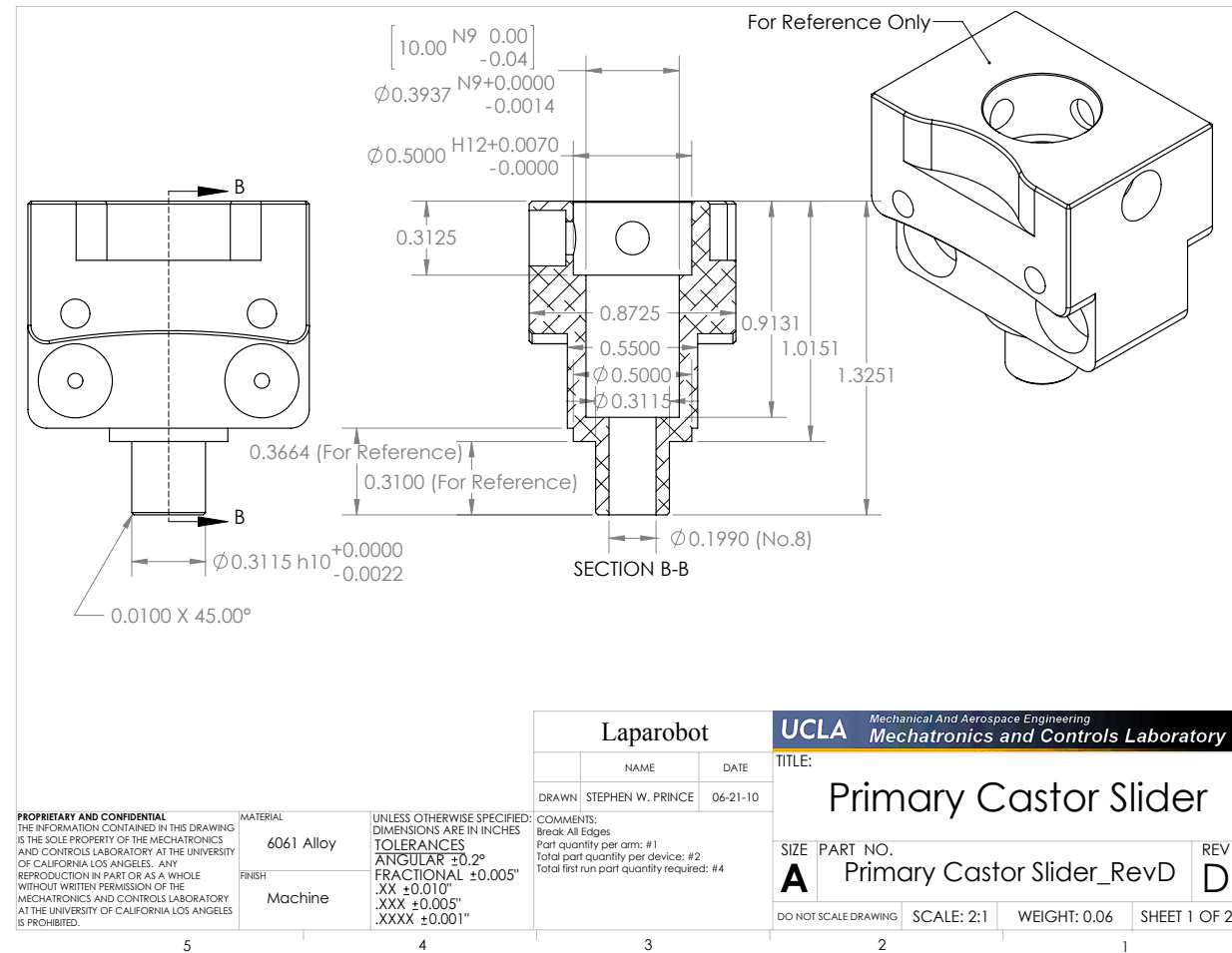


Figure A.17a: LapaRobot: Primary Castor Slider RevD CAD Drawing

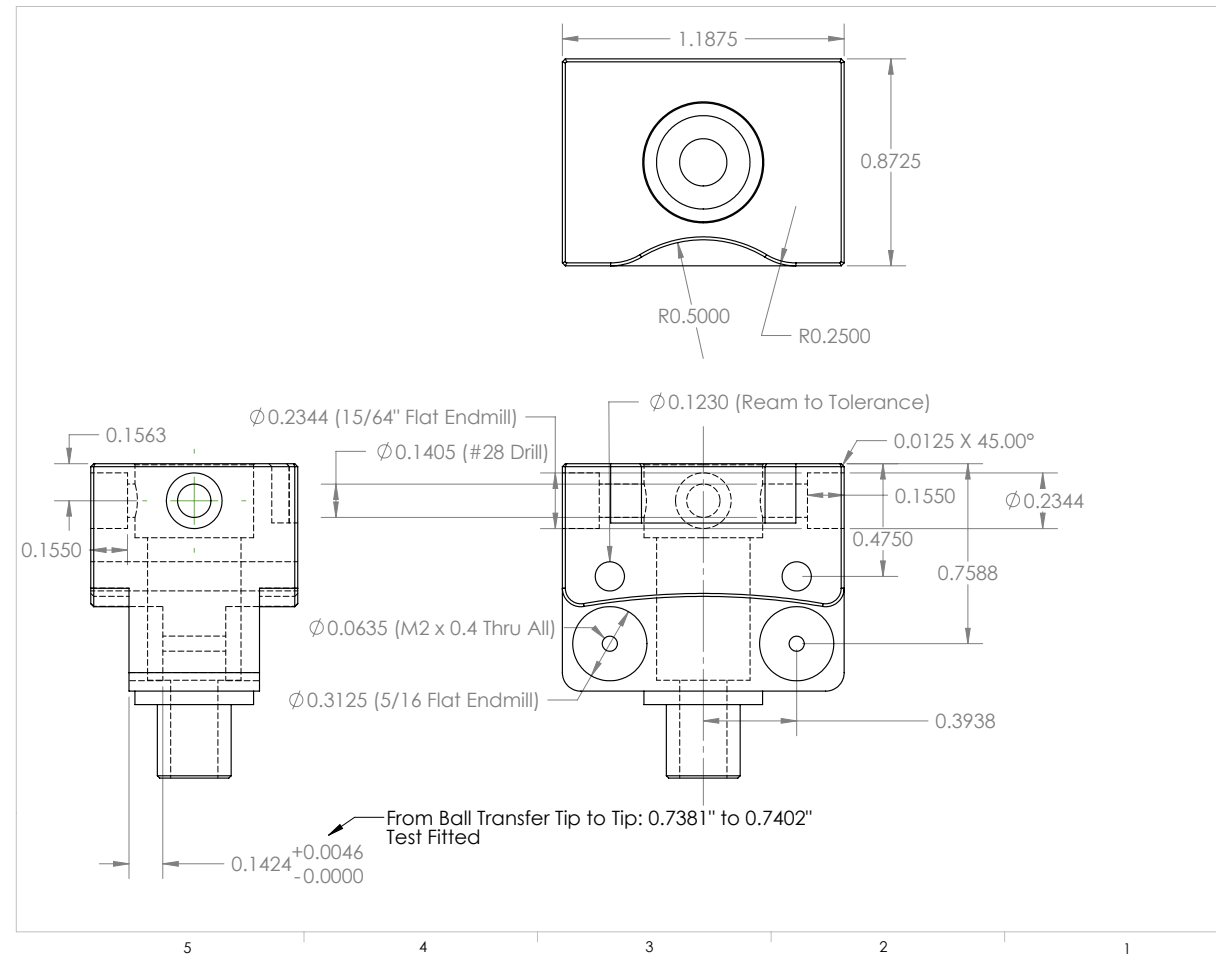


Figure A.17b: LapaRobot: Primary Castor Slider RevD CAD Drawing

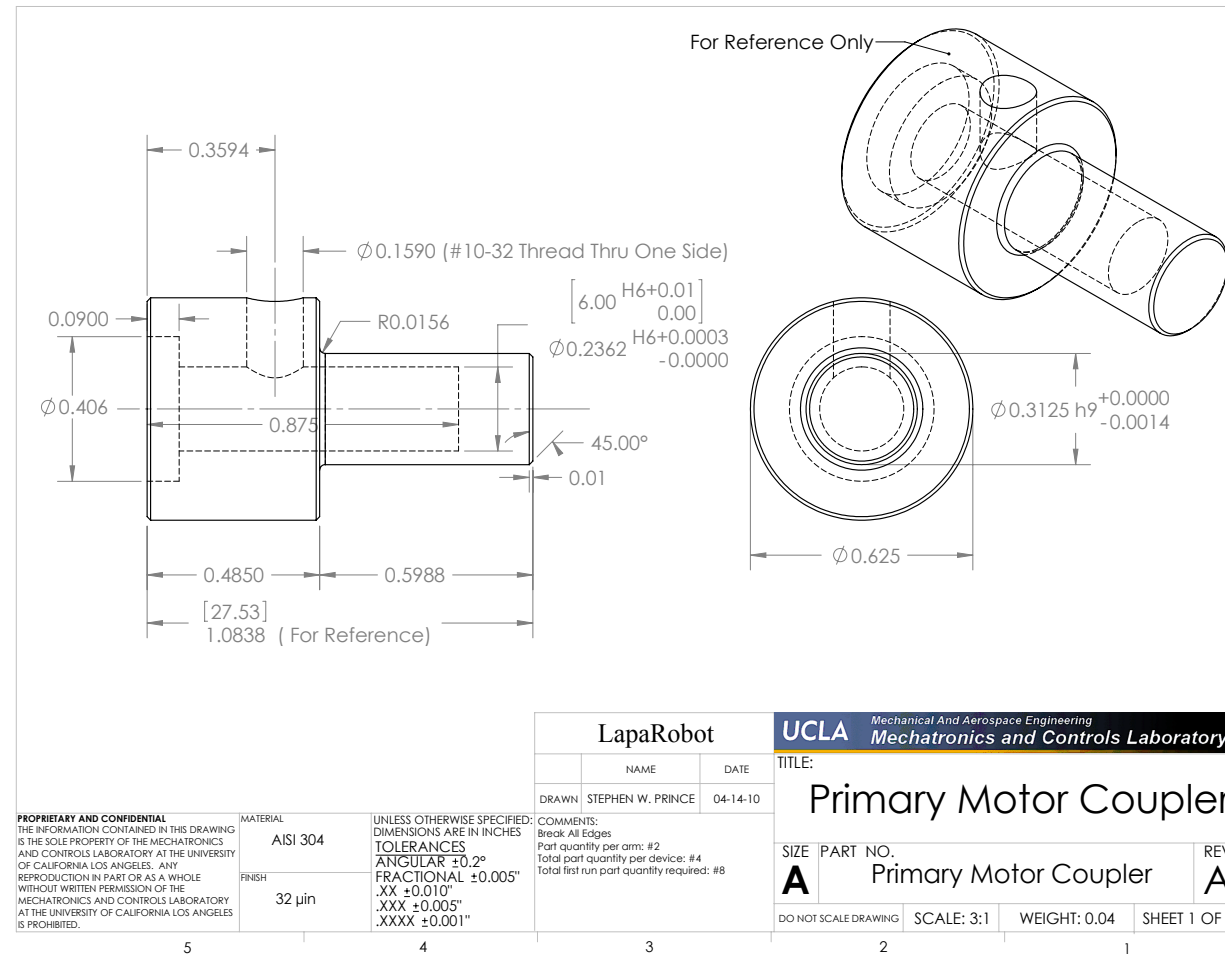


Figure A.18: LapaRobot: Primary Motor Coupler CAD Drawing

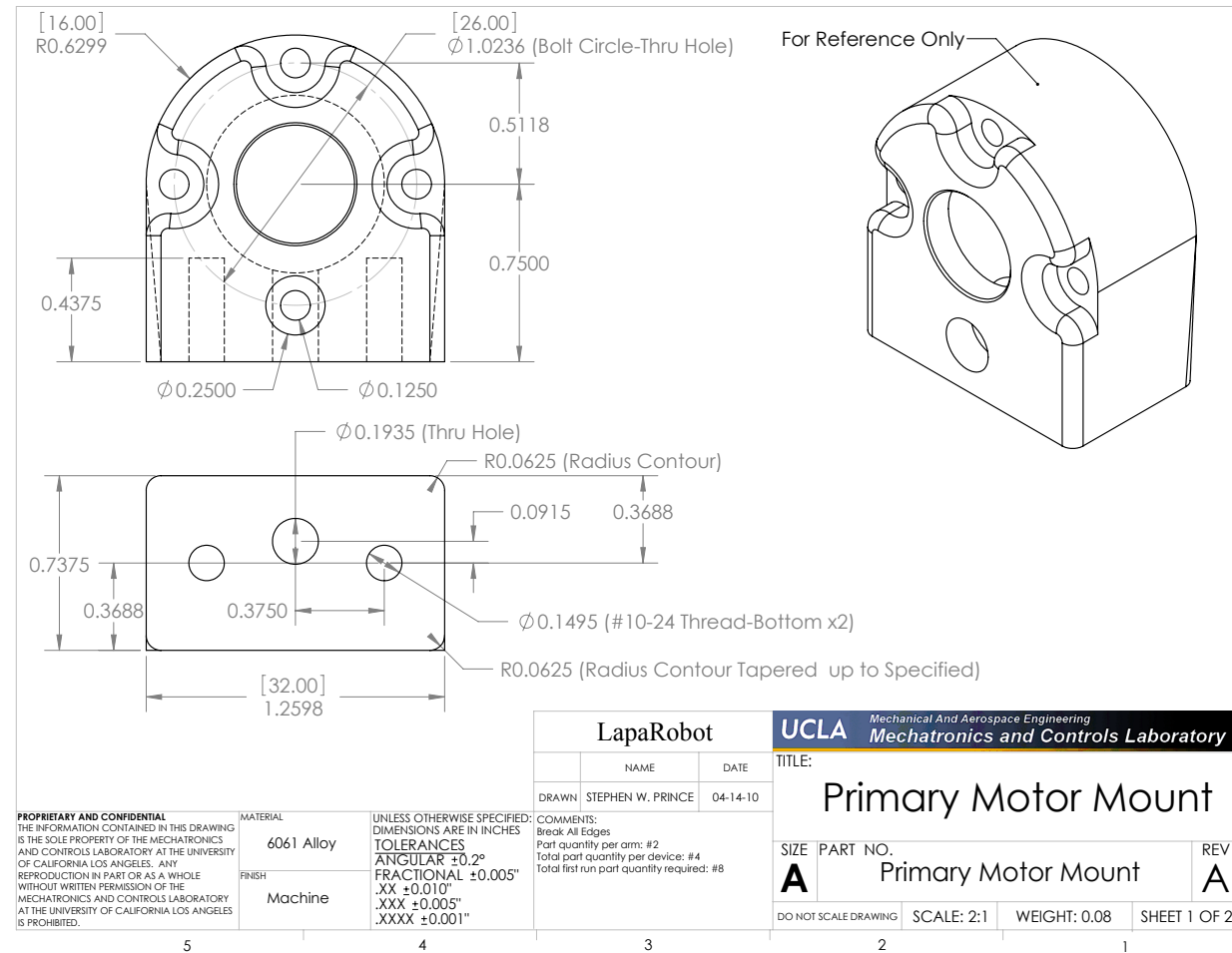


Figure A.19a: LapaRobot: Primary Motor Mount CAD Drawing

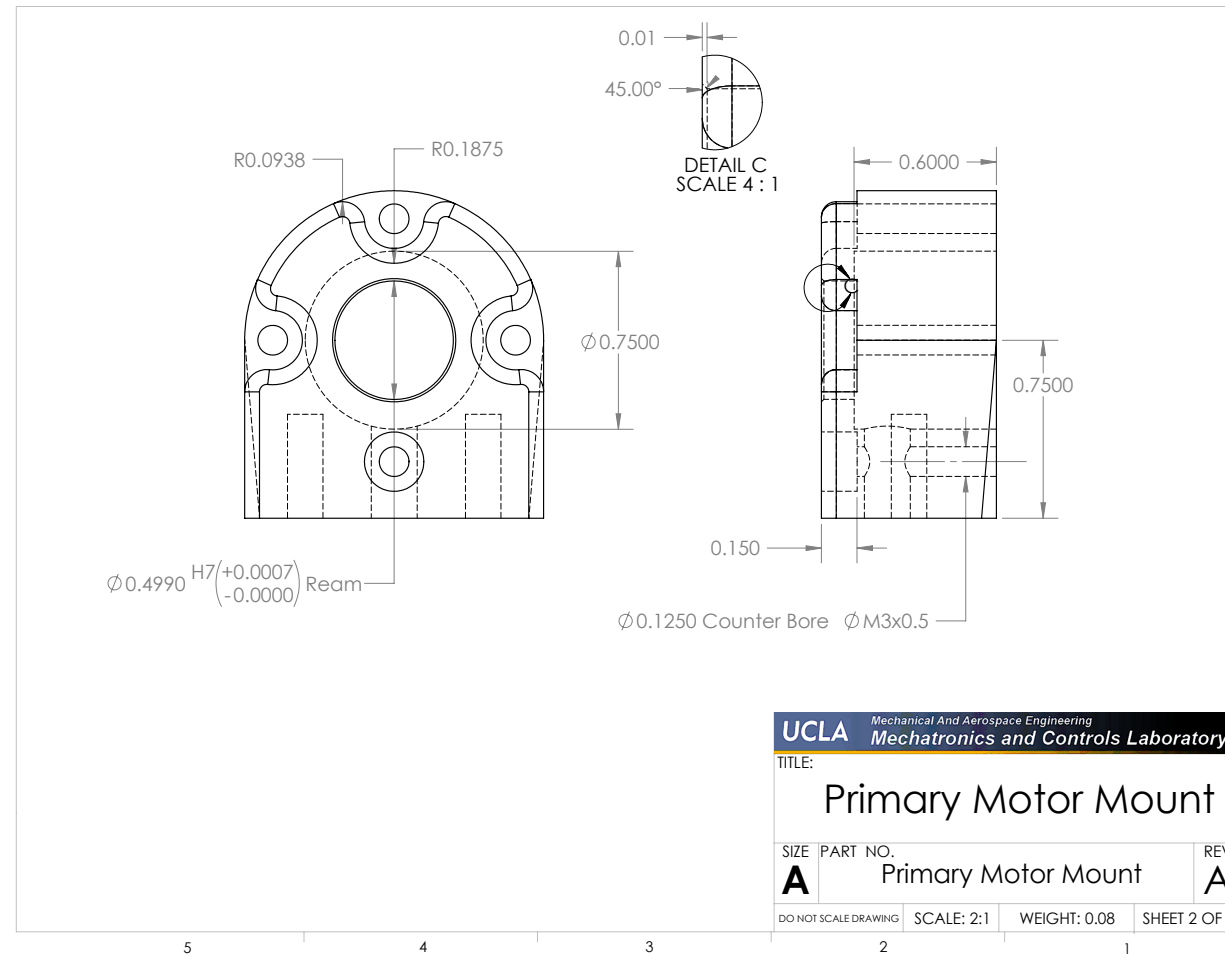


Figure A.19b: LapaRobot: Primary Motor Mount CAD Drawing

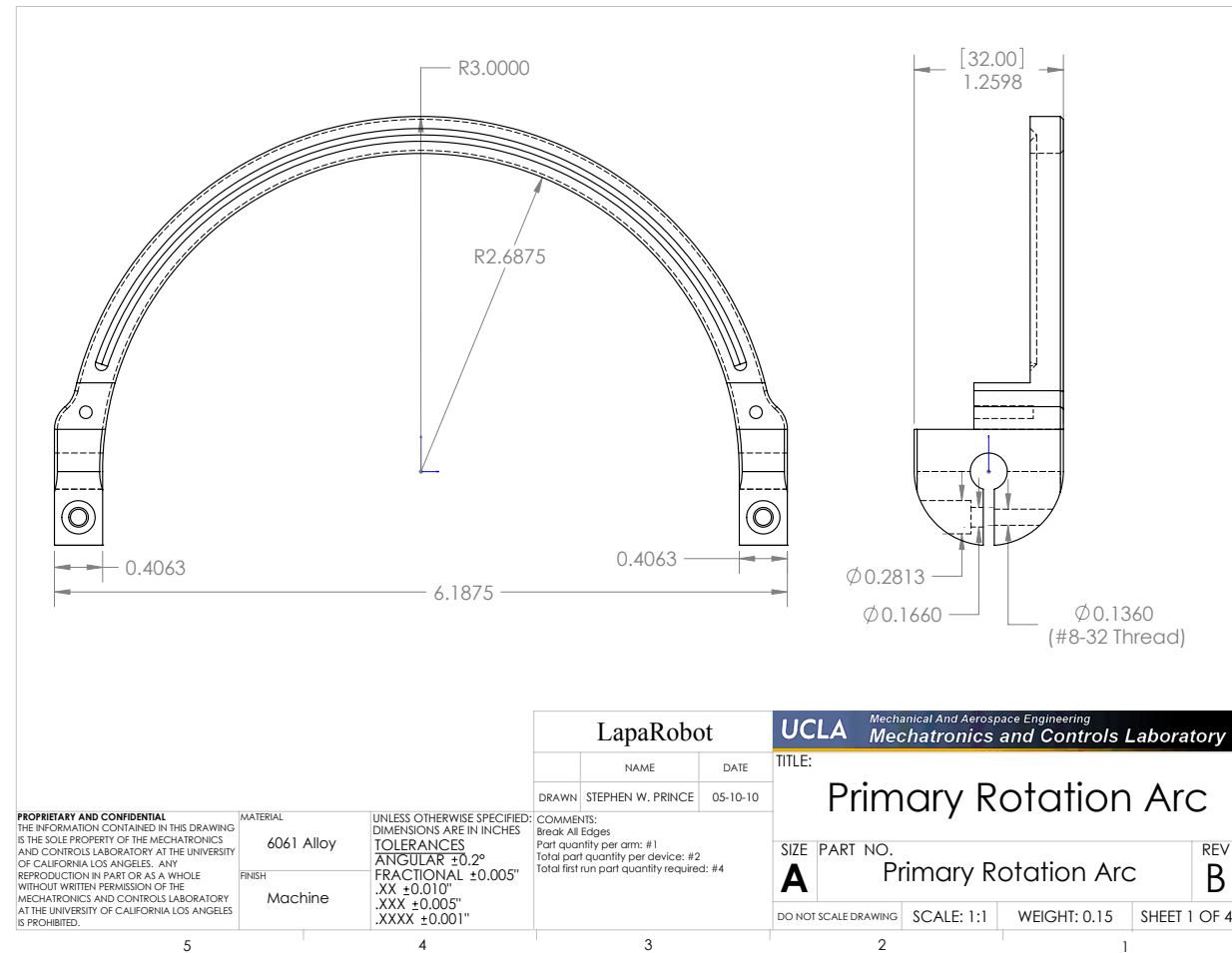


Figure A.20a: LapaRobot: Primary Rotation Arc CAD Drawing

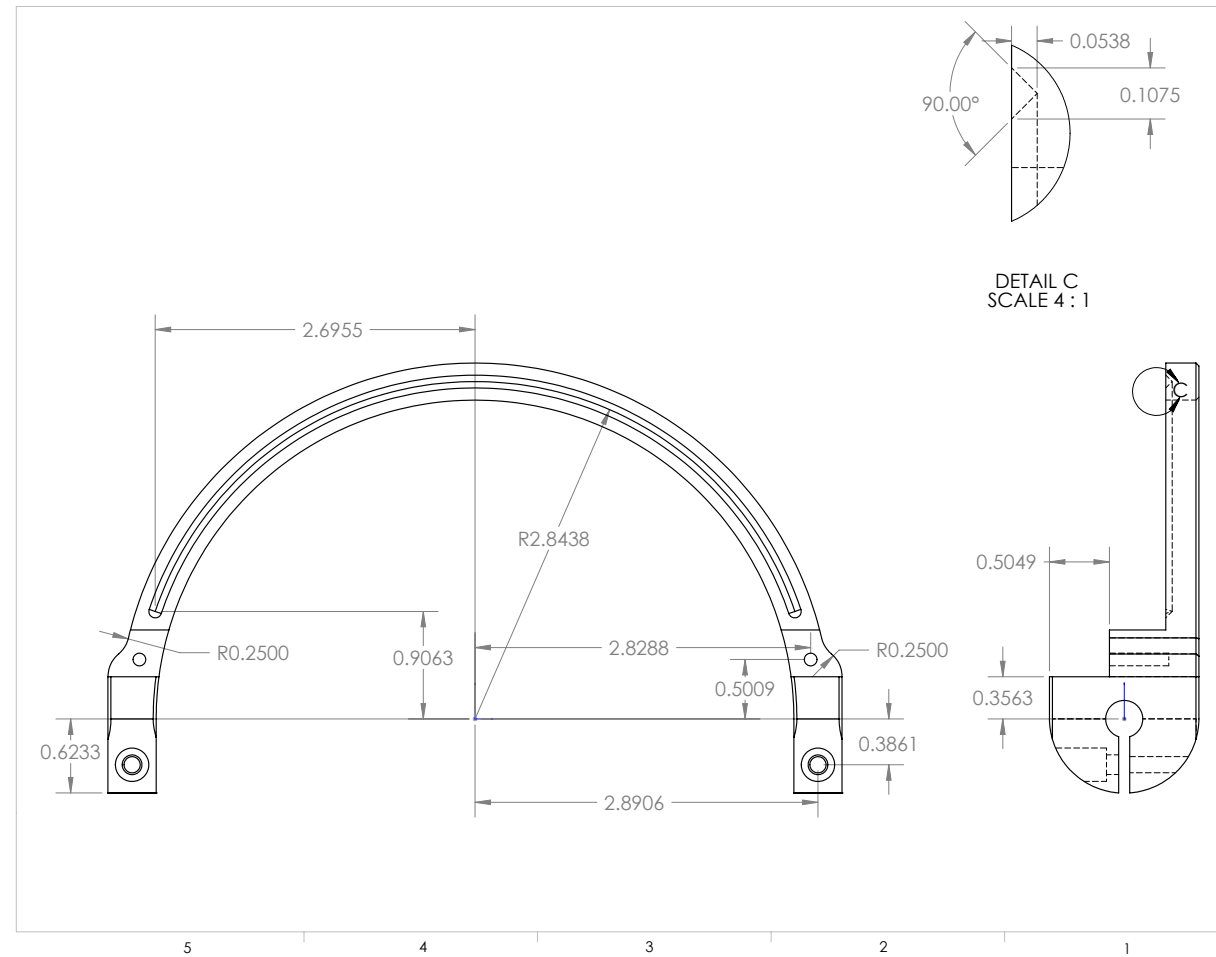


Figure A.20b: LapaRobot: Primary Rotation Arc CAD Drawing

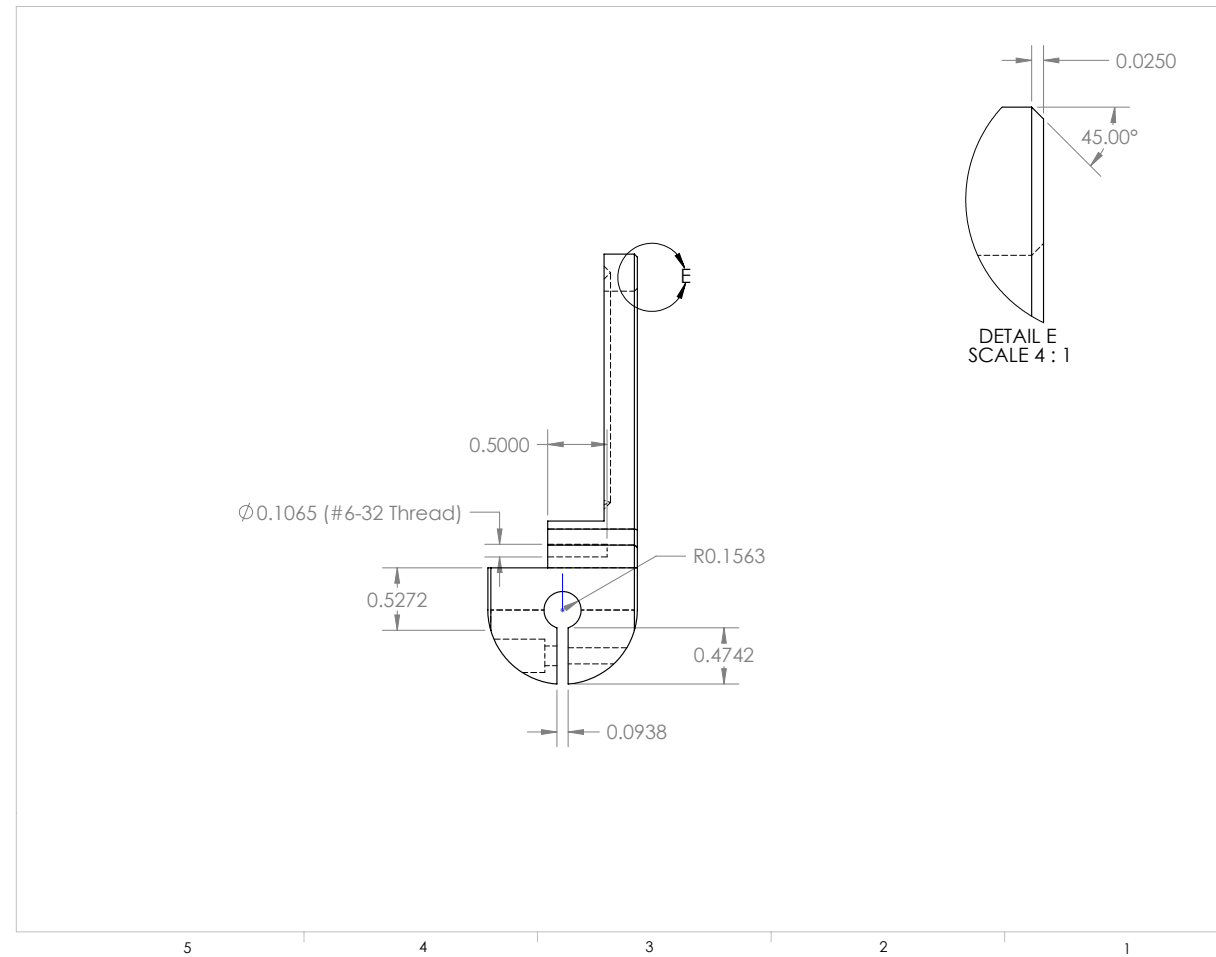


Figure A.20c: LapaRobot: Primary Rotation Arc CAD Drawing

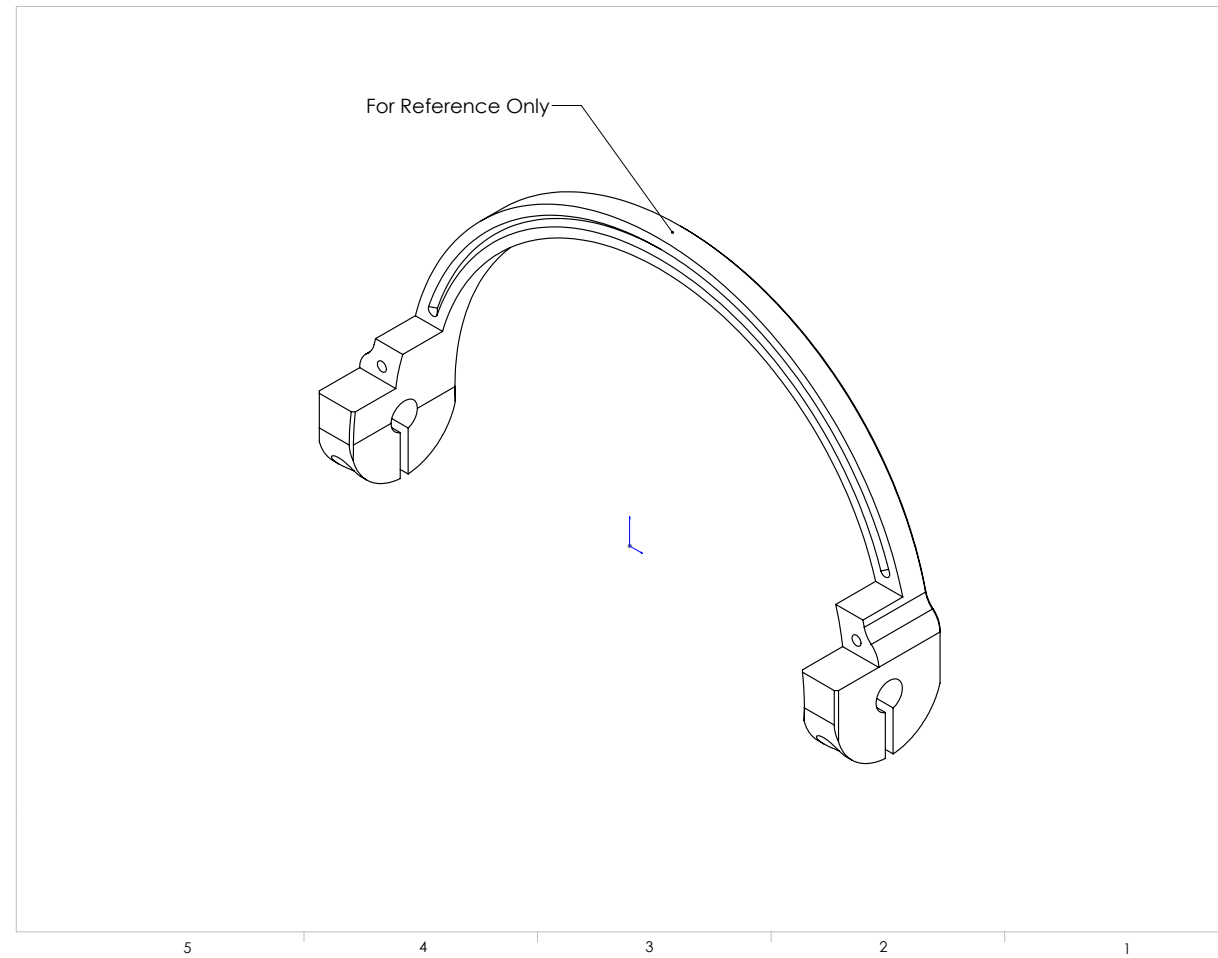


Figure A.20d: LapaRobot: Primary Rotation Arc CAD Drawing

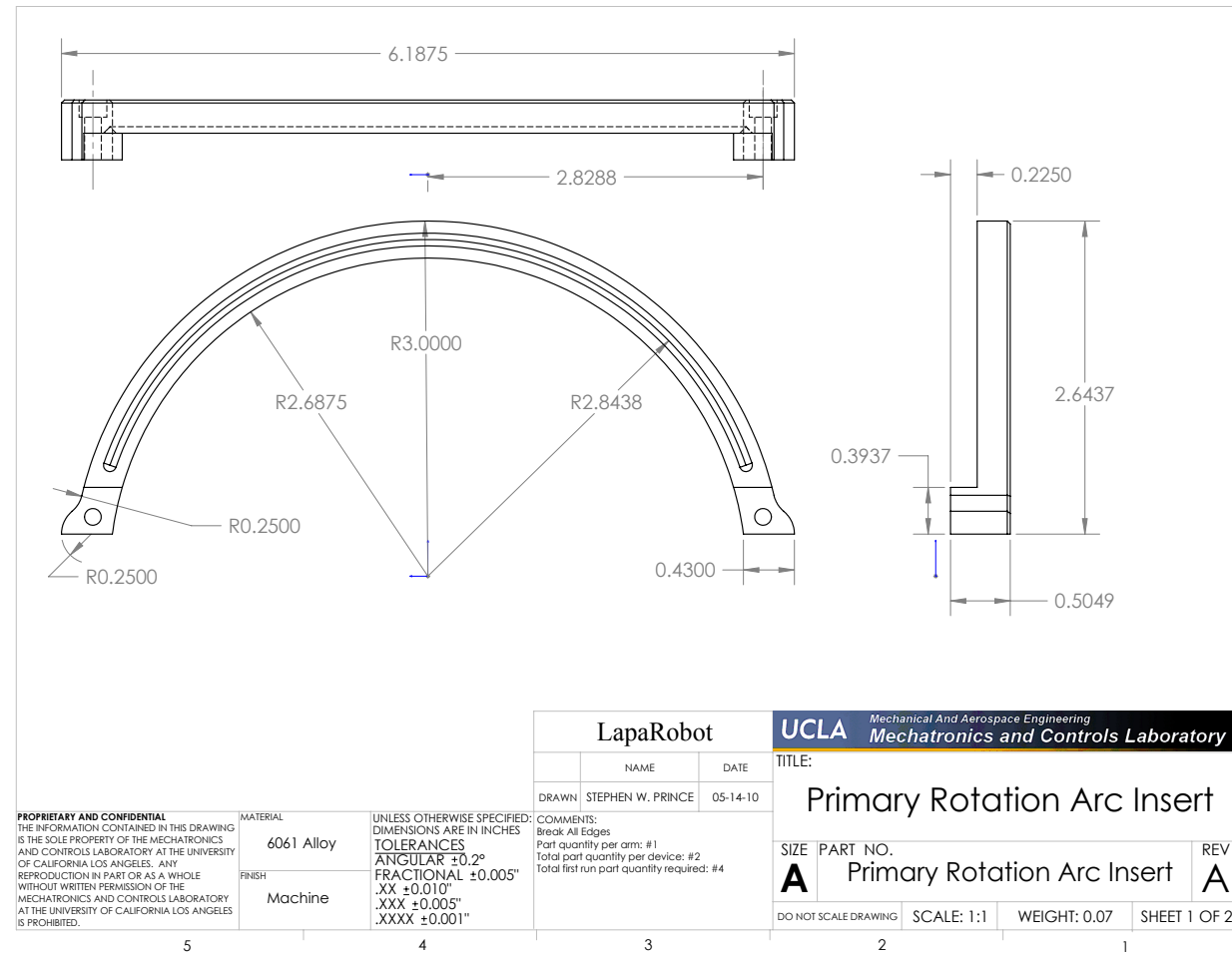


Figure A.21a: LapaRobot: Primary Rotation Arc Insert CAD Drawing

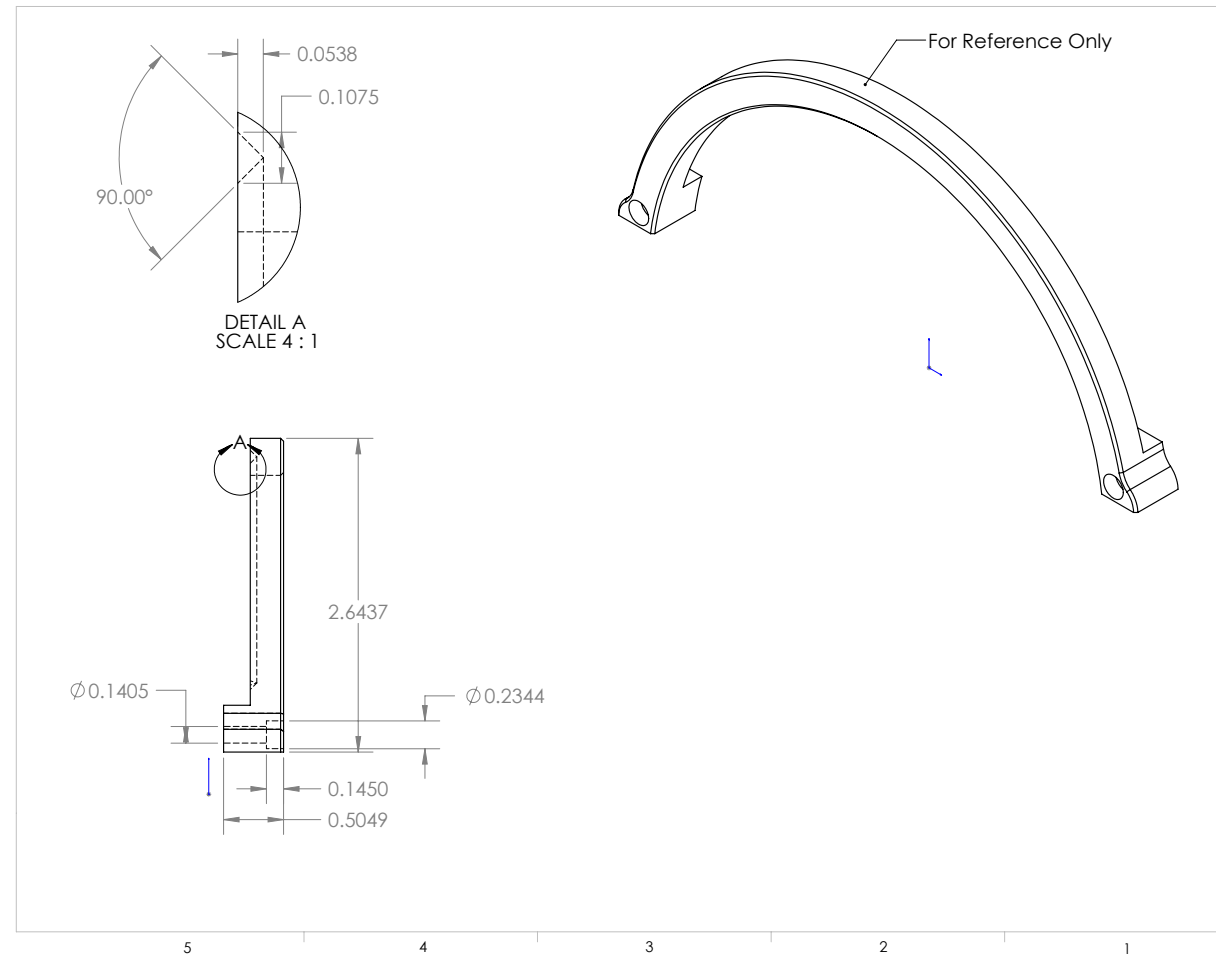


Figure A.21b: LapaRobot: Primary Rotation Arc Insert CAD Drawing

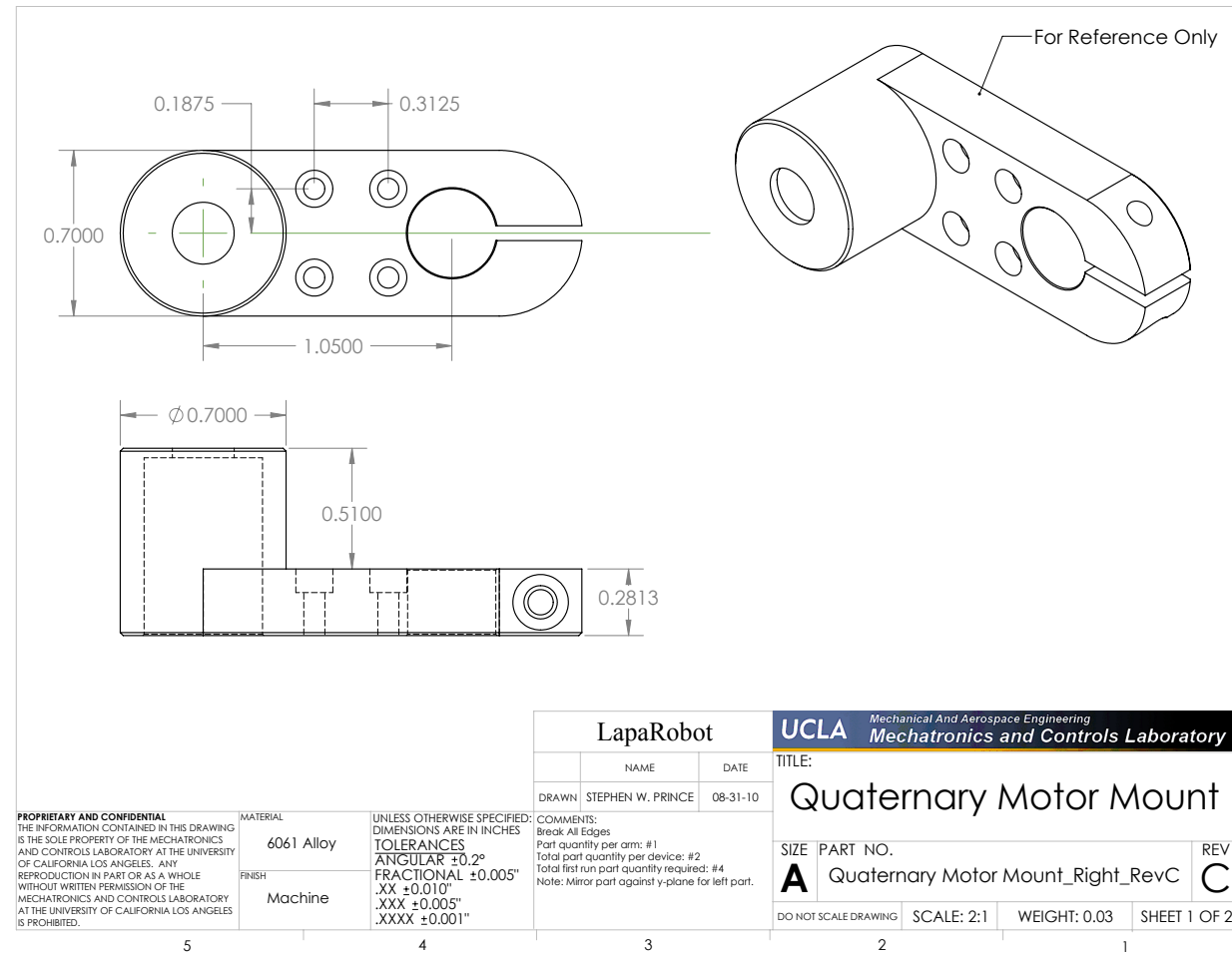


Figure A.22a: LapaRobot: Quaternary Motor Mount for Right Hand RevC CAD Drawing

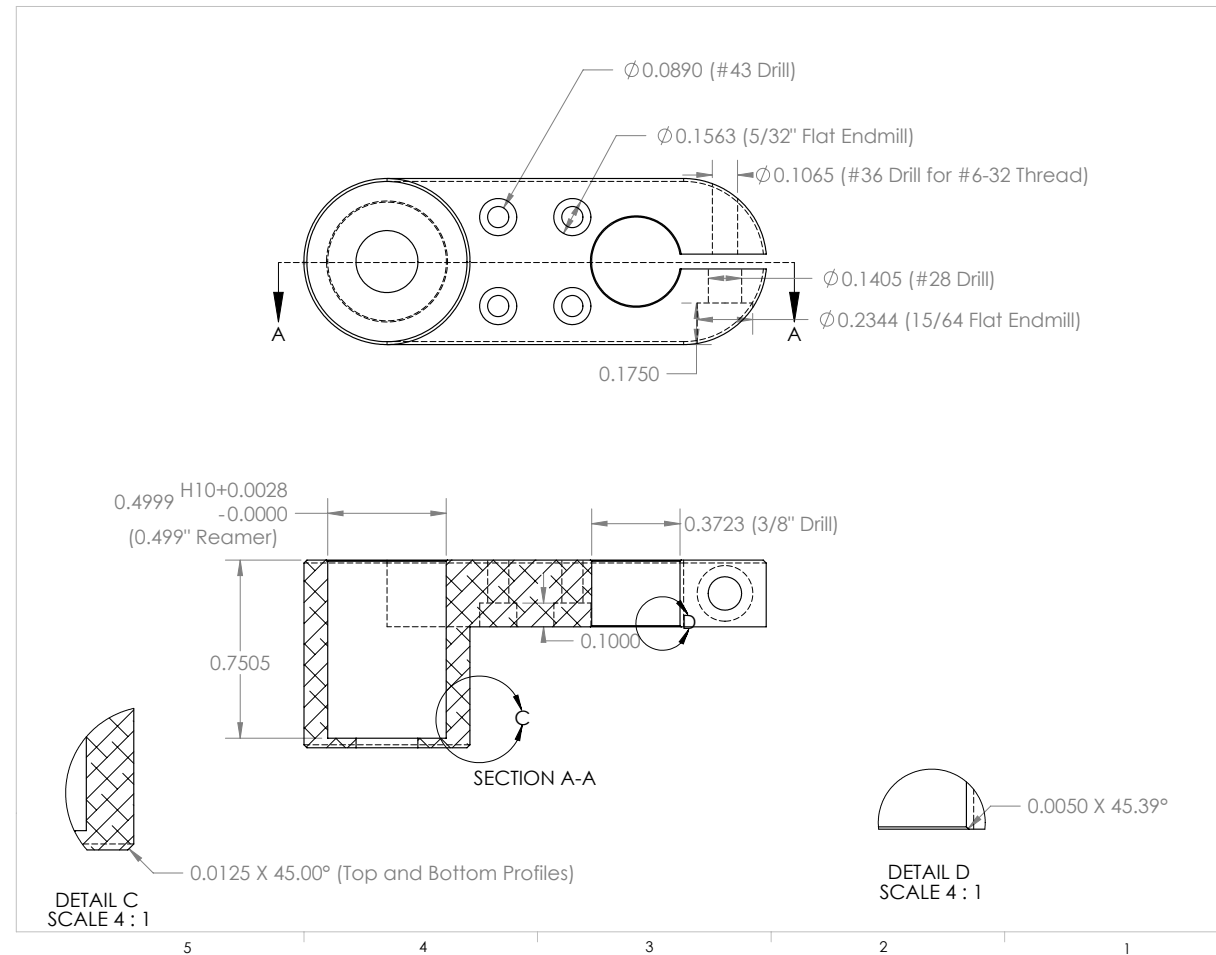


Figure A.22b: LapaRobot: Quaternary Motor Mount for Right Hand RevC CAD Drawing

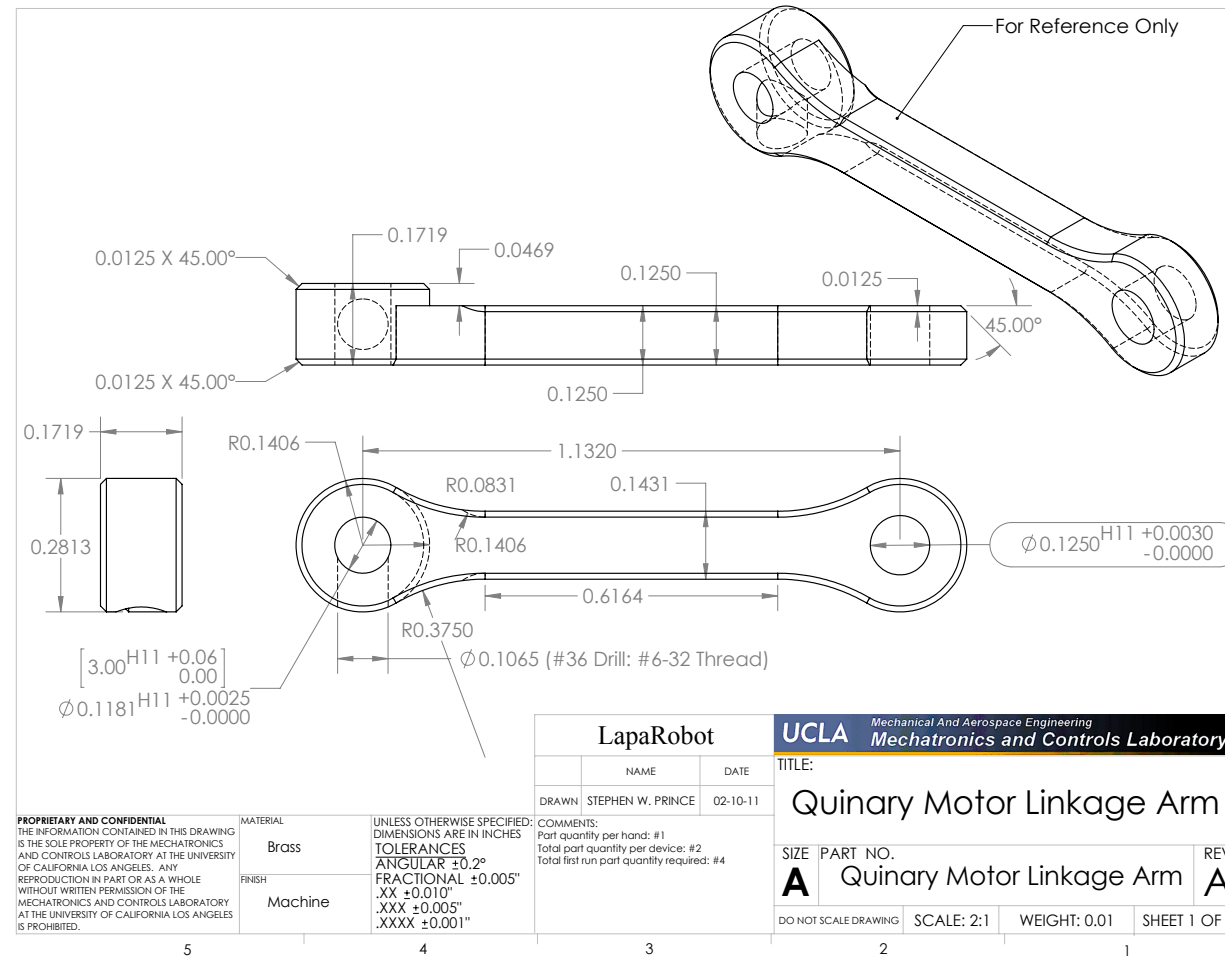


Figure A.23: LapaRobot: Quinary Motor Linkage Arm CAD Drawing

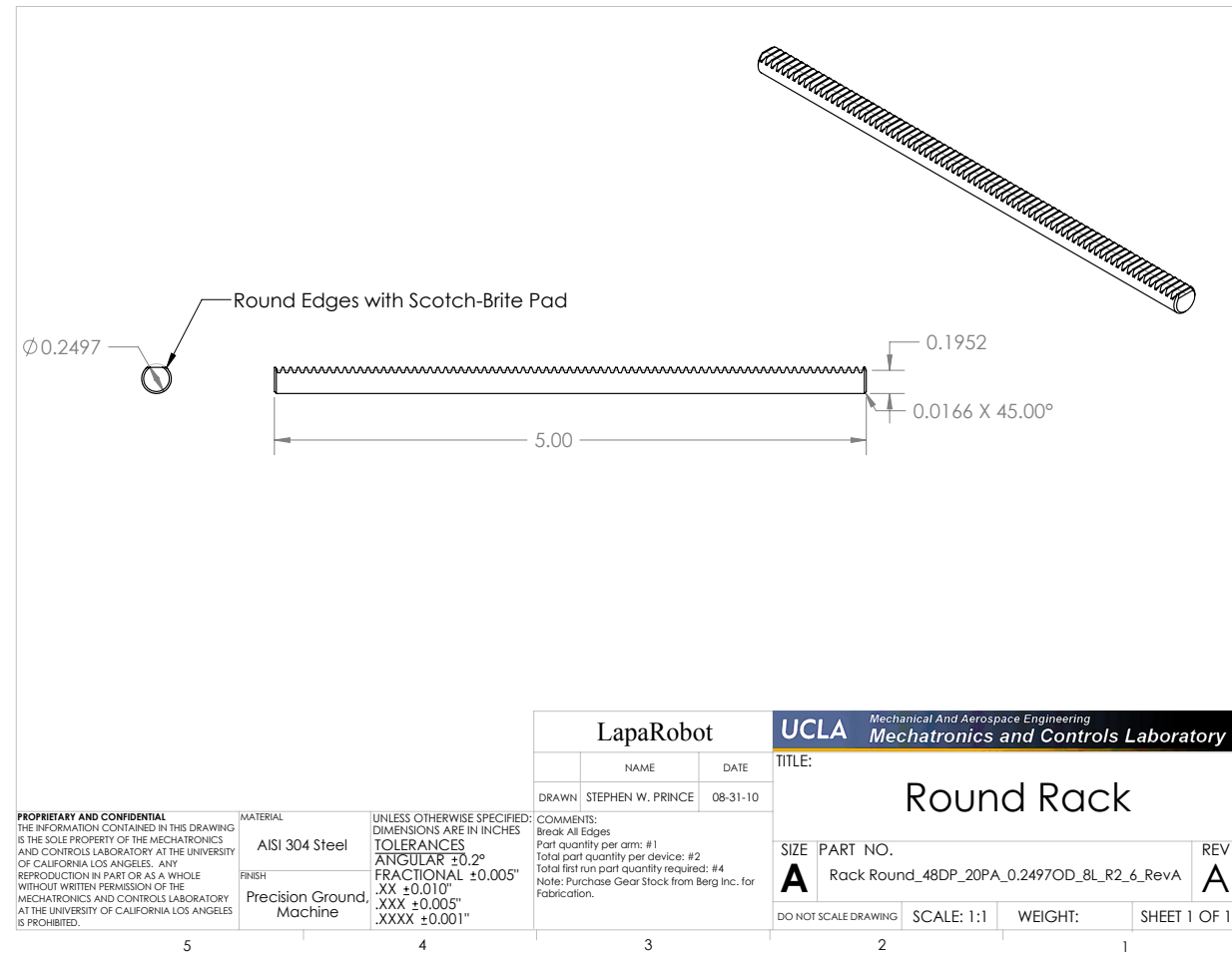


Figure A.24: LapaRobot: Rack Round (48DP-20PA) RevA CAD Drawing

Figure A.25: LapaRobot: Secondary Arc Motion Transfer Mount CAD Drawing

