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Micro-motion controller

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MICRO-MOTION CONTROLLER

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MICRO-MOTION CONTROLLER

By

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SENIOR DESIGN PROJECT REPORT

Submitted to
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MICRO-MOTION CONTROLLER

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ABSTRACT

Micro-motions in surgical applications are small motions in the range of a few millimeters and are common in ophthalmic surgery, neurosurgery, and other surgeries which require precise manipulation over short distances. Robotic surgery is replacing traditional open surgery at a rapid pace due to the obvious health benefits, however, most of the robotic surgical tools use robotic motion controllers that are designed to work over a large portion of the human body, thus involving motion of the entire human arm at shoulder joint. This requirement to move a large inertial mass results in undesirable, unwanted, and imprecise motion. This senior design project has created a 2-axis micro-motion “capable” platform, where the device studies the most common linear, 2-D surgical micro-motion of pinched human fingers in a damped and un-damped state. Through a system of printed and modeled parts in combination with motors and encoders a microsurgical controller was developed which can provide location-based output on a screen. Mechanical damping was introduced to research potential stability of micro-motion in any surgeon’s otherwise unsteady hand. The device is to also serve as a starter set for future biomedical device research projects in Santa Clara University’s bioengineering department. Further developments in the microsurgical controller such as further scaling, addition of a third axis, haptic feedback through the micro-controller, and component encasing to allow productization for use on an industrial robotic surgical device for clinical applications.

Keywords: Micro-motion, surgery, robotic motion controller

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TABLE OF CONTENTS

List of Figures

List of Tables

List of Abbreviations

BOM: Bill of Materials
CAD: Computer Aided Design
DOF: Degrees of Freedom
DIP: Distal Interphalangeal
IP: Interphalangeal
MCP: Metacarpophalangeal
PIP: Proximal Interphalangeal
TM: Trapeziometacarpal

1. Introduction

1.1 Problem Statement

Robotic surgery is replacing traditional open surgery at a rapid pace due to the obvious health benefits, such as reduced blood loss, reduced trauma, and faster recovery times. However, most of the robotic surgical applications use robotic motion controllers that are designed to work over a large portion of the human body, thus are mainly equipped with the ability to achieve large motions. These controllers mimic the human hand by providing 3 Degrees of Freedom (3-DOF) motion capability at the shoulder joint and another 3 Degrees of Freedom at the human wrist [1]. The net combined effect is 6 Degrees of Freedom (6 DOF) at the fingertip. In providing the ability to achieve large motions, little attention is paid to the need for moving the surgical robotic controllers by a “small” and precise amount to mimic the movement of a pair of pinched fingers. Micro-motions are small motions where the term “small,” while subjective and defined in context that is specific to applications, is generally recognized to be in the range of a few millimeters in surgical applications.

In any application that involves precision work, such as restoration of paintings, or microsurgery, it is the small (micro) motion of pinched fingers [2], see figure 1, that provides utmost control and precision over the task at hand by being able to manipulate the paint brush or the surgical tool in small motions (strokes). Seldom is bulky shoulder movement used for generating fine motion at the finger tips where motion of the pinched fingers provides better control and dexterity. Moving the shoulders for fine motion (strokes) at the finger tips requires moving a large mass, that of the entire arm, thus is subject to inertial overshooting and fatigue, both mental and physical. The lack of attention by the robotic motion control industry to micro-motion control in robotic controllers is the focus of this senior design project. This senior design project will take into account work done by the robotic motion controller industry, analyze several motion control implementations, and research a solution that will show the advantage of adding micro- motion control to existing robotic motion controllers which lack a dedicated micro-motion capability.

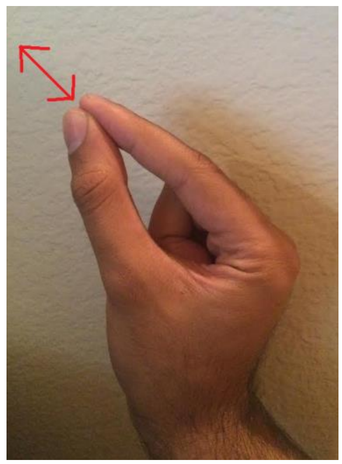


Figure1. Micro-motion of Pinched Fingers

1.2 Project Background and Motivation

The location of Santa Clara University, in the heart of Silicon Valley, provides SCU students access and opportunities to visit emerging technology companies. During a visit to a Sunnyvale-based medical device company, Intuitive Surgical, SCU bioengineering students availed an opportunity to tour the manufacturing facility and test drive a daVinci Surgical Robot.

The daVinci Surgical Robot consists of a master robot and a slave robot. A surgeon sits at the master robot and moves two motion controllers. The surgeon pinches a pen-like spindle and with wrist and shoulder motions, the surgeon moves the surgical tools on the slave robot [3]. The motions at the surgical controller are repeated by the slave robot on a patient who has no physical contact with the surgeon [3]. A nurse inserts surgical instruments into the arms of the slave robot that performs surgery. The daVinci Surgical Robot is a unique surgical robot with no competition to its abilities.