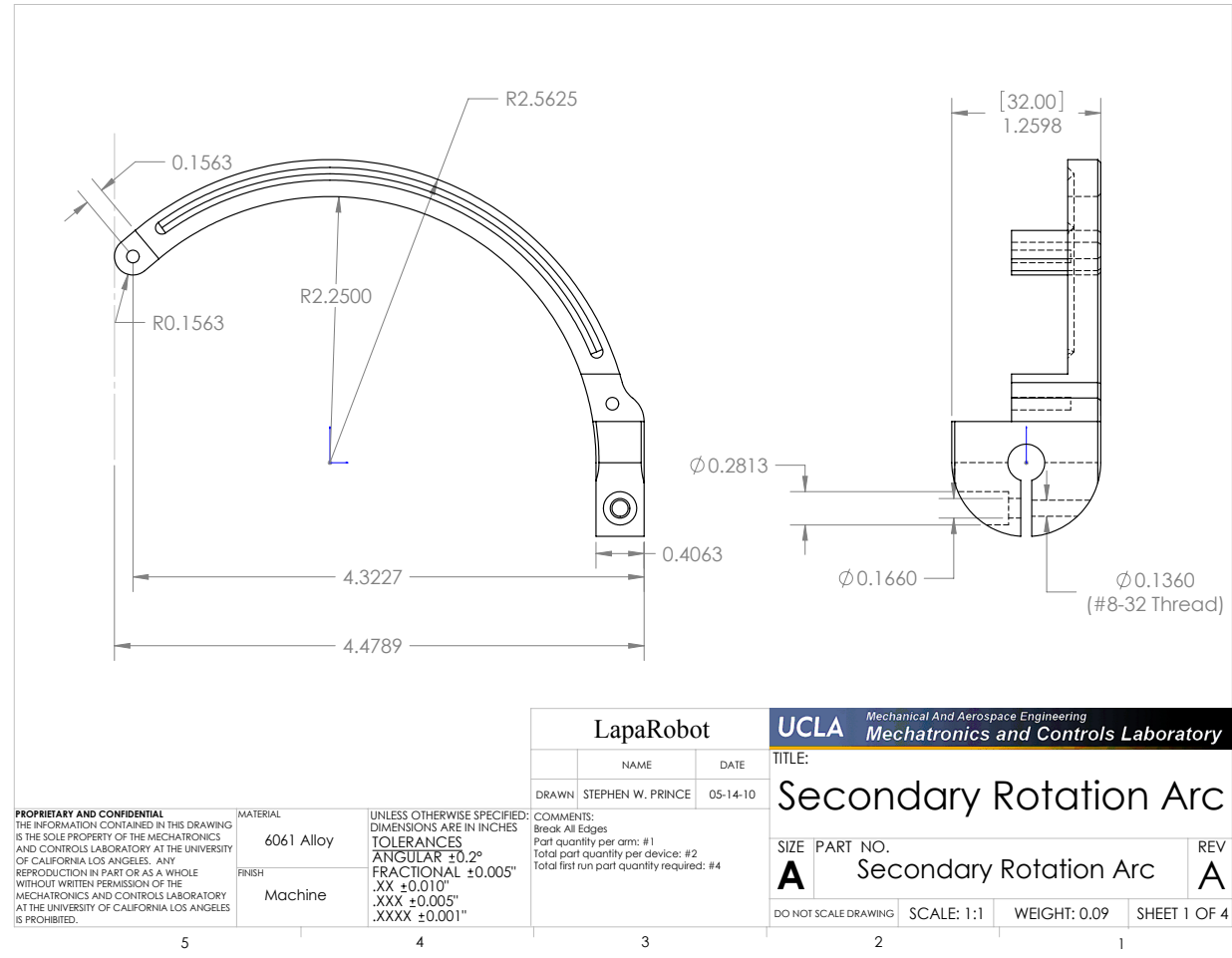


Figure A.26a: LapaRobot: Secondary Rotation Arc CAD Drawing

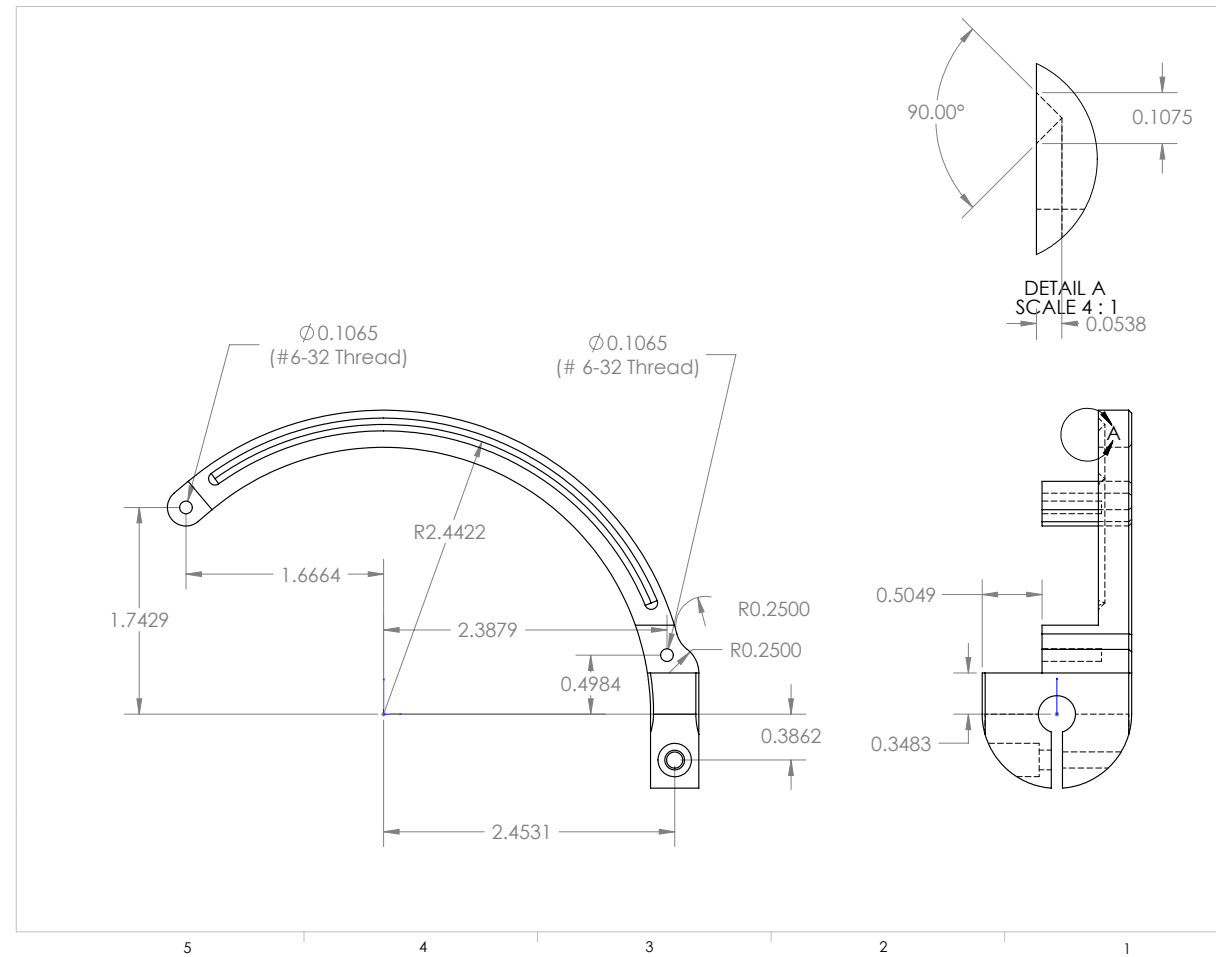


Figure A.26b: LapaRobot: Secondary Rotation Arc CAD Drawing

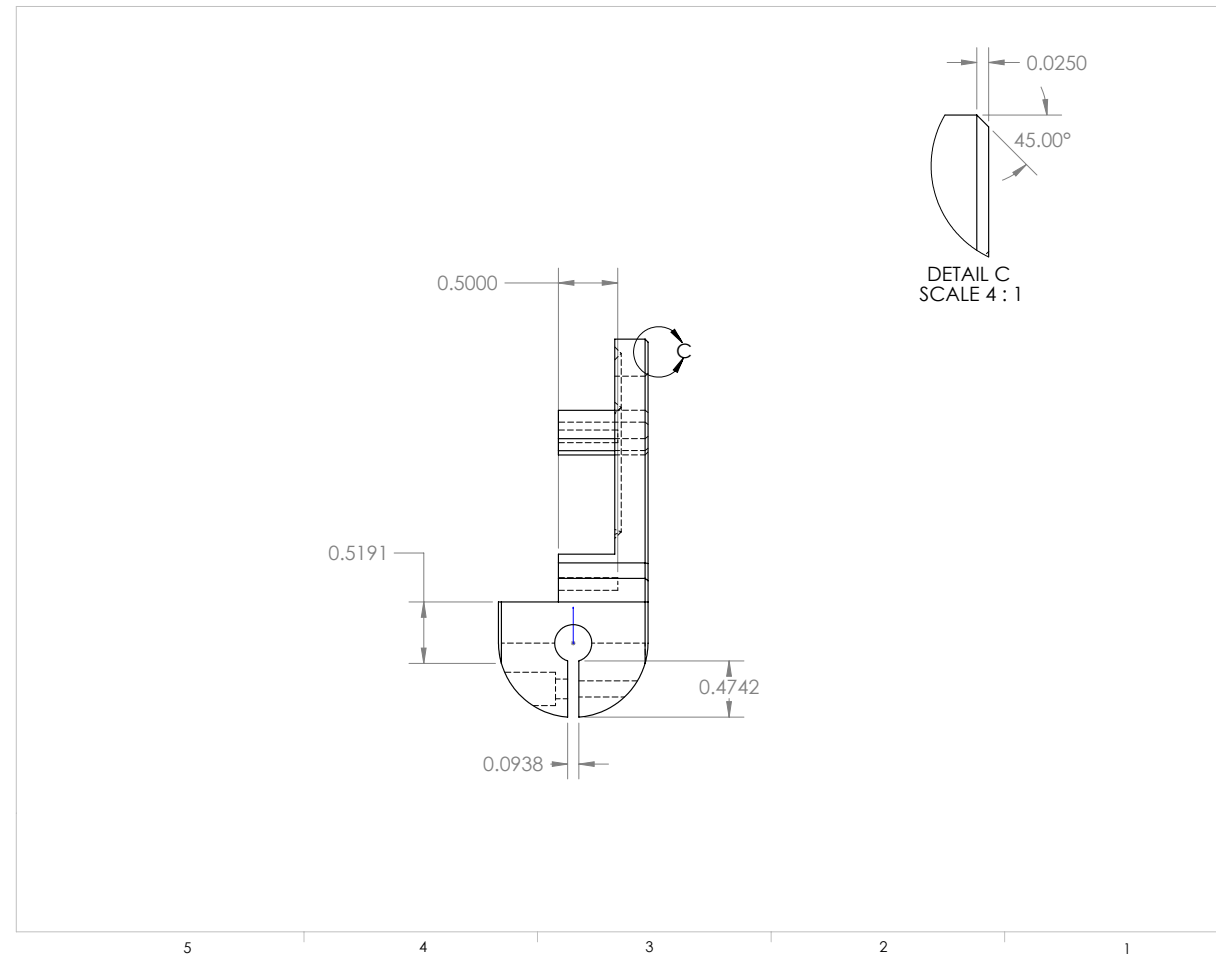


Figure A.26c: LapaRobot: Secondary Rotation Arc CAD Drawing

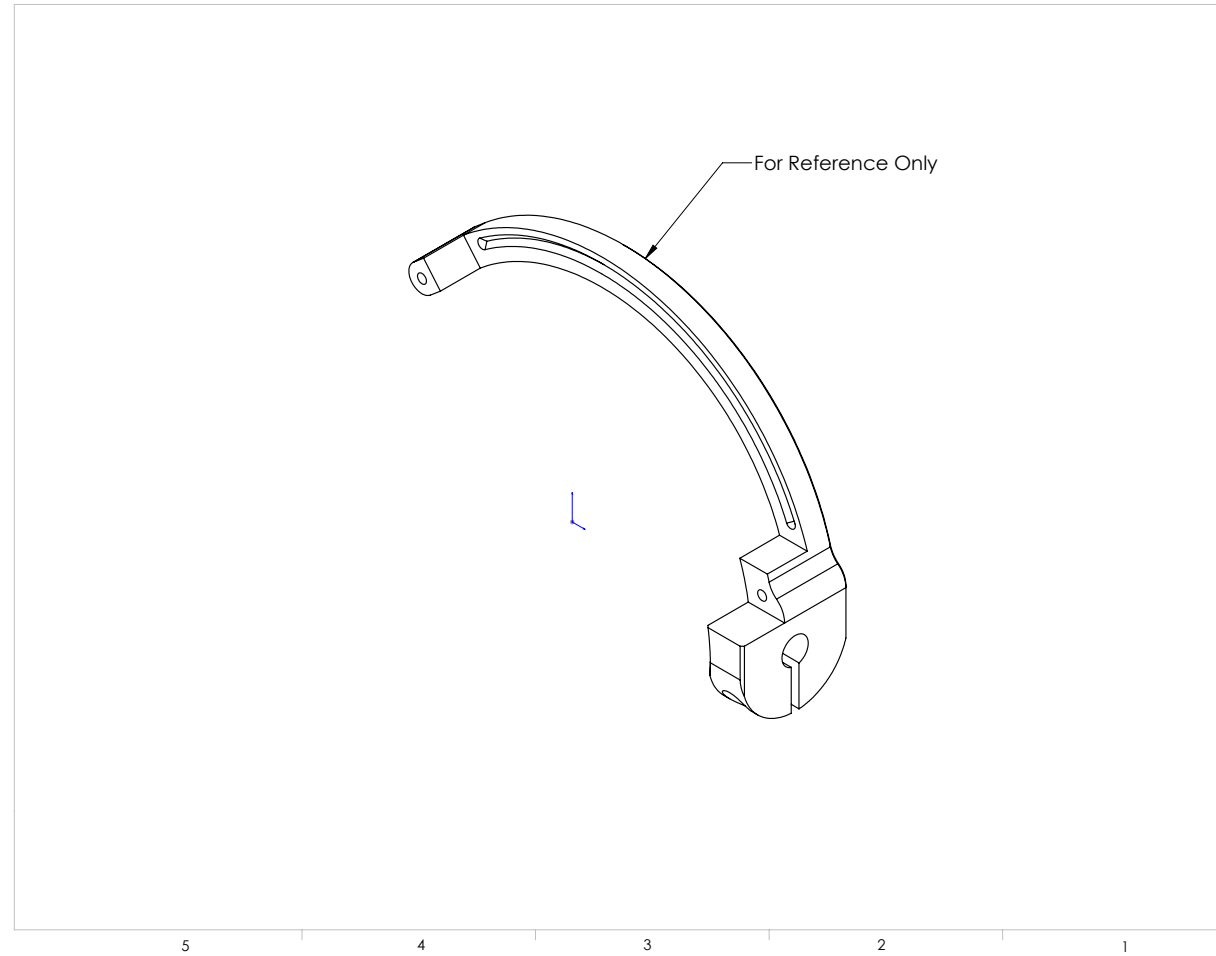


Figure A.26d: LapaRobot: Secondary Rotation Arc CAD Drawing

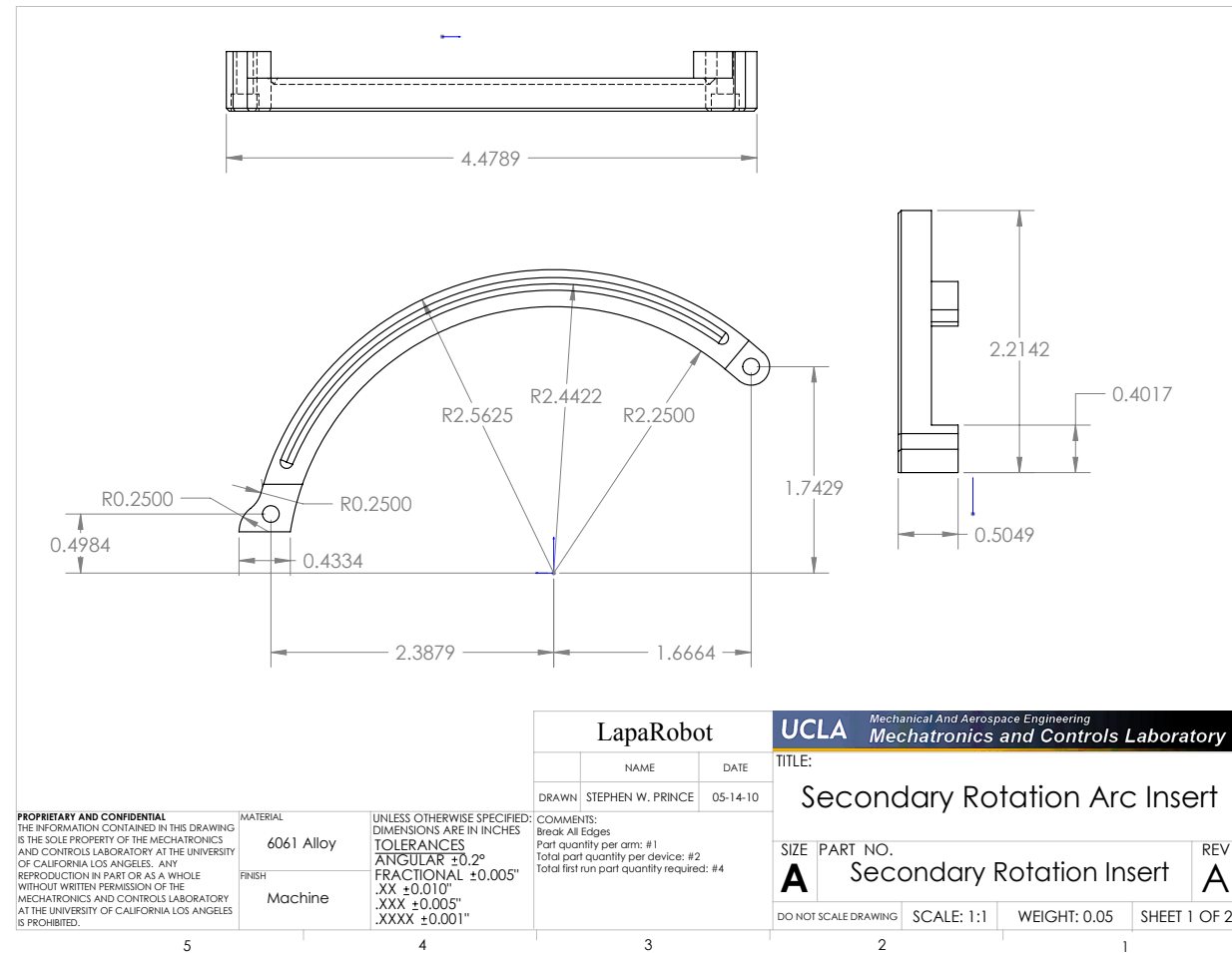


Figure A.27a: LapaRobot: Secondary Rotation Arc Insert CAD Drawing

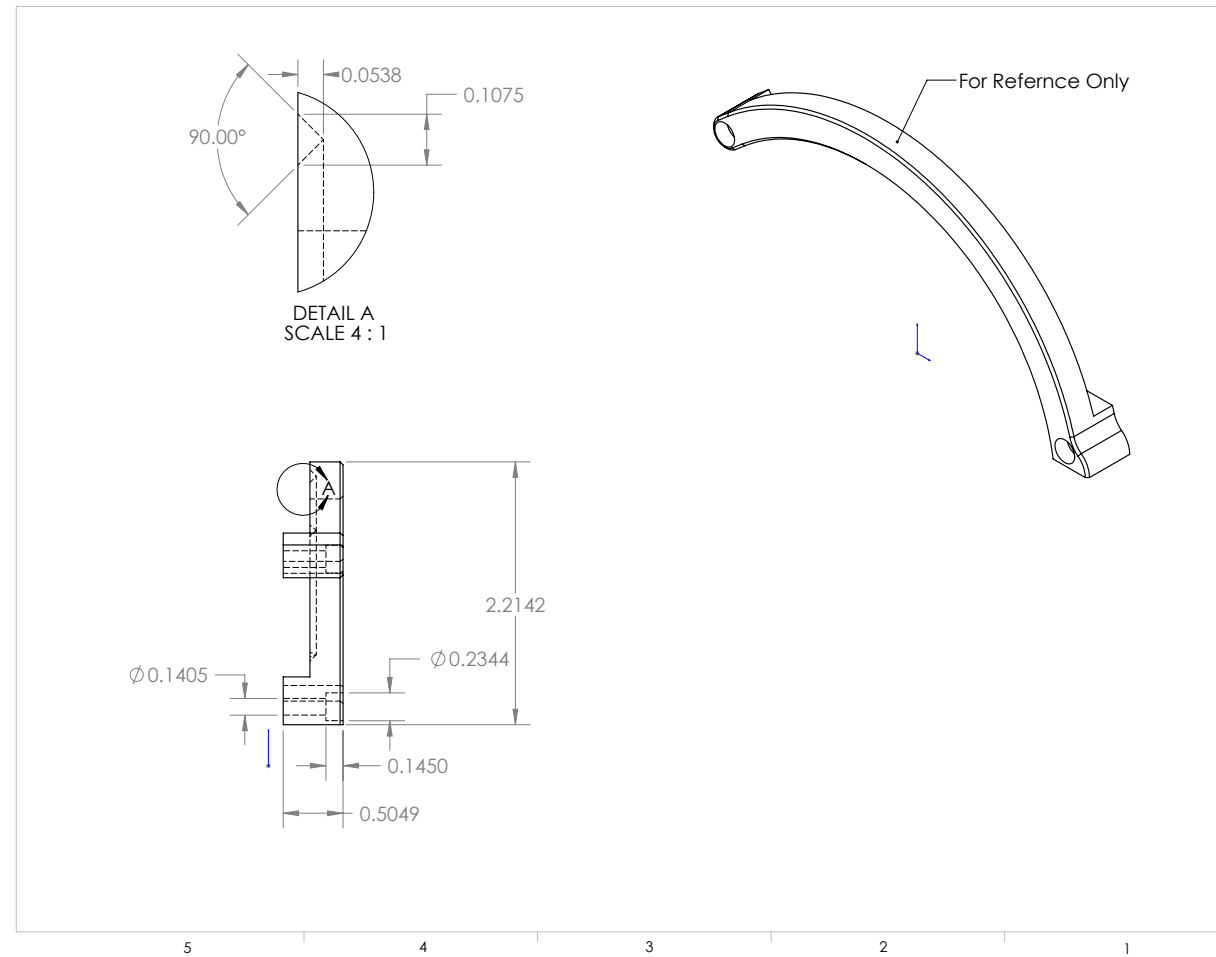


Figure A.27b: LapaRobot: Secondary Rotation Arc Insert CAD Drawing

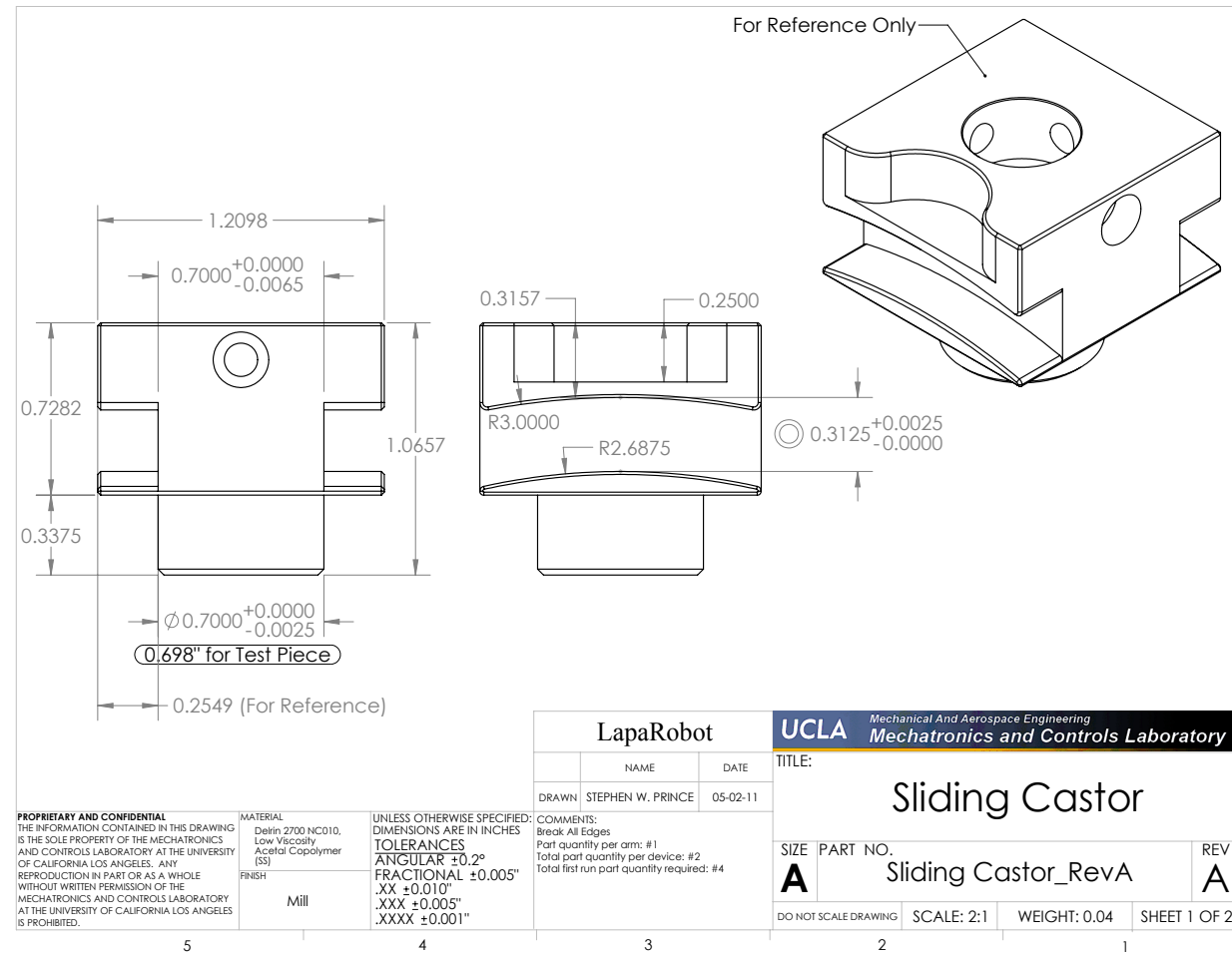


Figure A.28a: LapaRobot: Sliding Castor RevA CAD Drawing

Figure A.28b: LapaRobot: Sliding Castor RevA CAD Drawing

Figure A.29a: LapaRobot: Tertiary Motor Mount RevA CAD Drawing

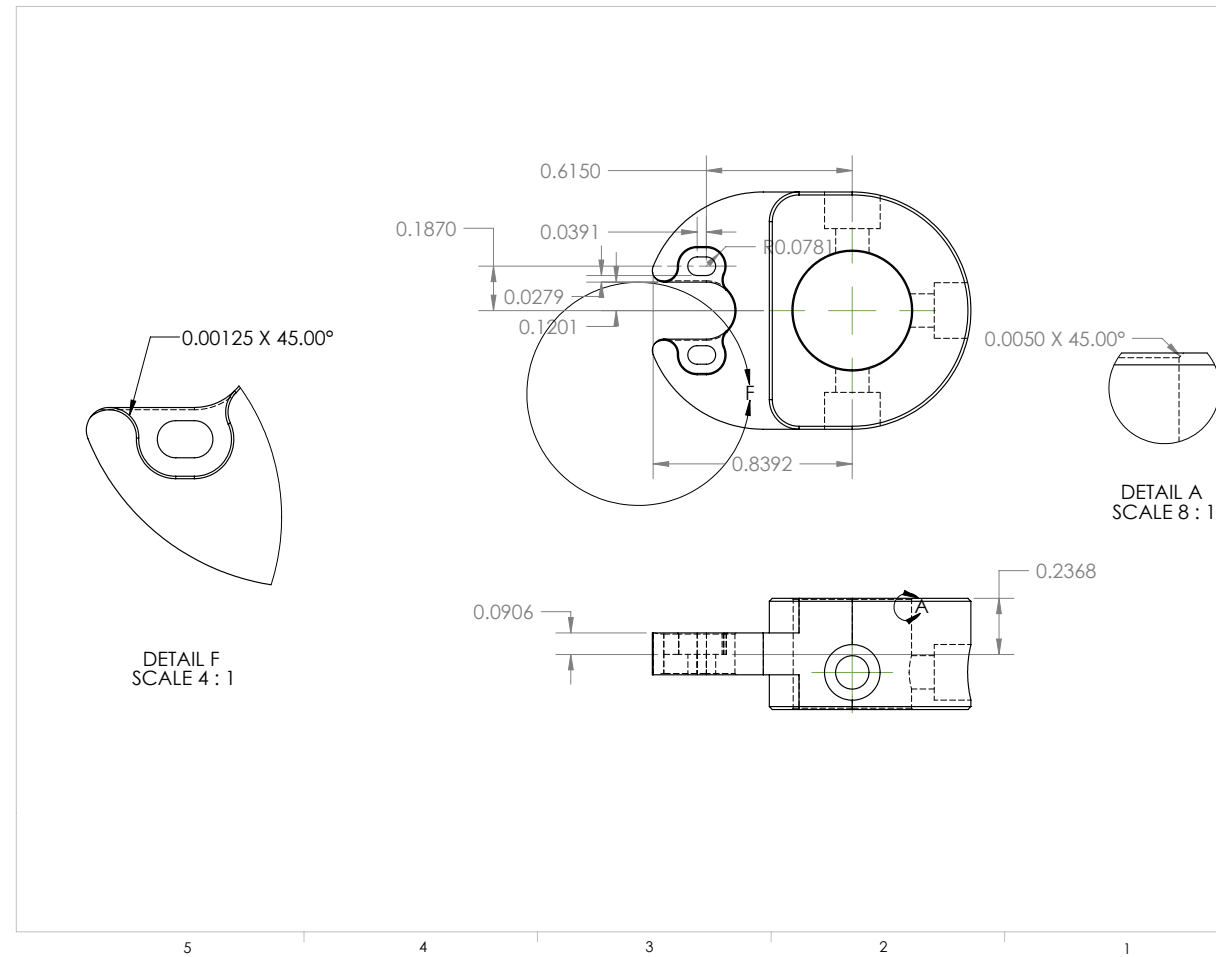


Figure A.29b: LapaRobot: Tertiary Motor Mount RevA CAD Drawing

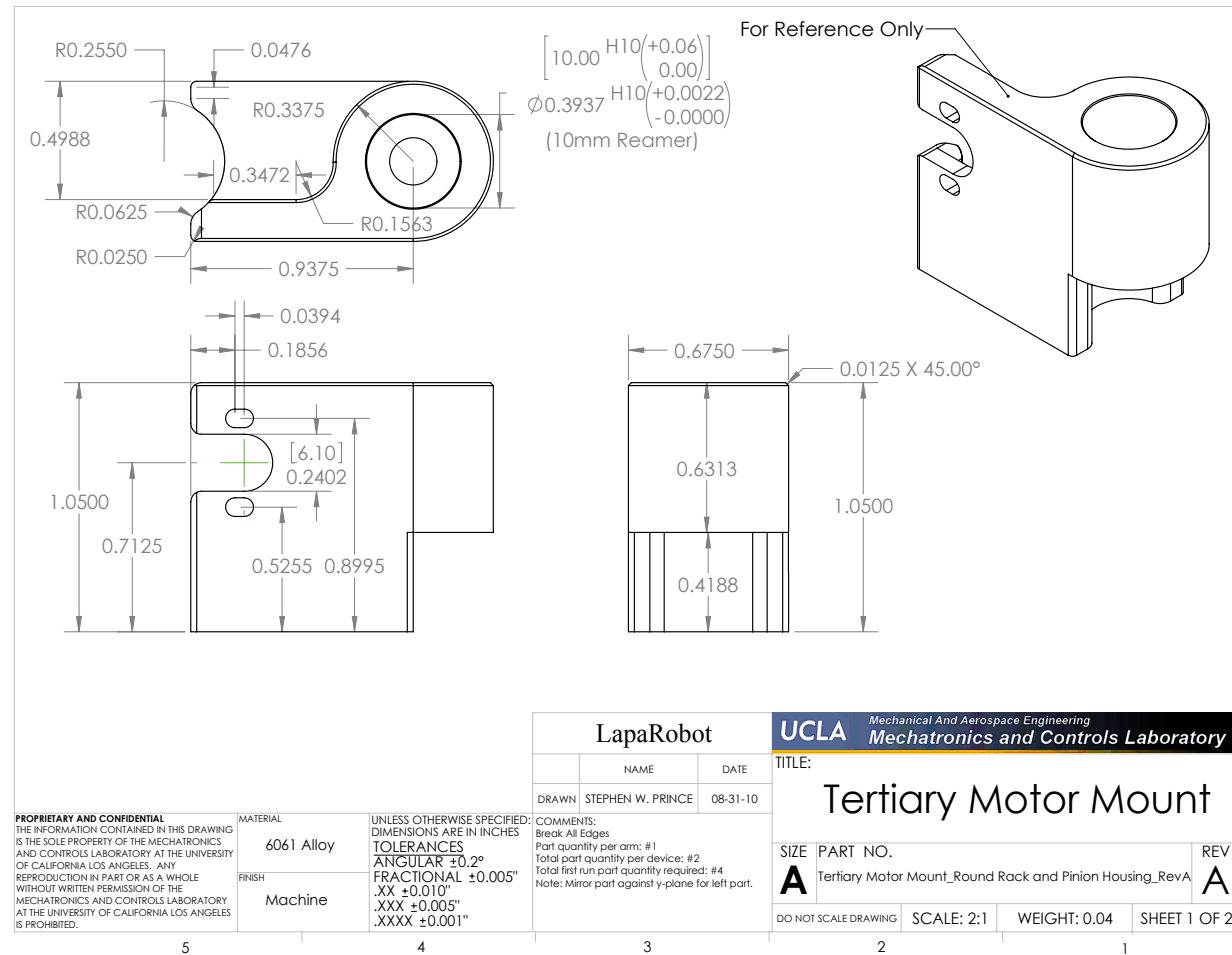


Figure A.30a: LapaRobot: Rack and Pinion Tertiary Motor Mount RevA CAD Drawing

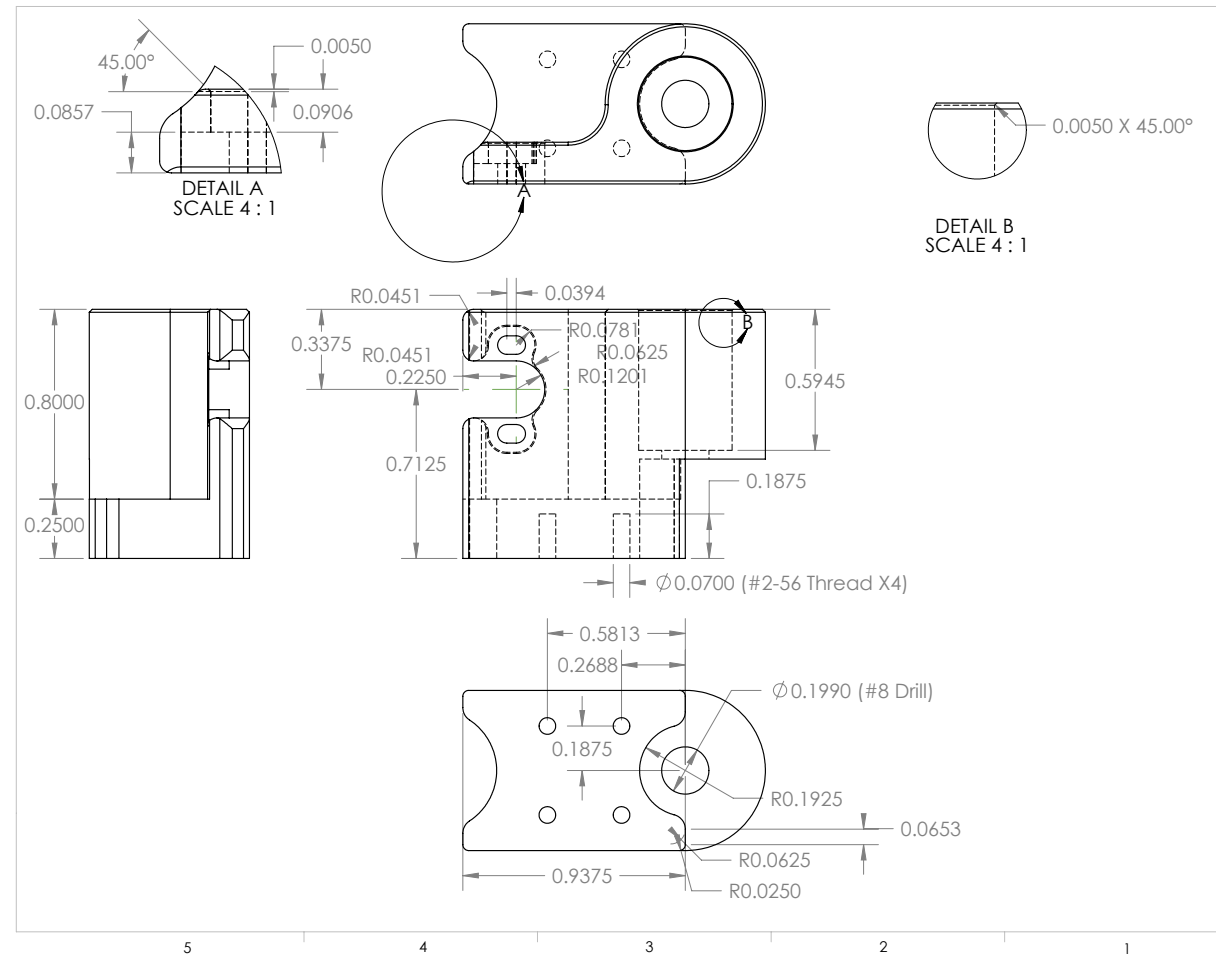


Figure A.30b: LapaRobot: Rack and Pinion Tertiary Motor Mount RevA CAD Drawing

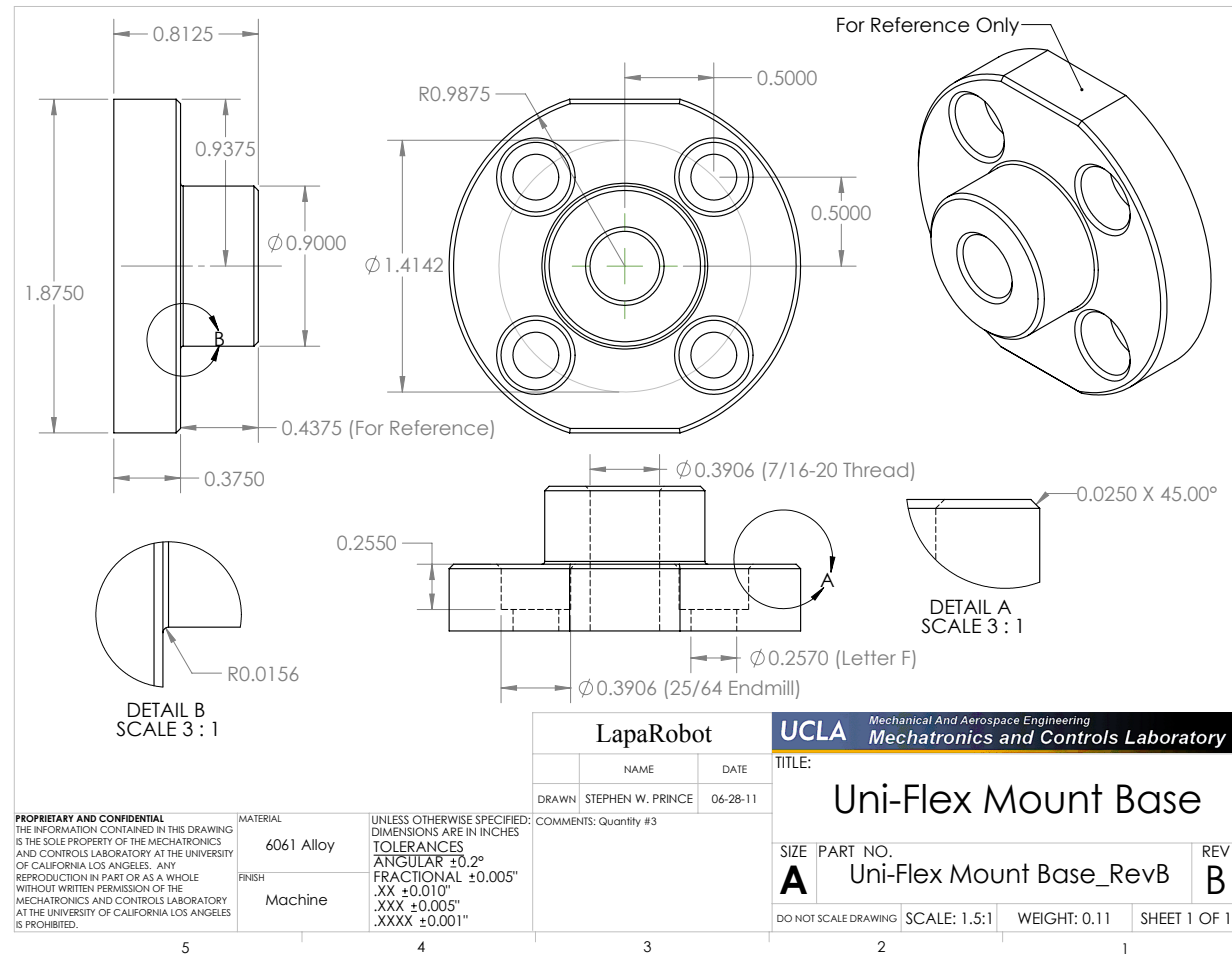


Figure A.31: LapaRobot: Uni-Flex Base Mount RevB CAD Drawing

APPENDIX B

Hardware Datasheets & Additional Schematics

B.1 Primary/Secondary Rotation Motor, Gearhead, & Encoder (Roll & Pitch Motions)

RE 25 Ø25 mm, Precious Metal Brushes CLL, 10 Watt, CE approved

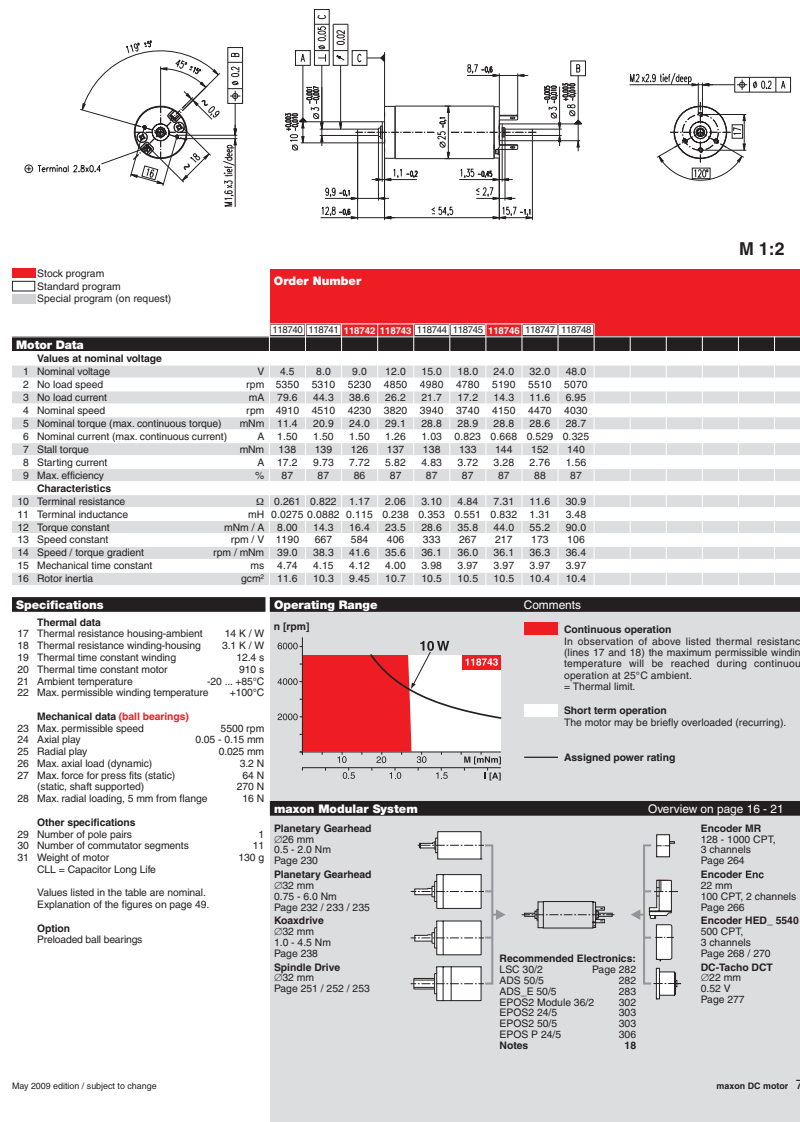
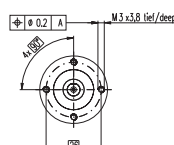
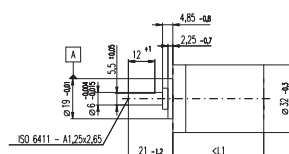