While there are other types of smaller and limited use surgical robots, the daVinci Surgical Robot has a 6 DOF motion controller for large motions, and thus is able to accommodate surgery over large parts of the human anatomy.

During a medical observer-ship program that focused on non-robotic micro surgical procedures in the field of neurosurgery and opthalmology, it was recognized that the capability of the daVinci can be increased by providing finer motion control to mimic the micro-motions made by pinched human fingers. The robot, in its present configuration, requires the surgeon to move his shoulder to achieve linear micro-motion at the finger tip. It is prudent to investigate the possibility of adding micro- motion abilities to the daVinci Surgical Robot, or any future robot that may perform the same functions that the daVinci does. In doing so, the capability of the robot controller will be extended to performing motions that are required by delicate micro surgeries.

1.3 Project Objectives

The goal of this senior design project is to create a 3-axis micro-motion “capable” platform. While the platform will be 3-axis capable, the direct purpose of the device is to study linear 2-D micro-motion of pinched human fingers in a damped and un-damped state. Mechanical damping is expected to add another level of stability to any surgeon’s otherwise unsteady hand.

Exhaustive research of published papers in various journals in the field of micro-motion revealed an ongoing interest and need for linear micro-motion capability in surgical tools. Additional research into types of micro-motion devices in existence revealed a large number of micro- motion capable devices that have the same end function, but their approach leaves a gap in the ability to achieve necessary micro-motion control with the desired operating precision. This micro-motion device will test linear micro-motion by combining two rotary axes, which in effect will provide linear motion with lesser amount of inertia while allowing simplified damping.

The device will also serve as a starter set for Santa Clara University's bioengineering program where the starter device will provide a mechanical device platform that can accommodate further development and spur innovation at both graduate and undergraduate levels. The device may also be used by Mechanical Engineering students to test micro-motions in projects such as training bomb-diffusing squads, testing the abilities of partially paralyzed patients, training motor functions of autistic children, etc. It may be used by Electrical and Computer Engineering students to enable haptics in projects that study the effect of haptics on improving the lives of bed-ridden patients and the elderly.

1.4 Literature Review

Several scholarly and research papers on micro-motions and micro surgeries were studied for this project. Their relevant summaries are listed below.

1.4.1 Visual Measurement of Microsurgical Motion with Application to Robotic Augmentation [4]

In microsurgery, involuntary hand motions limit a surgeon's degree of operating accuracy. Hand tremor is a known to be a significant problem in microsurgical applications, since a high degree of accuracy is required for microsurgery procedures. Therefore, methods of tremor cancelation are important for surgical tools. The system investigated in this paper is a handheld tremor canceling system called the Micron. This article presents an error analysis of the stereo vision based sensing application for controlling the Micron instrument. Problems of tremors present significant risk in the fields of ophthalmological (applications such as retinal vein cannulation) and neurological surgery. Most common erroneous or involuntary movement that affects microsurgery is the physiological tremor, where the tremor is considered to be any involuntary movement, or approximately rhythmic and roughly sinusoidal motion. Physiological tremor is a type that is inherent even in the movement of healthy subjects. In vitreoretinal microsurgery, an evident component of physiological tremor is the "neurogenic" component of 8-12 Hz, whose frequency is independent of the hand and arm's mechanical properties. The tool tip oscillation noticed during vitreoretinal microsurgery is in the order of 50 microns peak-to-peak (pp) or greater.

To overcome this problem, the intelligent active hand-held instrument, Micron, senses its motion. The Micron also distinguishes between desired and undesired motion by using advanced filtering techniques. Further, it actively compensates for undesired motion by applying an equal but opposite deflection sensed in its tip.

1.4.2 Robotic Assisted Microsurgery (RAMS): Application in Plastic Surgery [5]

The RAMS system allows for high dexterity microsurgical operations through the use of robotic arms. The robotic arms allow for improvements in areas such as motion scaling, articulation, and ergonomics. The surgeon benefits from the RAMS with improved precision and results. RAMS development started in the early 1990s using previously developed NASA telerobotics technology. The system consists of a six degree of freedom robot with a torso-shoulder-elbow body also to go along with a 3-degree of freedom wrist. RAMS is controlled by the surgeon but also acts as an assistant helping in areas such as accuracy, stability, and control. The system is also able to eliminate any tremors or slight unwanted motions of the surgeon during surgical operations. There are limitations to the RAMS system including limited dexterity and hand-eye coordination. There also exits a concern of unavailable haptic feedback that is a likely disconnect between the surgeon's sensory feeling and patient. RAMS has broadened its scope and encompasses operations ranging from cardiac surgery to plastic surgery. The future of RAMS is to continue to build on transcending the human limitations to make microsurgeries easier to perform in the long run.

1.4.3 Robotic Assisted Versus Pure Microsurgical Vasectomy Reversal: Technique and Prospective Database Control Trial [6]

Microsurgical vasectomy reversal can be a technically demanding procedure, one which may be aided through robotic assistance. Robotic assistance can provide the surgeon with improved visualization, tremor elimination, and decreased fatigue. During such a microsurgical procedure, the patient is placed in a supine position. An incision is made at the scrotum and the two ends of the vas are brought out of incision. The distal vas is dissected to allow for a tension-free connection between it and the proximal vas. The proximal vas is transected and depending on the sperm count either a RAVV or RAVE (robotic assisted) technique can be performed rather than a MVV/MVE. Statistical data supports that a greater sperm count per ejaculation rate is shown in patients who undergo RAVV/RAVE as compared to MVV/MVE. Reasoning for these results includes the robotic-assisted procedures providing a more stable operating platform for the surgeon, thereby increasing the rate of recovery and decreasing the duration time of the operation.

1.4.4. Performance of Robotic Augmentation in Microsurgery Scale Motions [7]

Development of a "steady hand" robot that can provide guidance and enforce safety constraints illustrates the potential promise of microsurgical applications. The platform for this robot has a seven degree of freedom manipulator with a force sensor to allow the robot to move in compliance with opposing forces during surgery. The robot is also equipped with a PC- based controller system that provides the operator an application interface. The steady hand robot proved to show greater operational accuracy during testing with higher success rates and faster trial times. The robotic system is less prone to errors and provides a greater spatial resolution to the operator. Robotic systems can improve microsurgical procedures through extensions of human capabilities, but the skill of the surgeon remains a highly important factor in the success of a surgical operation.

1.4.5 A Robotic System with Force Feedback for Micro-Surgery [8]

A robotic force feedback system for micro-surgery was developed which was called Micro-hand. This system was designed based on a master and slave type technical platform. The slave manipulator platform was designed by using macro and micro frames, and the Phantom that was developed by the Sensable Technology Company was used as the master manipulating control device. The interactive forces and torque input and output from the slave manipulators and the surgical environment were measured within a 6-dimensional arrangement of force and torque sensors. The sensor signals were then fed back to the master device. This is to enable a haptic system that provides force feedback to the surgeon during surgical procedures. The validity and performance of the system have been proven through animal experiments shown within the article that further show that a microsurgery robotic system with force feedback can be successfully deployed.

1.4.6 A Miniature Microsurgical Instrument Tip Force Sensor for Enhanced Force Feedback During Robot-Assisted Manipulation [9]

This paper shows the development of a miniature force sensor that was designed to measure contact forces at the tip of a microsurgical instrument in three dimensions and its application for scaled force feedback using a manipulated microsurgical assistant robot. The key features of the sensor are its small size, an innovative arrangement of flexure beams, and strain gauges to measure forces isotopically at the instrument tip about 40 mm from the sensor body for three-axis force-sensing resolution. The design, implementation, and testing of a miniature force sensor was further developed to quantify forces in three dimensions at the tip of the micro surgical instrument. The article further describes microsurgical force measurement experiments that show that usual forces on microsurgical instrument tips during retinal surgery are very miniscule and are below the threshold of controller tangible sensitivity. Measurements and comparisons of tremor within hands are both detected while holding microsurgical utensils in a fixed position.

1.4.7 A Study of Instrument Motion in Retinal Microsurgery [10]

This paper reports on high-precision recordings of hand-held instrument motion during actual vitreoretinal microsurgery. During the high-precision recordings of vitreoretinal microsurgery, movement of a hand-held instrument was recorded in six degrees of freedom. Data were acquired for 5 min by using an inertial sensing module that was specifically developed for use with a commercially available microsurgical instrument. The maximum velocity used by the surgeon was estimated at 0.70 m/s, and maximum acceleration at 30.1 m/s2. The RMS amplitude of tremor in the instrument tip motion was estimated to be 0.182 mm. The topic of manual accuracy in microsurgery has received attention for some time, but quantitative assessment of the problem posed by manual accuracy has been lacking. As a result, most efforts toward development of systems for the enhancement of microsurgical accuracy have proceeded forward without a complete and accurate description of the problem that must be solved. Further, the scarcity of data is exacerbated by the fact that studies such as that of physiological tremor and other undesired components of hand movement that have been conducted so far have been experimented under laboratory conditions. The application of the results of or the reliance on such studies hence requires careful consideration of the degree of surgical realism simulated in the study, and its effect on the relevance of collected data. “Quantification of instrument motion during actual microsurgery would obviate this consideration.”[10] An added capability of directly recording instrument motion during the vitreoretinal microsurgical procedure would allow quantification of various types of undesired motion (e.g., tremor, jerk) in authentic conditions, as well as determination of the “performance envelope” utilized by the surgeon in terms of velocity, acceleration, and frequency.[10] All of these additional and mandatory measurements will prove to be valuable in providing baseline data for the development of accuracy-enhancement systems.