Figure B.1a: Maxon Primary Rotation/Secondary 118743 Motor Datasheet

[57]

maxon gear



M 1:2

Planetary Gearhead	straight teeth
Output shaft	stainless steel
Shaft diameter as option	8 mm
Bearing at output	ball bearing
Radial play, 5 mm from flange	max. 0.14 mm
Axial play	max. 0.4 mm
Max. radial load, 10 mm from flange	140 N
Max. permissible axial load	120 N
Max. permissible force for press fits	120 N
Sense of rotation, drive to output	=
Recommended input speed	< 6000 rpm
Recommended temperature range	-20 ... +100°C
Extended area as option	-35 ... +100°C

Option: Low-noise version														
Stock program			Order Number											
Standard program														
Special program (on request)														
			166155	166158	166163	166164	166169	166174	166179	166184	166187	166192	166197	166202
Gearhead Data														
1	Reduction		3.7: 1	4.1	33.1	51.1	111.1	246.1	492.1	762.1	1181.1	1972.1	2829.1	4380.1
2	Reduction absolute		26 _{1/2}	67 _{6/8}	529 _{1/8}	1373 _{1/2}	3384 _{1/2}	4218 _{1/4}	8121 _{1/2}	981 _{1/2}	1507 _{1/2}	9514 _{1/2}	15050 _{1/2}	24301
3	Max. motor shaft diameter	mm	6	6	3	6	4	4	3	3	4	4	3	3
Order Number			166156	166159		166165	166170	166175	166180	166185	166188	166193	166198	166203
1	Reduction		4.8: 1	18.1		66.1	123.1	295.1	531.1	913.1	1414.1	2189.1	3052.1	5247.1
2	Reduction absolute		29 _{1/2}	142 _{1/8}	35	389 _{1/2}	1075 _{1/2}	2477 _{1/2}	4343 _{1/2}	6937 _{1/2}	10514 _{1/2}	15050 _{1/2}	21439 _{1/2}	35024 _{1/2}
3	Max. motor shaft diameter	mm	4	4		4	4	4	3	3	4	3	3	3
Order Number			166157	166160		166166	166171	166176	166181	166186	166189	166194	166199	166204