1.4.8 Performance of Robotic Augmentation in Microsurgery-Scale Motions [11]

This paper is part of the development process of a microsurgical “cooperating” assistant. To evaluate its potential for augmenting fine surgical motions, test of precision and operator perception in simple microsurgical scale pick and place motions are conducted. Such small motions are common in microsurgical procedures of micro-vascular anastomosis. The experiments reported in this article test the users’ ability to position a common surgical tool to the accuracies of 250, 200 and 150 micrometers. These experiments were performed by using two test platforms. The new “steady hand” robot designed for microsurgery and the LARS robot (a laparoscopic camera holding robot) were adapted for this purpose.

Comparative results for several parameters tested such as time, error rate, success rate, and number of attempts are included. Comparison of the performance of the two robots for these specific tasks is also included. Summarily, the results support the claim that the new “steady hand” robot surely augments basic human performance for microsurgery-scale motion.

2. Systems Level Overview

The microcontroller was developed using simple physics in undergraduate statics, dynamics, and mechanics courses. This allowed for accurate calculations and improvement of precision by allowing the focus to be the resolution of the microcontroller.

2.1 Degrees of Freedom

Degrees of freedom (DOF) is a numerical system used in mechanics to define the number of independent parameters to define a rigid body's configuration. To determine the DOF of a rigid body, the number of distinct ways it can be moved must be considered [12]. The position of a rigid body in can be defined by three components of translation and three components of rotation, along and about the x-axis, the y-axis, and the z-axis [13]. See figure 2.

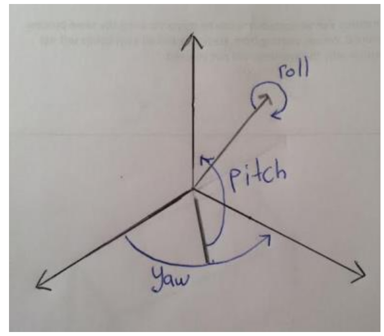


Figure 2. Degrees of Freedom of a Rigid Body on a Plane

2.2 Mechanical Joints

Kinematic pairs can be defined as a movable coupling of two rigid bodies imposing restraints on their relative motion by conditions of their linkage. These constraints result in a decrease of the degrees of freedom of the system and can be divided into two categories: lower pairs and higher pairs. Lower pairs may also be known as surface-contact pairs and are a type of joint that constrains contact between a point, line, or plane in a moving body to correspond to a point, line, or plane of a rigid body [14].

2.2.1 Prismatic Joint

A prismatic joint, as shown in figure 3, keeps two axes of two rigid bodies aligned. The two constrained rigid bodies are able to have an independent translational motion only along the axis of motion. By its very nature, a prismatic joint introduces five constraints thereby removing five degrees of freedom [14]. The joint, therefore has a DOF of 1.

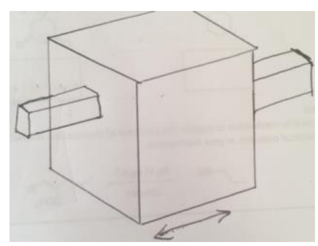


Figure 3. Prismatic Joint

2.2.2 Spherical Joint

A spherical joint, as shown in figure 4, is also known as a ball joint which keeps two spherical centers together by maintaining a point in the moving body which


Figure 4. Spherical Joint

maintains contact with the point in the fixed body. This joint has 3 degrees of freedom [14].

2.2.3 Revolute Joint

A revolute (cylindrical) joint, as shown in figure 5, requires the lines of the moving body and the fixed body to be co-linear. The two bodies have an independent rotary motion around their common axis. The revolute joint imposes five constraints of relative movement meaning that the joint has one degree of freedom [14].

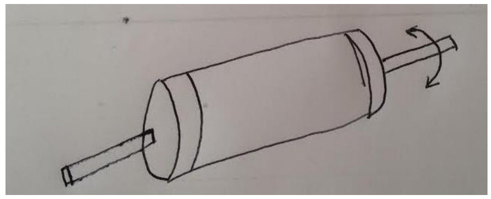


Figure 5. Revolute Joint

2.3 Degrees of Freedom applied to Human Shoulder & Elbow

The human arm overall is considered to have 7 degrees of freedom. Of those 7, the shoulder provides 3 and the elbow allows only 1. The first of the shoulder degrees of freedom is the allowance of pitch where the shoulder is able to move up and down. The shoulder also is able to move from side to side, a movement called yaw. The third degree is the shoulder roll where the shoulder is able to rotate similar to the motion of screwing a light bulb. The only degree of freedom of the elbow is the pitch movement where the elbow can move up and down through a bending motion.

2.4 Degrees of Freedom applied to Human Wrist

Of the 7 DOFs in a human arm, the remaining 3 degrees of freedom are present in the human wrist. These 3 DOFs are independent of movements within the shoulder or elbow. The first DOF in the human wrist is the pitch movement where the wrist is able to move up and down. The second DOF is the yaw movement shown through the flex motion of the wrist moving from side to side. The third DOF in the human wrist is the roll movement where it is able to rotate like a knob [1].

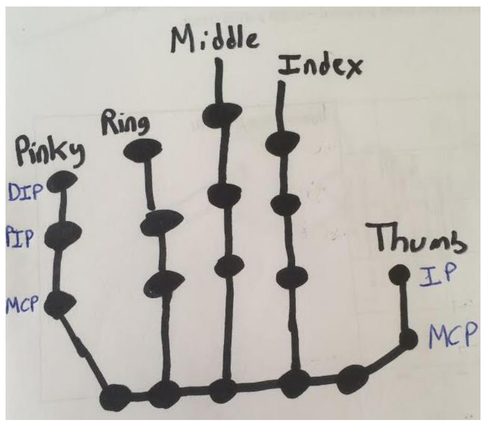


Figure 6. Degrees of Freedom in Human Hand

2.5 Degrees of Freedom applied to Human Hand

The motion of the human hand is articulate and complex with a varying number of configurations and gestures of the hand and fingers. In total there are roughly around 30 degrees of freedom in the human hand. Only three of the overall seven degrees of freedom of the human arm are required to move the human hand at any point in space. Hand motion captures hand postures as well as finger motions, both of which are highly constrained, which in turn affects the size and dimensions of the space of its range of motion [12].

In the skeletal model of the human hand, seen in figure 6, each of the four fingers have 4 marked DOFs, where the DIP, PIP, and IP joints each account for one degree of freedom. The MCP joint and TM joint (located at the thumb) each has two degrees of freedom. A combination of these joints is able to provide precise micro-motion in pinched fingers [13].

2.6 Bionic Arms in Robots

Developing a functional bionic arm that shares the same number of degrees of freedom as a regular arm can be challenging. Teams from institutions such as Stanford have prototyped designs that work to achieve reasonable performance and functionality of a human arm [15]. In addition to focusing on the degrees of freedom of the robotic arm, actuation scheme of motors and circuits are needed to operate the arm to exhibit the expected range of motion.

For the robotic arm designed at Stanford [15], the actuator scheme consists of a stepper motor, timing belt, cable circuit, series compliance, and output link. The arm is powered by the stepper motor. Coupled reduction motion mechanisms are controlled through belts and circuits. Use of belts and circuits results in low friction, low stiction, and zero backlash enabling the bionic arm to move in increments smaller than 0.5 mm.

2.7 Degree of Freedom and Haptics

2.7.1 Introduction to Haptics

Haptic, is the term derived from the Greek word, haptesthai, which means sense of touch. Due to its origin, haptic is defined as science which recreates the sense of touch using technology. This technology allows users to sense and manipulate three dimensional virtual objects with respect to features such as shape, weight, surface textures, and temperature. In order to use haptic devices, users feed information to the computer through their movements, and receive information back from the computer in the form of a sensation. This exchange in information is referred to as a haptic interface.

2.7.2 Haptic Devices

People receive and spread information throughout a 3-dimensional space. In a virtual world, users can access information by imitating any 3-dimensional space. To add realism by incorporating the sense of touch, a device was created that allows users to interact with a computer by receiving tactile feedback [8].

Force feedback is the area of haptics that deals with devices that interact with the muscles and tendons that give the humans the sensation of a force being applied; it features hardware and software that stimulates humans' sense of touch and feel through tactile vibrations or force feedback. These devices consist of robotic manipulators that push back against a user with the forces that correspond to a virtual environment. Tactile feedback makes use of devices that interact with the nerve endings in the skin to indicate properties such as heat, pressure, and texture [16]. These indicate whether or not the user is in contact with the virtual object. Other tactile feedback devices have been used to stimulate the texture and orientation of a virtual object. Creating a force feedback device requires a great deal of math and engineering, as well as computer graphics and computer language skills.

2.7.3 Uses of Haptic Technologies

Haptics is used in many fields, medical and non-medical depending upon the number of degrees of freedom presented by the application. A few common uses seen are:

- **Medical Simulators:** A virtual environment system that has been developed is being used in further developing the virtual reality based needle procedures and surgical simulators that enable medical trainees to see, touch, and manipulate realistic models of organs and biological tissues. Research is centered about the development of both instrumented hardware and software algorithms for real-time displays.
- **Collaborative Haptics:** The use of haptics to improve human-computer interactions as well as human-human interactions mediated by computers is under exploration. A multimodal-shared virtual environment system has been developed. Experiments with it have been performed on human subjects to study the role of haptic feedback in collaborative tasks and determine if haptic communication through force feedback can potentially facilitate a sense of collaboration with a remote partner [3].
- **Surgical Applications:** Haptics are used for manipulating micro and macro robots for minimally invasive surgeries. An example of this is the da Vinci Robot made by Intuitive Surgical [3]. This system comprises of input via a digital interface and an