1	Reduction		5.8: 1	21.1		79.1	132.1	318.1	589.1	1093.1	1526.1	2362.1	3389.1	6285.1
2	Reduction absolute		29 _{1/2}	239 _{1/4}		389 _{1/2}	1075 _{1/2}	2477 _{1/2}	4343 _{1/2}	6937 _{1/2}	10514 _{1/2}	15050 _{1/2}	21439 _{1/2}	35024 _{1/2}
3	Max. motor shaft diameter	mm	3	3		3	3	4	4	4	3	3	3	3
Order Number			166161			166167	166172	166177	166182		166190	166195	166200	
1	Reduction		23: 1			86.1	159.1	411.1	636.1		1694.1	2548.1	3656.1	
2	Reduction absolute		57 _{1/2}			1497 _{1/2}	1587 _{1/2}	4070 _{1/2}	7948 _{1/2}		17423 _{1/2}	25602 _{1/2}	37506 _{1/2}	
3	Max. motor shaft diameter	mm	4			3	3	4	4		3	3	3	
Order Number			166162			166168	166173	166178	166183		166191	166196	166201	
1	Reduction		28: 1			103.1	190.1	456.1	706.1		1828.1	2623.1	4060.1	
2	Reduction absolute		139 _{1/2}			3589 _{1/2}	1216 _{1/2}	6840 _{1/2}	10817 _{1/2}		22389 _{1/2}	32552 _{1/2}	49343 _{1/2}	
3	Max. motor shaft diameter	mm	3			3	3	3	3		3	3	3	
4	Number of stages		1	2	2	3	3	4	4	5	5	5	5	5
5	Max. continuous torque	Nm	0.75	2.25	2.4	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
6	Intermittently permissible torque at gear output	Nm	1.1	3.4	3.4	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
7	Max. efficiency	%	80	75	75	70	70	60	60	60	50	50	50	50
8	Weight	g	118	162	162	194	194	226	226	226	258	258	258	258
9	Gearbacklash no load		0.7	0.8	0.8	0.7	0.7	0.7	0.7	0.7	1.0	1.0	1.0	1.0
10	Mass inertia	gcm ²	1.5	1.9	1.9	2.3	2.3	2.7	2.7	2.7	3.2	3.2	3.2	3.2
11	Average length L ₀ 1	mm	26.4	36.3	36.3	43.0	43.0	49.0	49.0	49.7	56.4	56.4	56.4	56.4



maxon Modular System													
* Motor	Page	* Sensor / Brake	Page	Overall length [mm] = Motor length + gearhead length + (sensor / brake) + assembly parts									