output device called a manipulator. A console houses the input handles, a display system, the digital interface, and the electronic controller. The tool handles serve as manipulators that are high-resolution input devices that read instructions regarding spatial position, orientation, and grip commands from the surgeon, and as haptic input. The image of the surgical site is transmitted to the surgeon through this high-resolution display. The system projects images of the surgical site atop the surgeon's hands through mirrored optics while the controller transforms the motion of the tools into the camera frame of reference. In this arrangement, the system restores hand-eye coordination and provides a natural correspondence in the motions. The user interface allows the surgeon to control the camera positioning while keeping the enslaved instrument tips in the operator's view. This is necessary to reposition the instruments in their work space and to focus the camera. The orientation and alignment is always known for the application, and positional alignment can be adjusted to permit repositioning of the handles without the instrument tips.

2.7.4 Examples of Haptic Devices

- **Phantom by Sensable Technologies:** The Phantom haptic interface is a small desktop device that appears similar to a desk lamp. Instead of a bulb on the end of the arm, this device has a stylus type-grip or a finger cradling thimble for the user's fingertip. When connected to a computer and mapped with application software, the device works akin to a tactile mouse, except that in recognizes input and output in three dimensions. Three motors, which are sized for the application, provide force feedback to the user by exerting feedback pressure on the grip or the thimble. A small robot arm with three revolute joints each is also connected to a computer-controlled electrical motor. The user controls a stylus that is attached to the end of the device. Because of the motor size and torque capacity deployed and by sending appropriate current draw commands to the motors, this device can exert up to 1.5 pounds of force at the tip of the stylus in any of the 3 dimensions (directions) [16].
- **Omega 3 by Force Dimension:** Force Dimension makes a precision haptic device called Omega 3. Finely designed around a unique parallel kinematic structure, Omega 3 has been optimized for high-end force feedback. The Omega 3 is specifically designed for demanding applications where performance and reliability are critical.

Its great mechanical stiffness combined with its embedded controller enables the rendering of high contact forces [17].

- **CyberGrasp by Immersion Corporation:** The Cyber Glove is a lightweight glove with flexible sensors that accurately measures the position and movement of the user's wrist and fingers. The CyberGrasp is an exoskeleton-type device that fits over a Glove, providing force feedback. The CyberGrasp is used jointly with a position tracker to measure the virtual orientation of the forearm in three-dimensional space [18].

3. Micro-motion Controller

3.1 Mechanical Design Process

The mechanical design process consisted primarily of Computer Aided Modeling (CAD) and prototyping. However, it may be broken into other components. The flowchart in figure 7 shows the steps of the design process and its related interactions.