RE 25	77/79			81.0	90.9	90.9	97.6	97.6	104.3	104.3	111.0	111.0	111.0
RE 25	77/79	MR	264	92.0	101.9	101.9	108.6	108.6	115.3	115.3	122.0	122.0	122.0
RE 25	77/79	Enc 22	266	95.1	105.0	105.0	111.7	111.7	118.4	118.4	125.1	125.1	125.1
RE 25	77/29	HEd_5540	269/270	110.8	111.7	111.7	118.4	118.4	125.1	125.1	131.8	131.8	131.8
RE 25	77/79	DCT 22	277	103.3	113.2	113.2	119.9	119.9	126.6	126.6	133.3	133.3	133.3
RE 25, 20 W	78			69.5	79.4	79.4	86.1	86.1	92.8	92.8	99.5	99.5	99.5
RE 25, 20 W	78	MR	264	80.5	90.4	90.4	97.1	97.1	103.8	103.8	110.5	110.5	110.5
RE 25, 20 W	78	HEd_5540	269/272	90.9	100.2	100.2	106.8	106.9	113.6	113.6	120.3	120.3	120.3
RE 25, 20 W	78	DCT22	277	91.8	101.7	101.7	108.4	108.4	115.1	115.1	121.8	121.8	121.8
RE 25, 20 W	78	AB 28	316	103.6	113.5	113.5	120.2	120.2	126.9	126.9	133.6	133.6	133.6
RE 25, 20 W	78	HEd_5540 / AB 28	269/316	120.8	130.7	130.7	137.4	137.4	144.1	144.1	150.8	150.8	150.8
RE 25, 20 W	78	AB 28	316	115.3	125.2	125.2	131.9	131.9	138.6	138.6	145.3	145.3	145.3
RE 25, 20 W	79	HEd_5540 / AB 28	269/316	132.2	142.1	142.1	148.8	148.8	155.5	155.5	162.2	162.2	162.2
A-max 26	105-112			71.2	81.1	81.1	87.8	87.8	94.5	94.5	101.2	101.2	101.2
A-max 26	105-112	MEnc 13	276	78.3	88.2	88.2	94.9	94.9	101.6	101.6	108.3	108.3	108.3
A-max 26	105-112	MR	264	80.0	89.9	89.9	96.6	96.6	103.3	103.3	110.0	110.0	110.0
A-max 26	106-112	Enc 22	267	85.6	95.5	95.5	102.2	102.2	108.9	108.9	115.6	115.6	115.6
A-max 26	106-112	HEd_5540	269/271	90.0	99.9	99.9	106.6	106.6	113.3	113.3	120.0	120.0	120.0
RE-max 29	136/138			71.2	81.1	81.1	87.8	87.8	94.5	94.5	101.2	101.2	101.2
RE-max 29	139/138	MR	264	80.0	89.9	89.9	96.6	96.6	103.3	103.3	110.0	110.0	110.0