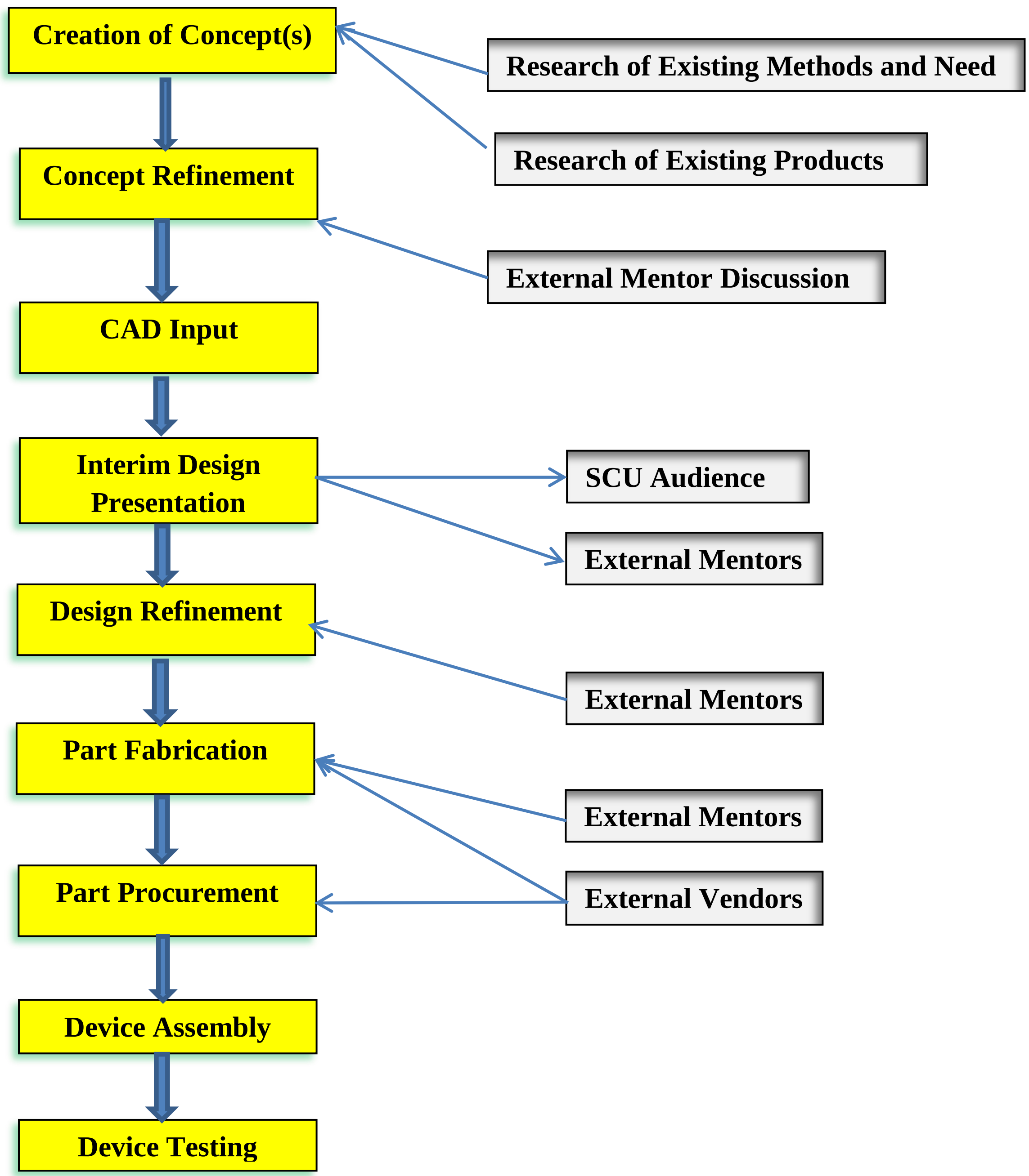


Figure 7. The Design Process Flowchart

3.2 Design Details

The first axis of the micro-motion controller will consist of a link that can host a pinch-like simulated mechanism (similar to a clothes-line clip) that allows fingers to grasp onto a virtual object. See figure 8. It is also configured to accept other kind of end effectors. Once the user pinches their fingers and the pinch is completed, the pinch mechanism itself can move in small amounts (micro-motion) in the X, Y directions where the combined motion is provided by two rotary joints.

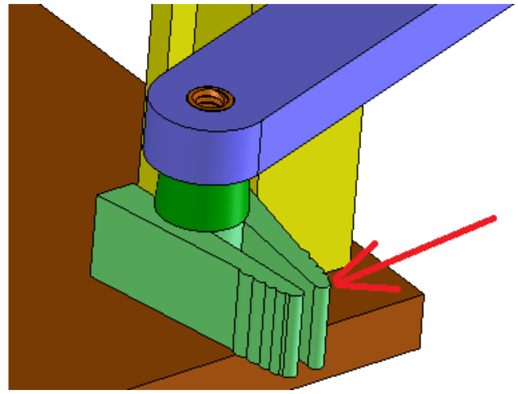


Figure 8. End Effector

The second axis also comprises of a link. Both the links incorporate a driving drum at the end of the link. The drums are driven by a threaded capstan (which almost looks like a screw thread). The drive mechanism is mainly that of capstan and a pulley (drum) which are connected via a wire rope. See figure 9. The wire rope is made of tungsten filaments which are of very small diameter. The wire rope is anchored into the drum and wrapped around the capstan for a few turns. As the capstan turns, the wire rope unravels and wraps thus driving the drum. This wire drive allows the device to achieve a high driving torque ratio. See Appendix E for ratio calculations.

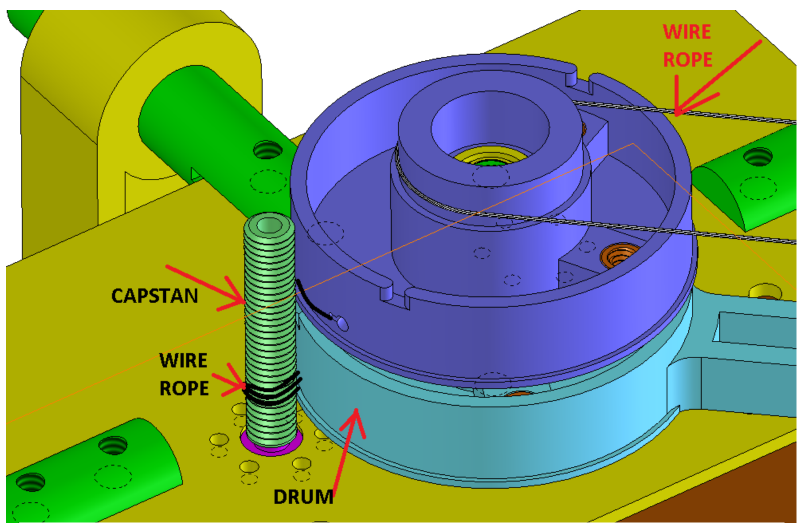


Figure 9. Wire Rope Drive Mechanism

These micro-motions in the X and Y directions, made by pinched human fingers, are then read by encoders and the motion input is translated by the encoder as motion output to either another micro-controller or a graphical program which pictorially characterizes the input. The micro-motion device also has an elastomer damper on both the axes to dampen vibrations in the most precise human motion and has motors on each axis (for future use) that can also provide haptic feedback to the pinched fingers.