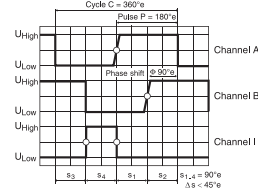
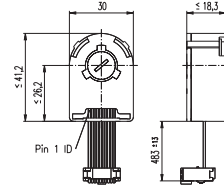
May 2009 edition / subject to change

maxon gear 233

Figure B.1b: Maxon Primary Rotation/Secondary 166165 Motor Gearhead Datasheet [58]

Encoder HEDL 5540, 500 CPT, 3 Channels, with Line Driver RS 422

maxon sensor



☒ Stock program
☐ Standard program
☐ Special program (on request)

Order Number

110512 110514 110516

Type

Counts per turn	500	500	500
Number of channels	3	3	3
Max. operating frequency (kHz)	100	100	100
Max. speed (rpm)	12000	12000	12000
Shaft diameter (mm)	3	4	6

maxon Modular System

Motor	Page	Gearhead	Page	Brake	Page	Overall length [mm]	See Gearhead
RE 25	77/79					75.3	
RE 25	77/79	GP 26 / GP 32	230/232				
RE 25	77/79	KD 32, 1.0 - 4.5 Nm	238				
RE 25	77/79	GP 32, 0.75 - 6.0 Nm	233/235				
RE 25	77/79	GP 32 S	251-253				
RE 25, 20 W	79			AB 28	316	105.7	
RE 25, 20 W	79	GP 26 / GP 32	230/232	AB 28	316		
RE 25, 20 W	79	KD 32, 1.0 - 4.5 Nm	238	AB 28	316		
RE 25, 20 W	79	GP 32, 0.75 - 6.0 Nm	233/235	AB 28	316		
RE 25, 20 W	79	GP 32 S	251-253	AB 28	316		
RE 35, 90 W	81					91.7	
RE 35, 90 W	81	GP 32, 0.75 - 4.5 Nm	232				
RE 35, 90 W	81	GP 32, 0.75 - 6.0 Nm	234/235				
RE 35, 90 W	81	GP 32, 4.0 - 8.0 Nm	237				
RE 35, 90 W	81	GP 42, 3.0 - 15 Nm	240				
RE 35, 90 W	81	GP 32 S	251-253				
RE 35, 90 W	81			AB 28	316	124.1	
RE 35, 90 W	81	GP 32, 0.75 - 4.5 Nm	232	AB 28	316		
RE 35, 90 W	81	GP 32, 0.75 - 6.0 Nm	234/235	AB 28	316		
RE 35, 90 W	81	GP 42, 3.0 - 15 Nm	240	AB 28	316		
RE 35, 90 W	81	GP 32 S	251-253	AB 28	316		
RE 35, 90 W	81	GP 32, 4.0 - 8.0 Nm	237	AB 28	316		
RE 40, 150 W	82					91.7	
RE 40, 150 W	82	GP 42, 3.0 - 15 Nm	240				
RE 40, 150 W	82	GP 52, 4.0 - 30 Nm	243				
RE 40, 150 W	82			AB 28	316	124.2	
RE 40, 150 W	82	GP 42, 3.0 - 15 Nm	240	AB 28	316		
RE 40, 150 W	82	GP 52, 4.0 - 30 Nm	243	AB 28	316		
A-max 26	106-112					63.5	
A-max 26	106-112	GP 26, GS 30	230/231				
A-max 26	106-112	GP 32, 0.4 - 2.0 Nm	234				
A-max 26	106-112	GP 32, 0.75 - 6.0 Nm	233/236				
A-max 26	106-112	GS 36, 0.1 - 0.6 Nm	239				
A-max 26	106-112	GP 32 S	251-253				
A-max 32	114/116					82.3	
A-max 32	114/116	GP 32, 0.75 - 6.0 Nm	234/236				
A-max 32	114/116	GS 38, 0.1 - 0.6 Nm	239				
A-max 32	114/116	GP 32 S	251-253				

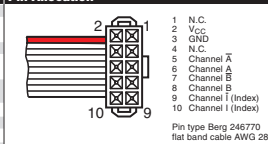
Technical Data

Supply voltage	5 V ± 10 %
Output signal	EIA Standard RS 422
driver used:	DS26LS31
Phase shift Φ	90° ± 45°
Signal rise time	180 ns
(typically, at $C_L = 25$ pF, $R_L = 2.7$ k Ω , 25°C)	
Signal fall time	40 ns
(typically, at $C_L = 25$ pF, $R_L = 2.7$ k Ω , 25°C)	
Index pulse width	90°
Operating temperature range	-40 ... +100°C
Moment of inertia of code wheel	≤ 0.6 gcm ²
Max. angular acceleration	250 000 rad/s ²
Output current per channel	min. -20 mA, max. 20 mA
Option	1000 counts per turn, 2 channels

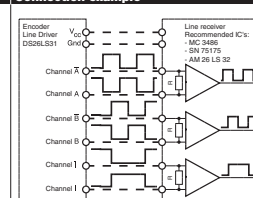
The index signal I is synchronised with channel A or B.

270 maxon sensor

Pin Allocation



Connection example



Terminal resistance R = typical 100 Ω
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Figure B.1c: Maxon 110512 Motor Encoder Datasheet [59]

B.2 Tertiary/Quaternary/Quinary Motor, Gearhead, & Encoder (Yaw, Depth, & Pitch Motions)

RE 13 Ø13 mm, Precious Metal Brushes, 2 Watt, CE approved

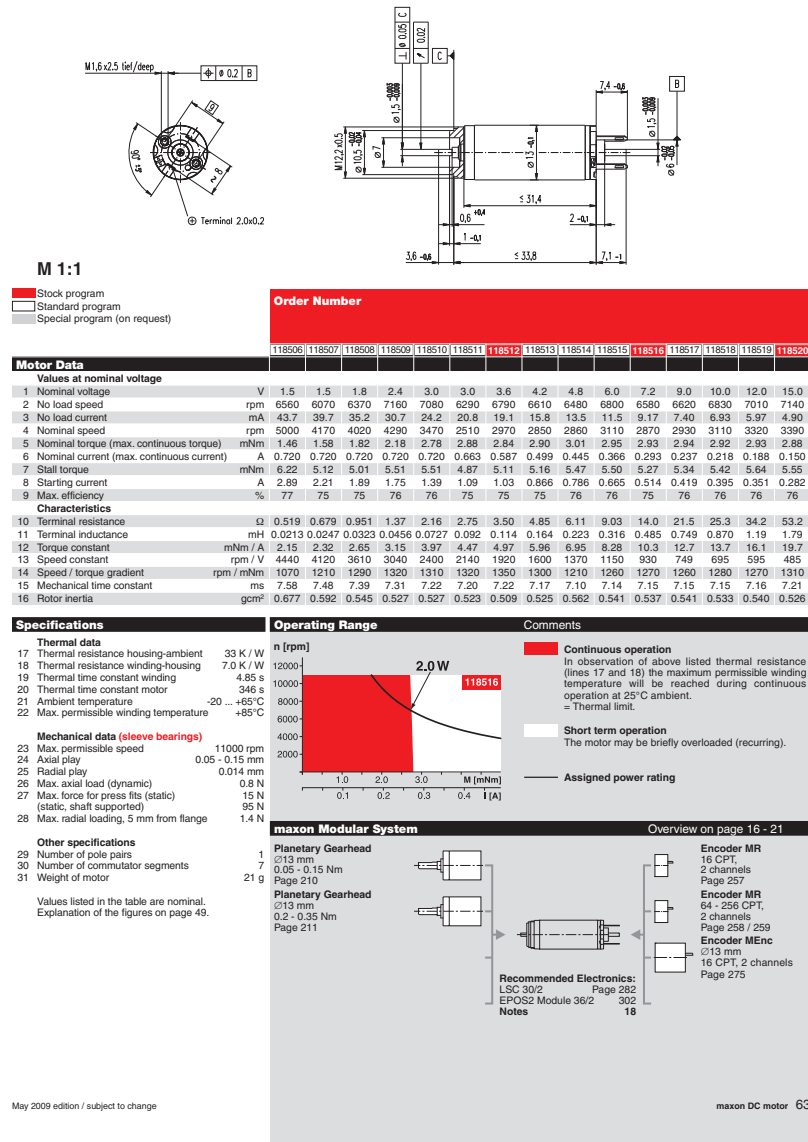
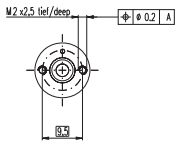
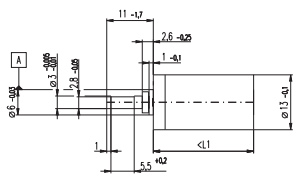


Figure B.2a: Maxon Tertiary/Quaternary/Quinary 118520 Motor Datasheet

[60]

Planetary Gearhead GP 13 A Ø13 mm, 0.2 - 0.35 Nm



Technical Data

Planetary Gearhead	straight teeth
Output shaft	stainless steel, hardened
Bearing at output	sleeve bearing
Radial play, 6 mm from flange	max. 0.055 mm
Axial play	0.02 - 0.10 mm
Max. permissible axial load	8 N
Max. permissible force for press fits	100 N
Sense of rotation, drive to output	=
Recommended input speed	< 8000 rpm
Recommended temperature range	-15 ... +100°C
Extended area as option	-35 ... +100°C
Number of stages	1 2 3 4 5
Max. radial load,	6 mm from flange 8 N 12 N 16 N 20 N 20 N

maxon gear

- Stock program
Standard program
Special program (on request)

Order Number

110313	110314	110315	110316	110317
--------	--------	--------	--------	--------

Gearhead Data

1 Reduction	4.1 : 1	17 : 1	67 : 1	275 : 1	1119 : 1
2 Reduction absolute	97/14	3249/196	185193/2744	10556001/28416	60189207/237824
3 Max. motor shaft diameter	mm 1.5	1.5	1.5	1.5	1.5
Order Number	352365	352366	352367	352368	352369
1 Reduction	5.1 : 1	26 : 1	131 : 1	664 : 1	3373 : 1
2 Reduction absolute	86/13	4355/169	287499/2187	18974736/13561	125233279/11293
3 Max. motor shaft diameter	mm 1.5	1.5	1.5	1.5	1.5
4 Number of stages	1	2	3	4	5
5 Max. continuous torque	Nm 0.20	0.20	0.30	0.30	0.35
6 Intermittently permissible torque at gear output	Nm 0.30	0.30	0.45	0.45	0.53
7 Max. efficiency	% 91	83	75	69	62
8 Weight	g 11	14	17	20	23
9 Average backlash no load	° 1.0	1.2	1.5	1.8	2.0
10 Mass inertia	gcm ² 0.025	0.015	0.015	0.015	0.015
11 Gearhead length L1*	mm 16.0	19.9	23.7	27.6	31.4

*For A-max 12 and RE-max 13 L1 is + 0.2 mm



maxon Modular System

+ Motor	Page	+ Sensor / Brake	Page	Overall length [mm]	= Motor length + gearhead length + (sensor / brake) + assembly parts				
RE 13	57/59			35.4	39.3	43.1	47.0	50.8	
RE 13, 0.75 W	59	MR	257-259	42.5	46.4	50.2	54.1	57.9	
RE 13, 0.75 W	59	MEnc 13	275	43.2	47.1	50.9	54.8	58.6	
RE 13	61/63			47.6	51.5	55.3	59.2	63.0	
RE 13, 2 W	63	MR	257-259	54.7	58.6	62.4	66.3	70.1	
RE 13, 2 W	63	MEnc 13	275	55.4	59.3	63.1	67.0	70.8	
RE 13, 1.5 W	65/67			38.5	42.4	46.2	50.1	53.9	
RE 13, 1.5 W	67	MR	257-259	44.6	48.5	52.3	56.2	60.0	
RE 13, 1.5 W	67	MEnc 13	275	46.5	50.4	54.2	58.1	61.9	
RE 13, 3 W	69/71			50.7	54.6	58.4	62.3	66.1	
RE 13, 3 W	71	MR	257-259	56.8	60.7	64.5	68.4	72.2	
RE 13, 3 W	71	MEnc 13	275	58.7	62.6	66.4	70.3	74.1	
A-max 12	91/92			37.6	41.5	45.3	49.2	53.0	
A-max 12, 0.5 W	92	MR	257-259	41.7	45.6	49.4	53.3	57.1	
RE-max 13	119/120			36.9	40.8	44.6	48.5	52.3	
RE-max 13, 0.75 W	120	MR	257-259	41.6	45.5	49.3	53.2	57.0	
RE-max 13	121/122			47.9	51.8	55.6	59.5	63.3	
RE-max 13, 2 W	122	MR	257-259	52.6	56.5	60.3	64.2	68.0	
EC 13, 6 W	144			37.4	41.3	45.1	49.0	52.8	
EC 13, 12 W	145			49.6	53.5	57.3	61.2	65.0	

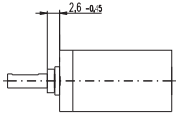
Option Ball Bearing

Order Number

4.1 : 1	144300	131 : 1	352393
5.1 : 1	352391	275 : 1	144303
17 : 1	144301	664 : 1	352394
26 : 1	352392	1119 : 1	144304
67 : 1	144302	3373 : 1	352395

Technical Data

Planetary Gearhead	straight teeth
Output shaft	stainless steel, hardened
Bearing at output	preloaded ball bearings
Radial play, 6 mm from flange	max. 0.04 mm
Axial play at axial load	< 5 N 0 mm > 5 N max. 0.04 mm
Max. permissible axial load	8 N
Max. permissible force for press fits	25 N
Sense of rotation, drive to output	=
Recommended input speed	< 8000 rpm
Recommended temperature range	-15 ... +100°C
Extended area as option	-35 ... +100°C
Number of stages	1 2 3 4 5
Max. radial load,	6 mm from flange 10 N 15 N 20 N 20 N 20 N
Gearhead values according to sleeve bearing version	



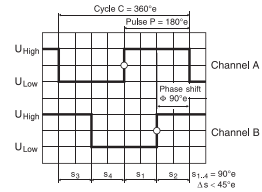
Gearhead length: L1 + 0.2 mm

May 2009 edition / subject to change

maxon gear 211

Figure B.2b: Maxon Tertiary/Quaternary/Quinary 110315 Motor Gearhead Datasheet [61]

maxon sensor



Stock program

Standard program

Special program (on request)

Order number

323049323050334910323051323052323053323054

Type

Counts per turn

Number of channels

Max. operating frequency (kHz)

Max. speed (rpm)

overall length

overall length

64

64

100

128

128

256

256

2

2

2

2

2

2

2

80

80

100

160

160

320

320

75000

75000

60000

75000

75000

75000

75000

Maxon Modular System

Motor

Page

± Gearhead

Page

± Brake

Page

Overall length [mm] / • See Gearhead

RE 8, 0.5 W

51

22.6

RE 8, 0.5 W

51

GP 8, 0.002 - 0.03 Nm

205

•

RE 8, 0.5 W

51

GP 8, 0.01 - 0.1

206

RE 10, 0.75 W

53

22.8

RE 10, 0.75 W

53

GP 10, 0.005 - 0.15 Nm

207/208

•

RE 10, 1.5 W

55

30.4

RE 10, 1.5 W

55

GP 10, 0.005 - 0.15 Nm

207/208

•

A-max 12, 0.5 W

102

25.3

A-max 12, 0.5 W

102

GP 10, 0.005 - 0.15 Nm

207/208

•

A-max 12, 0.5 W

102

GS 12, 0.01 - 0.02 Nm

209

•

A-max 12, 0.5 W

102

GP 13, 0.05 - 0.15 Nm

210

•

A-max 12, 0.5 W

102

GP 13, 0.2 - 0.35 Nm

211

•

RE 13, 0.75 W

58

26.3

RE 13, 0.75 W

58

28.7

RE 13, 0.75 W

59

GP 13, 0.05 - 0.15 Nm

210

•

RE 13, 0.75 W

59

GP 13, 0.2 - 0.35 Nm

211

•

RE 13, 2 W

62

38.5

RE 13, 2 W

63

40.9

RE 13, 2 W

63

GP 13, 0.05 - 0.15 Nm

210

•

RE 13, 2 W

63

GP 13, 0.2 - 0.35 Nm

211

•

RE 13, 1.5 W

66

28.4

RE 13, 1.5 W

67

30.8

RE 13, 1.5 W

67

GP 13, 0.05 - 0.15 Nm

210

•

RE 13, 1.5 W

67

GP 13, 0.2 - 0.35 Nm

211

•

RE 13, 3 W

70

40.6

RE 13, 3 W

71

43.0

RE 13, 3 W

71

GP 13, 0.05 - 0.15 Nm

210

•

RE 13, 3 W

71

•

RE-max 13, 0.75 W 120

25.2

RE-max 13, 0.75 W 120

25.2

RE-max 13, 0.75 W 120

•

RE-max 13, 0.75 W 120

•

RE-max 13, 2 W 122

36.2

RE-max 13, 2 W 122

36.2

RE-max 13, 2 W 122

•

RE-max 13, 2 W 122

•

Technical Data

Supply voltage

5 V ± 5 %

Output compatible

TTL

Phase shift φ

90° ± 45°

Operating temperature range

-25 ... +85 °C

Moment of inertia of code wheel

≤ 0.005 gcm²

Output current per channel

max. 5 mA

Pin Allocation

Pin 1

Pin 2

Pin 3

Pin 4

Pin 5

Pin 6

Pin 7

Pin 8

Pin 9

Pin 10

Motor +

VCC

GND

Channel A

Channel A

Channel B

Channel B

N.C.

Order Number 323049 - 323054, exkl. 334910

Pin 1 - 10 / X = 0.3 ± 0.05

Compatible connector: Molex 52207-1085, Type 1-84953-0

Adapter print to DIN 41651, Art. No. 327086

Order Number 334910

Pin 1 - 8 / X = 0.3 ± 0.03

Compatible connector: Molex 52745-0896

Connection example

Encoder

Line Driver

V_{CC}

GND

Channel A

Channel A

Channel A

Channel A

Line receiver

Recommended IC's

MC 5486

SN 75175

AM 26 LS 32

Figure B.2c: Maxon Tertiary/Quaternary/Quinary 323054 Motor Encoder Datasheet [62]

APPENDIX C

Additional Images

C.1 LapaRobot 2.2 CAD Models

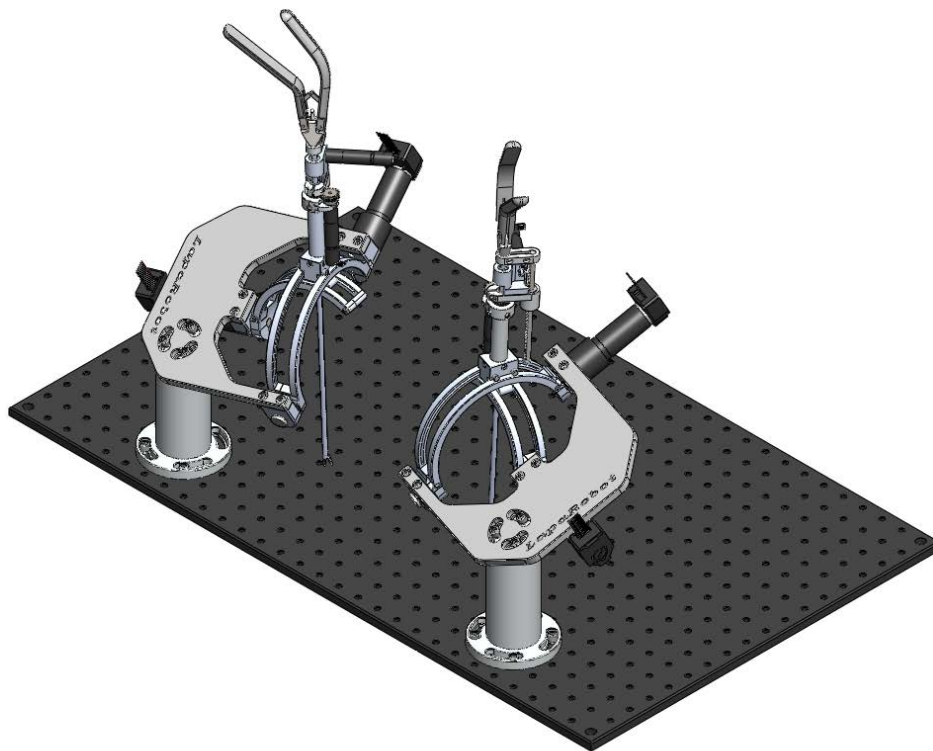


Figure C.1: LapaRobot 2.2 Surgical Station CAD Model, Isometric View

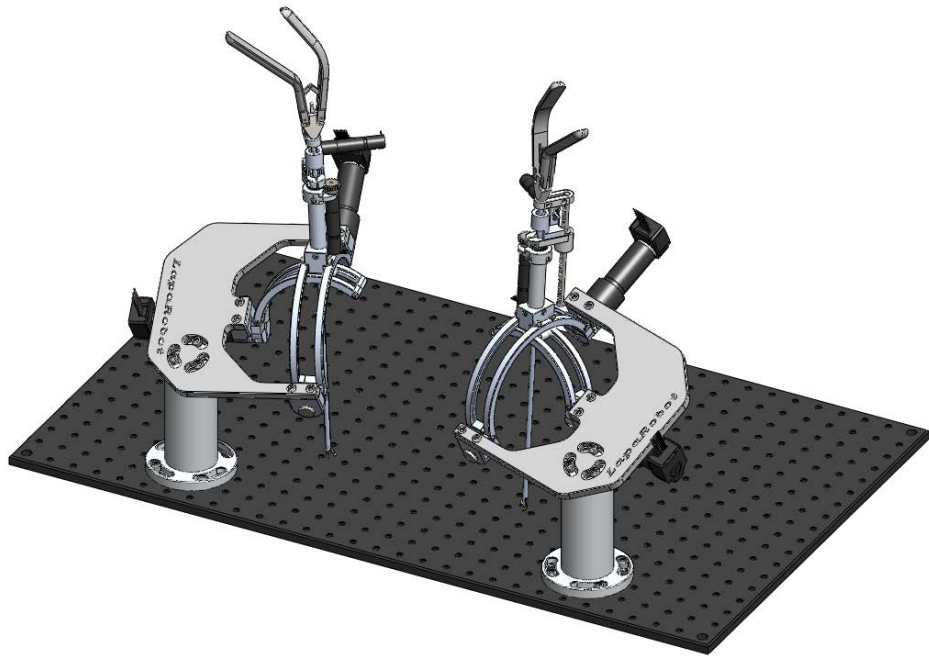


Figure C.2: LapaRobot 2.2 Surgical Station CAD Model, Trimetric View

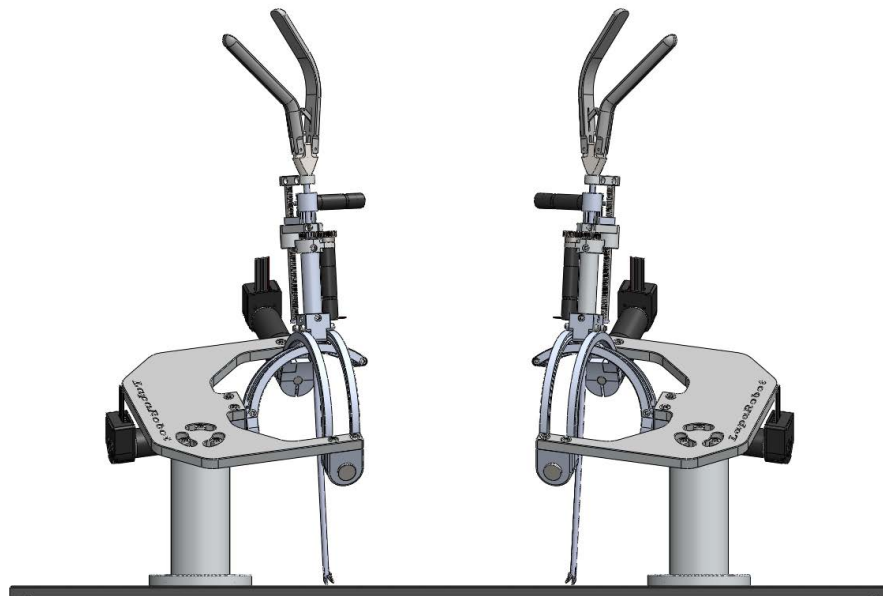


Figure C.3: LapaRobot 2.2 Surgical Station CAD Model, Front View

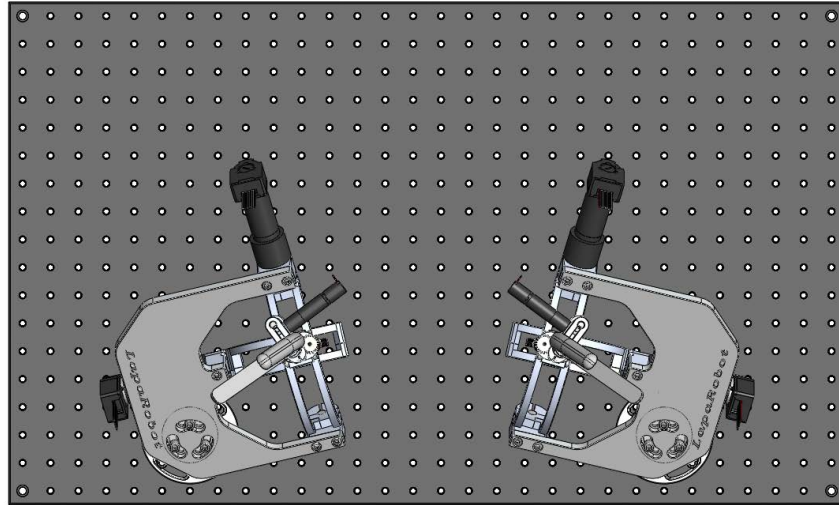


Figure C.4: LapaRobot 2.2 Surgical Station CAD Model, Top View

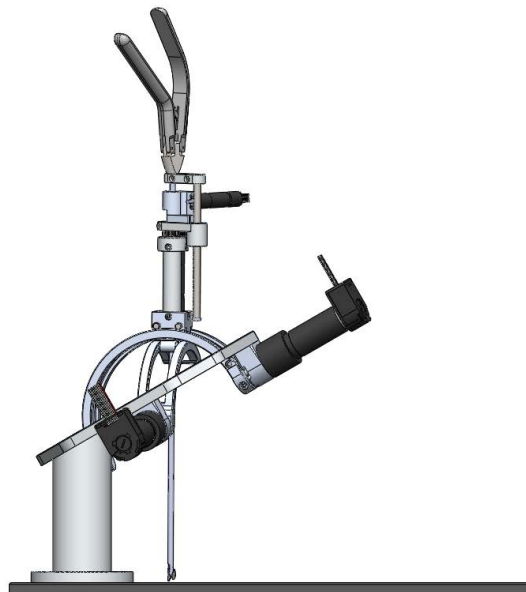


Figure C.5: LapaRobot 2.2 Surgical Station CAD Model, Right View

C.2 Four-Bar Mechanism CAD Models

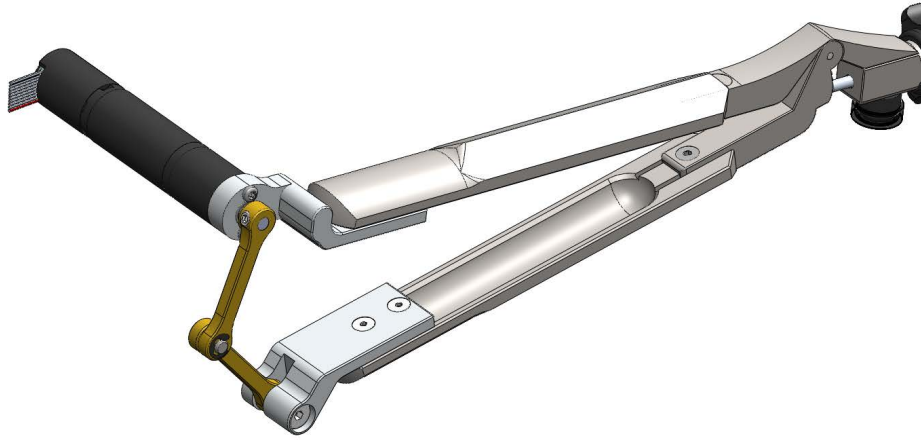


Figure C.6: Four-Bar Grasping Mechanism CAD Model, Isometric View

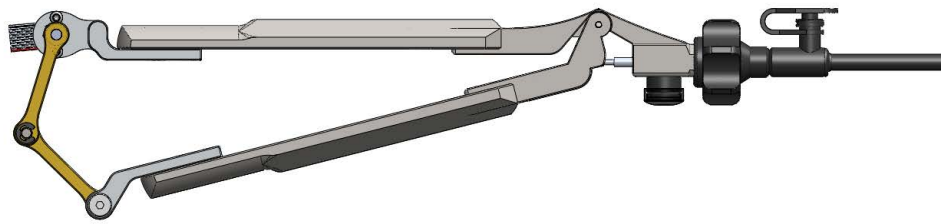


Figure C.7: Four-Bar Grasping Mechanism CAD Model, Front View

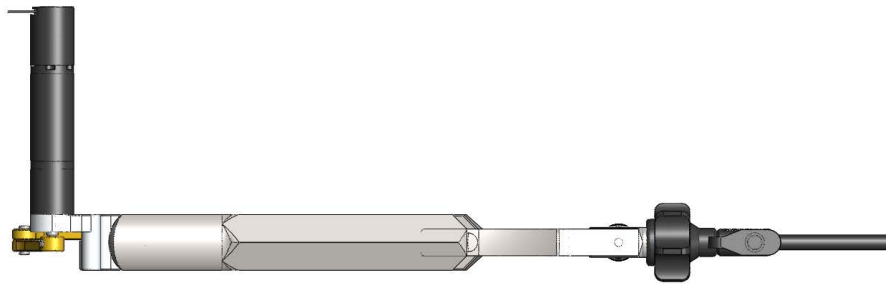


Figure C.8: Four-Bar Grasping Mechanism CAD Model, Top View

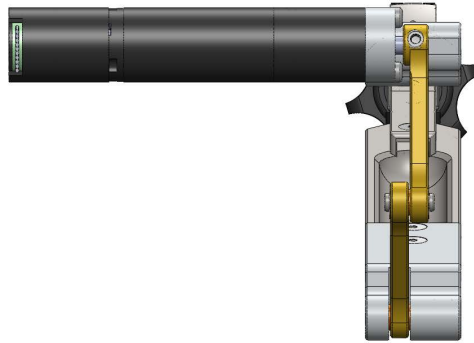


Figure C.9: Four-Bar Grasping Mechanism CAD Model, Side View



Figure C.10: Four-Bar Grasping Mechanism CAD Model, Isometric View

C.3 Input LapaRobot 2.3

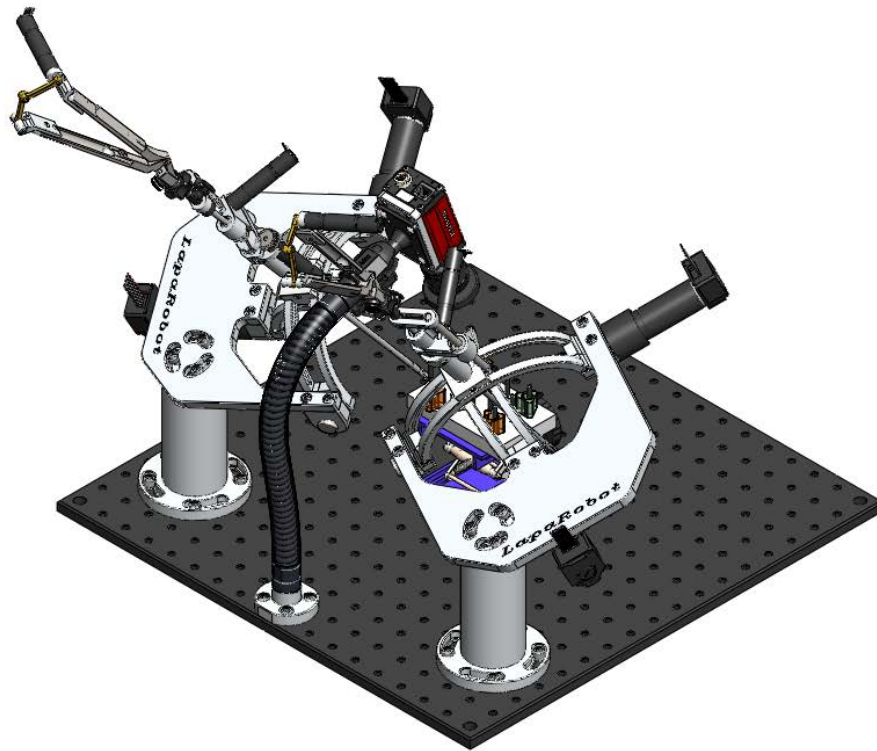


Figure C.11: LapaRobot 2.3 Surgical Station CAD Model, Isometric View

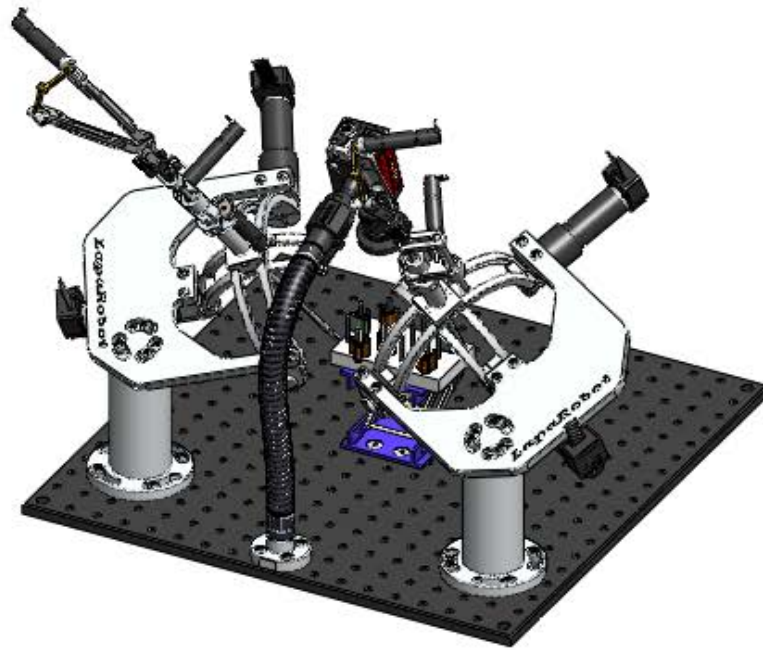


Figure C.12: LapaRobot 2.3 Surgical Station CAD Model, Trimetric View

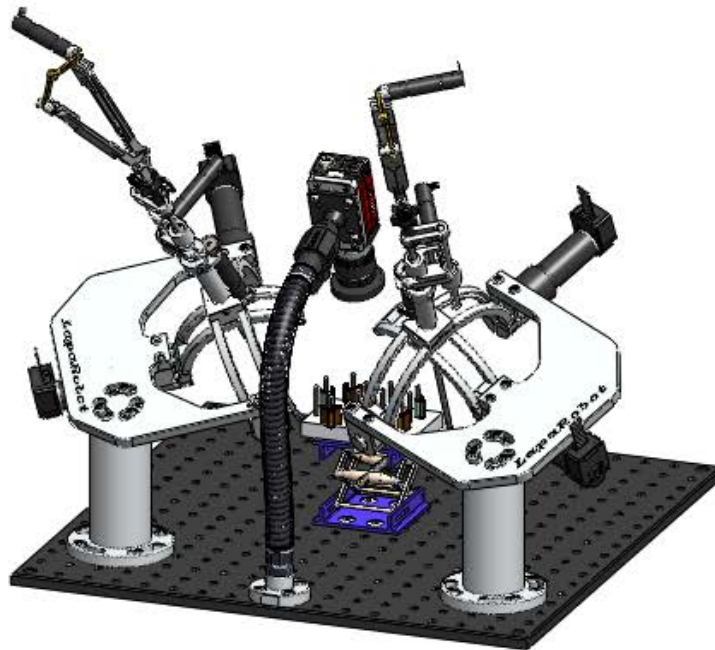


Figure C.13: LapaRobot 2.3 Surgical Station CAD Model, Dimetric View

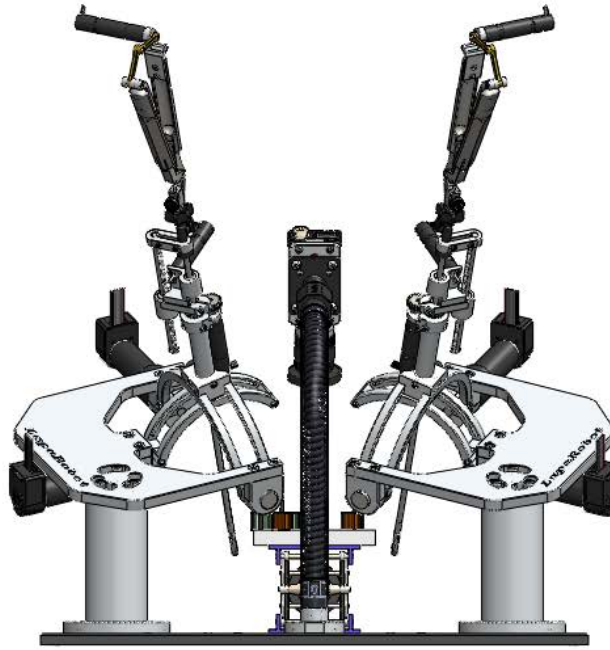


Figure C.14: LapaRobot 2.3 Surgical Station CAD Model, Front View

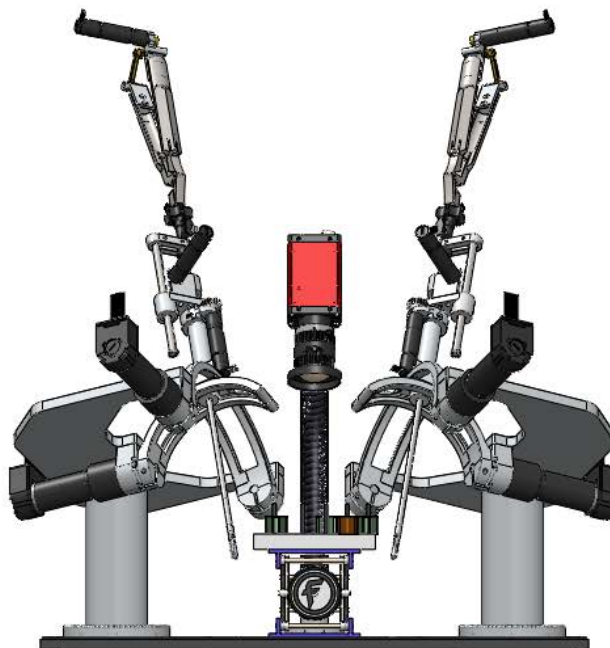


Figure C.15: LapaRobot 2.3 Surgical Station CAD Model, Back View



Figure C.16: LapaRobot 2.3 Surgical Station CAD Model, Left View

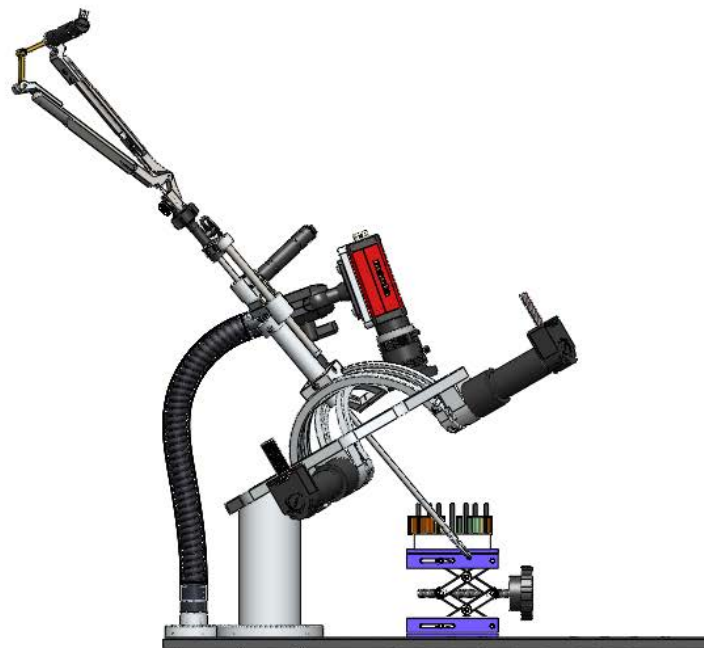


Figure C.17: LapaRobot 2.3 Surgical Station CAD Model, Right View

C.4 LapaRobot 2.3 Prototype Images



Figure C.18: LapaRobot 2.2 Surgical Station Prototype, Front View

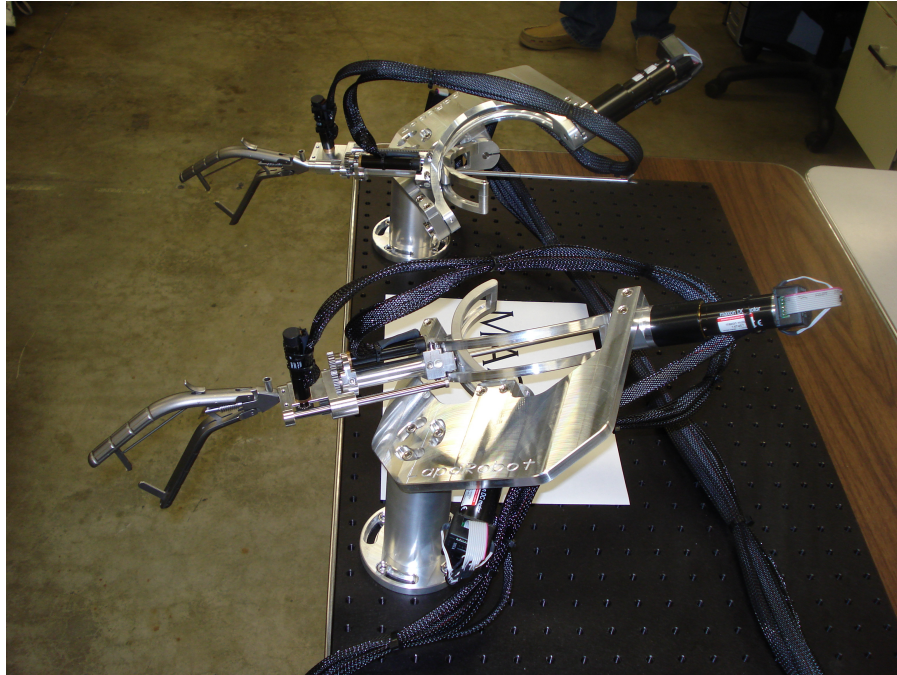


Figure C.19: LapaRobot 2.2 Surgical Station Prototype, Side View



Figure C.20: LapaRobot 2.2 Master/Slave Surgical Stations, Prototype



Figure C.21: LapaRobot 2.2 Master/Slave Surgical Stations Prototype, Side View

C.5 LapaRobot 2.3 Prototype Images

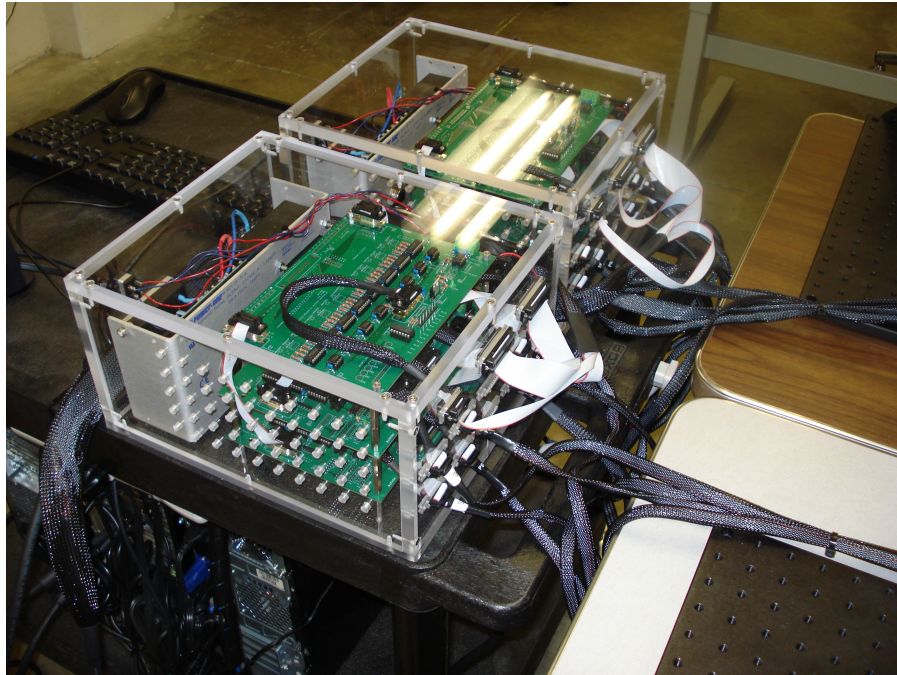


Figure C.22: LapaRobot Control Hardware Prototype

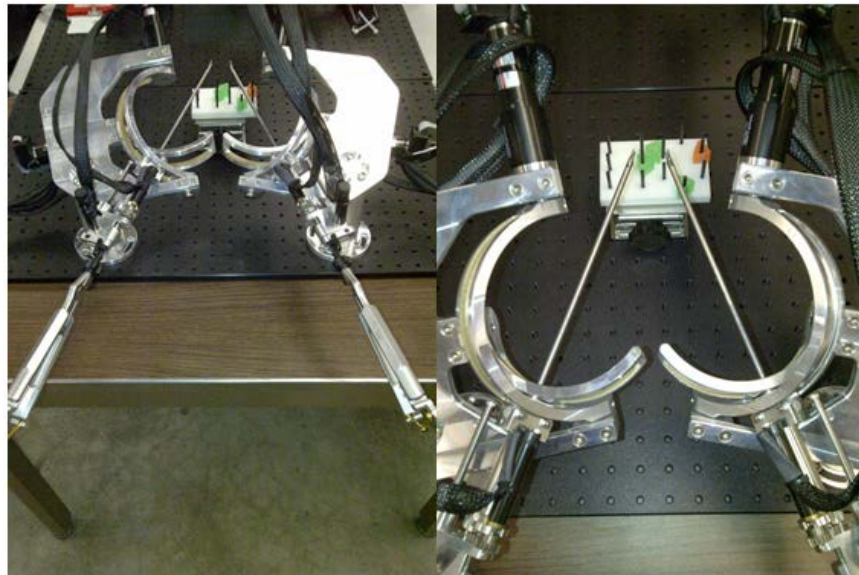


Figure C.23: LapaRobot 2.3 Surgical Station Prototype, Front View

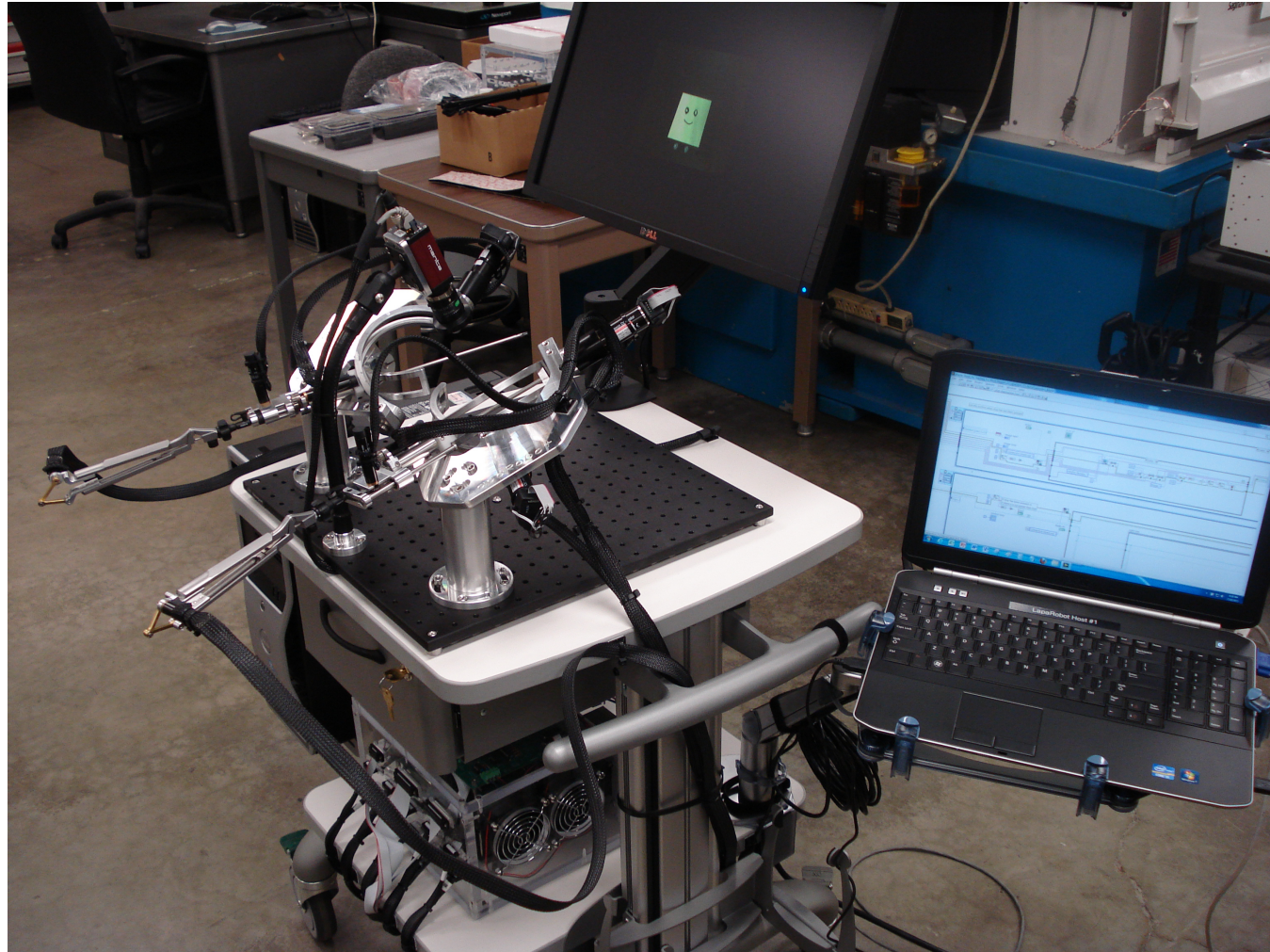


Figure C.24: LapaRobot 2.3 Surgical Station, Isometric View

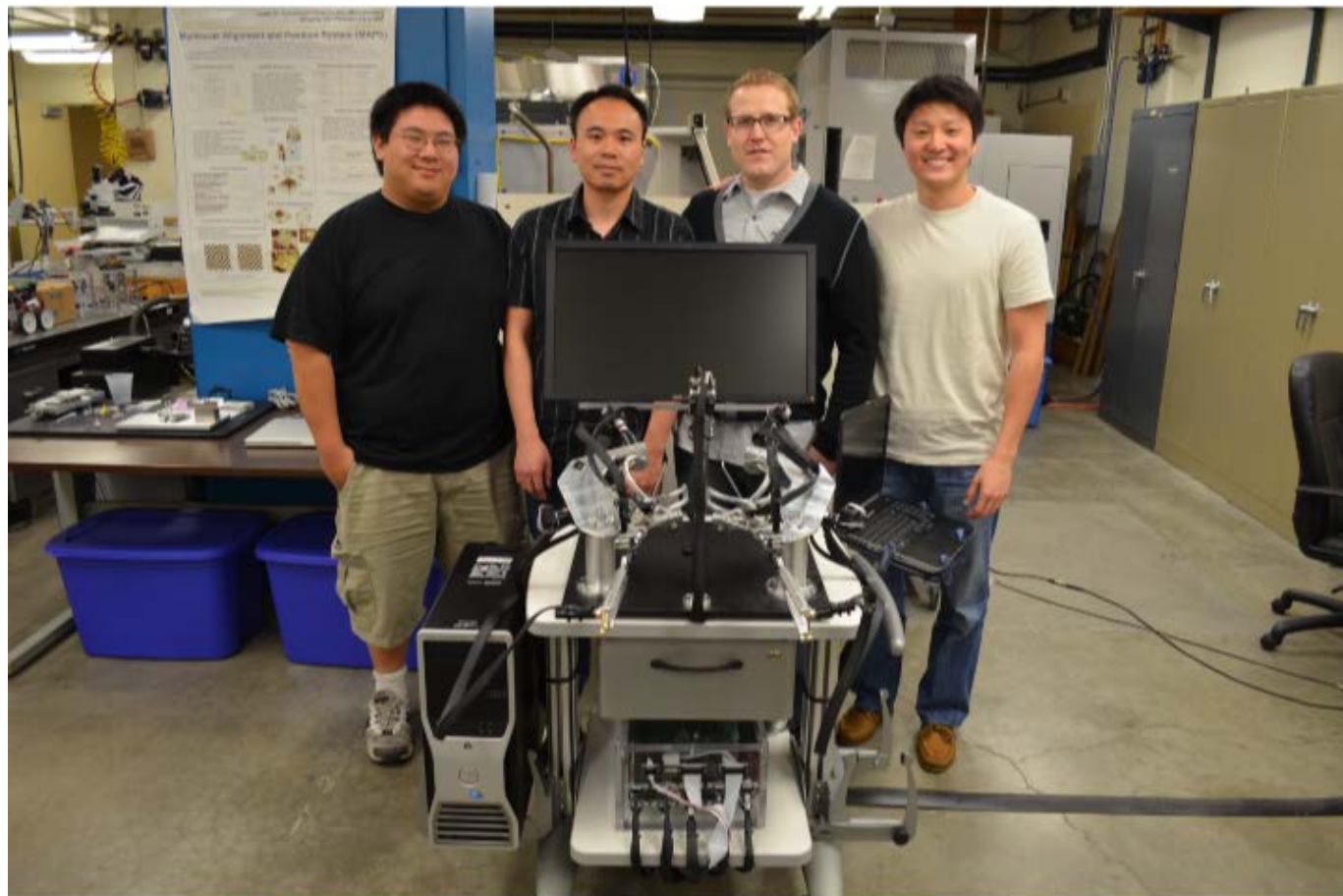


Figure C.25: The LapaRobot Contributing Engineers at the *University of California, Los Angeles*: Kevin Chu, Christopher Lim, Stephen W. Prince, Christopher Kang (From Left to Right)



Figure C.26: The LapaRobot at the *Eisenhower Medical Center* in *Rancho Mirage, CA* with Christopher Kang (Left) and Stephen W. Prince (Right)



Figure C.27: The LapaRobot at the *Eisenhower Medical Center* in *Rancho Mirage, CA* with Holly Chung (Left) and Stephen W. Prince (Right)

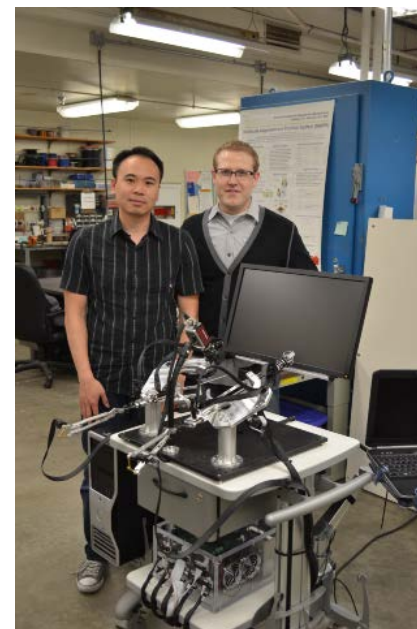
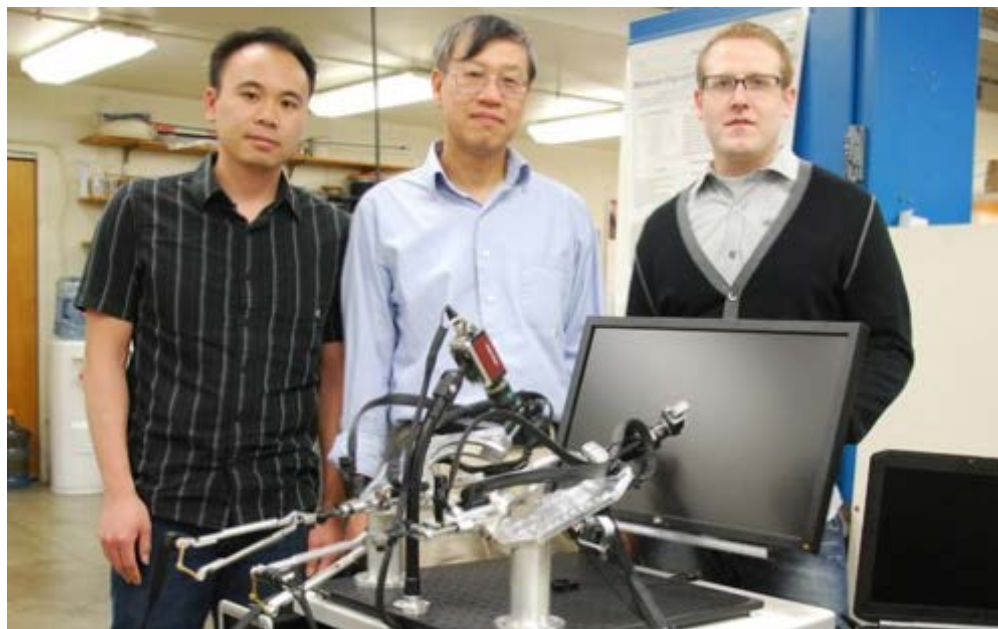


Figure C.28: The LapaRobot Engineers at the *University of California, Los Angeles*: Christopher Lim (Left); Professor Tsu-Chin Tsao (Middle); Stephen W. Prince (Right)

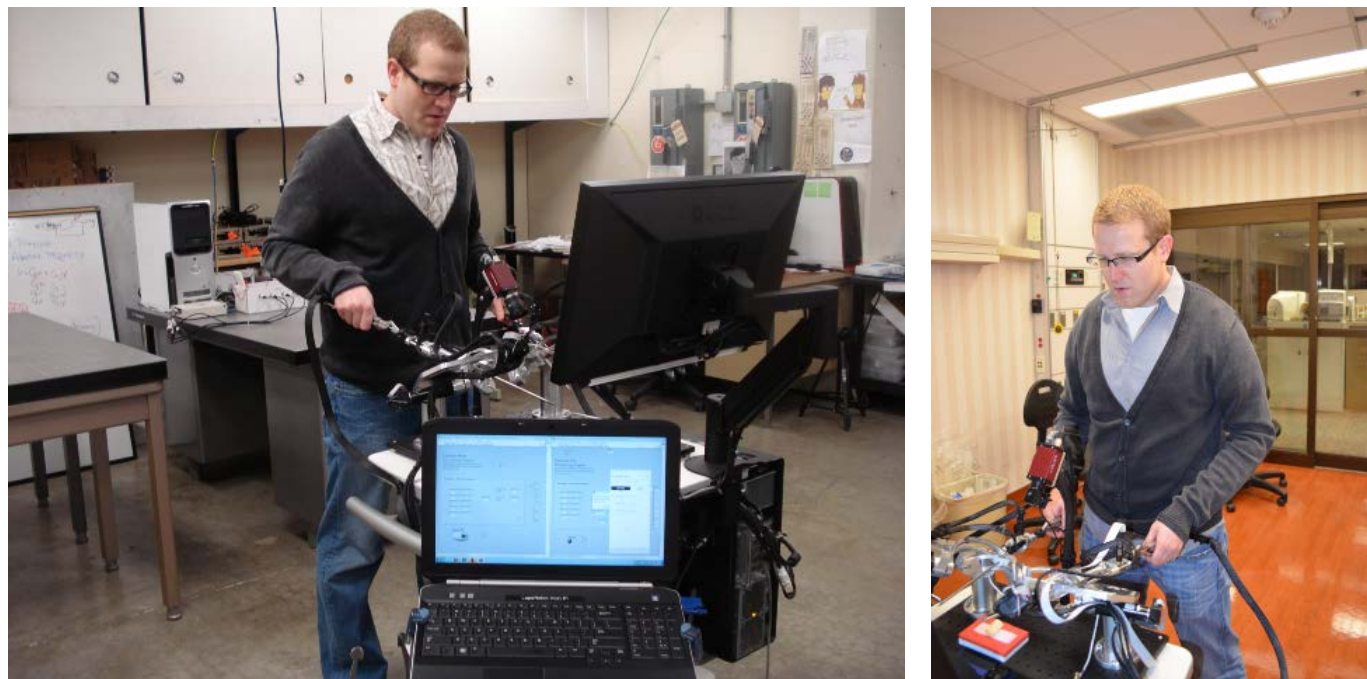


Figure C.29: The LapaRobot at the *University of California, Los Angeles* (Left) and at the *Eisenhower Medical Center in Rancho Mirage, CA* (Right) with Stephen W. Prince

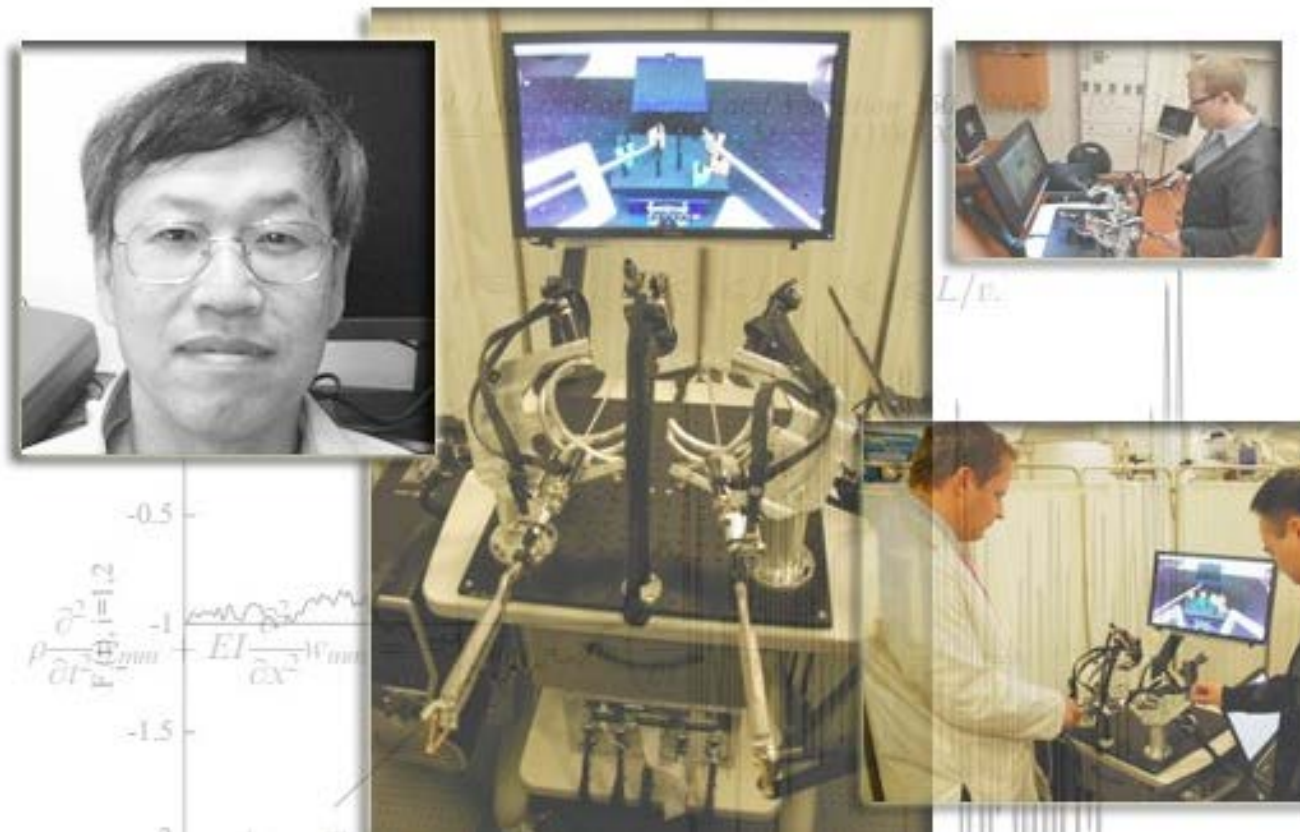


Figure C.30: The LapaRobot System, Developed at the *University of California, Los Angeles* with Professor Tsu-Chin Tsao (Top Left); Stephen W. Prince (Top Right); Dr. Erik P. Dutson (Bottom Left); Christopher Lim (Bottom Right)