The micro controller device can similarly replicate micro-motions if used in conjunction with another similar 3-D micro-controller. The latter part is a development project for future student teams.

3.3 Primary Mechanical Components

This section lists and describes the primary mechanical components. General and basic common place hardware like screws and threaded nuts are omitted.

3.3.1 Capstan

A capstan is a vertical-axled rotating member that was initially developed for use on sailing vessels for the application of forces to ropes and cables for the purpose of deploying sails. It can be simply referred to as a rotating cylinder or a pole that may be plain on its periphery or have mechanical screw threads on its diameter. See figure 9.

3.3.2 Wire Rope

Wire rope is a type of mechanical cable which consists of several strands of metal wire laid (or 'twisted') into a helix. The term cable is often used interchangeably with wire rope. However, in general, wire rope refers to diameters larger than 3/8ths of an inch. Wire ropes of sizes smaller than 3/8ths of an inch are designated as mechanical cable or cords [19]. Initially wrought iron wires were used, but today steel is the main material used for wire ropes. Exotic materials such as tungsten are used in wire rope for medical applications.

An eye splice or other turnbuckles may be used to terminate the loose end of a wire rope. The strands of the end of a wire rope are unwound a certain distance, and plaited back into the wire rope, forming the loop, or an eye, called an eye splice, or crimped.

3.3.3 Mechanical Links

A mechanical linkage is an assembly of mechanical members connected to manage the direction of forces and movement. The geometry of a given link is considered to be rigid. The connections between rigid links are modeled to be providing ideal movement, such as pure rotation or pure sliding for example, and are they are called joints. A linkage modeled as a network of two or more rigid links and one or more ideal joints is called a kinematic chain.

Linkages may be constructed from closed chains, or open chains, or be a combination of both open and closed chains. Each link in a kinematic chain is connected to one or more other rigid links by a joint. The motion of an ideal joint is typically associated with a subgroup of the group of Euclidean displacements. The number of motion parameters in the subgroup is termed as the degrees of freedom (DOF) of the joint. Mechanical linkages are designed such that they transform a given input force and movement into a corresponding desired output force and movement. The ratio of the output force to the input force is known as the mechanical advantage of the linkage. The ratio of the input speed to the output speed is known as the speed ratio. Mechanical advantage and the speed ratio are defined such that they yield the same number in an ideal linkage [20].

A kinematic chain in which one link is fixed or stationary is called a mechanism, and a linkage that is designed to be stationary is called a structure. The links used in this device are links in motion. These links are 3 D printed from a material called ABS. It is easier to print links in 3 D when making a few since it is the most economical and expeditious way. Since the device moves in X and Y, it uses two main links, one for each axis.

3.3.4 Bearings

A bearing is a machine element that reduces friction and constrains relative motion between moving parts to achieve only the desired motion. For example, a bearing may be designed to provide free linear motion of the moving part or for free rotation around a fixed axis; or, it may even prevent a motion by controlling the vectors of normal forces that bear on the moving parts. Many bearings facilitate the desired motion as much as possible, such as by minimizing friction. Bearings are broadly classified according to their type of operation, the motions allowed, or to the directions of the loads (forces) applied to their parts [21].

The bearing used for this device is a flanged bearing. The device has minimal loading in axial and thrust direction. Ball bearings have flanges as options to their configurations. The flange is designed to aid in mounting and positioning. This is especially true for miniature and instrument bearings but applies to other ball bearing types [22].

There are several specifications to consider when selecting a flange-mounted bearing.

- **Maximum speed:** It is the highest speed that the bearing can safely function at before failure. It is influenced by load characteristics, bearing lubrication, and temperature.
- **Bearing life**: It is known as the rated life L10, a statistical measure of the life of 90% of a group of identical ball bearings, which will be achieved or exceeded.

- **Bearing loads:** They are either a combination of radial loads and thrust forces or they act alone. If the bearing is required to absorb thrust forces (along the axis of the bearing) in addition to radial loads, the following considerations much be made concerning the magnitude of the thrust force. When the applied thrust loads are half that of the radial load, the selection should be made based upon the applied radial load. When thrust loads are equal to or greater than half of the applied radial load, then the selection should be based upon the total applied load (radial and thrust loads combined) as the net equivalent applied radial load.

3.3.5 Shafts

A mechanical shaft is a bar in a machine which holds or turns other parts that move or spin. In this device, two shafts are used for different reasons. A drive shaft is used to allow pivoting of the drive pulleys (drums). Another shaft is used to support the motor mounting plate in position. See figure 10. Shafts can be made from many materials depending on the strength needed. This device uses shafts made of 303 stainless steel, that does not rust.

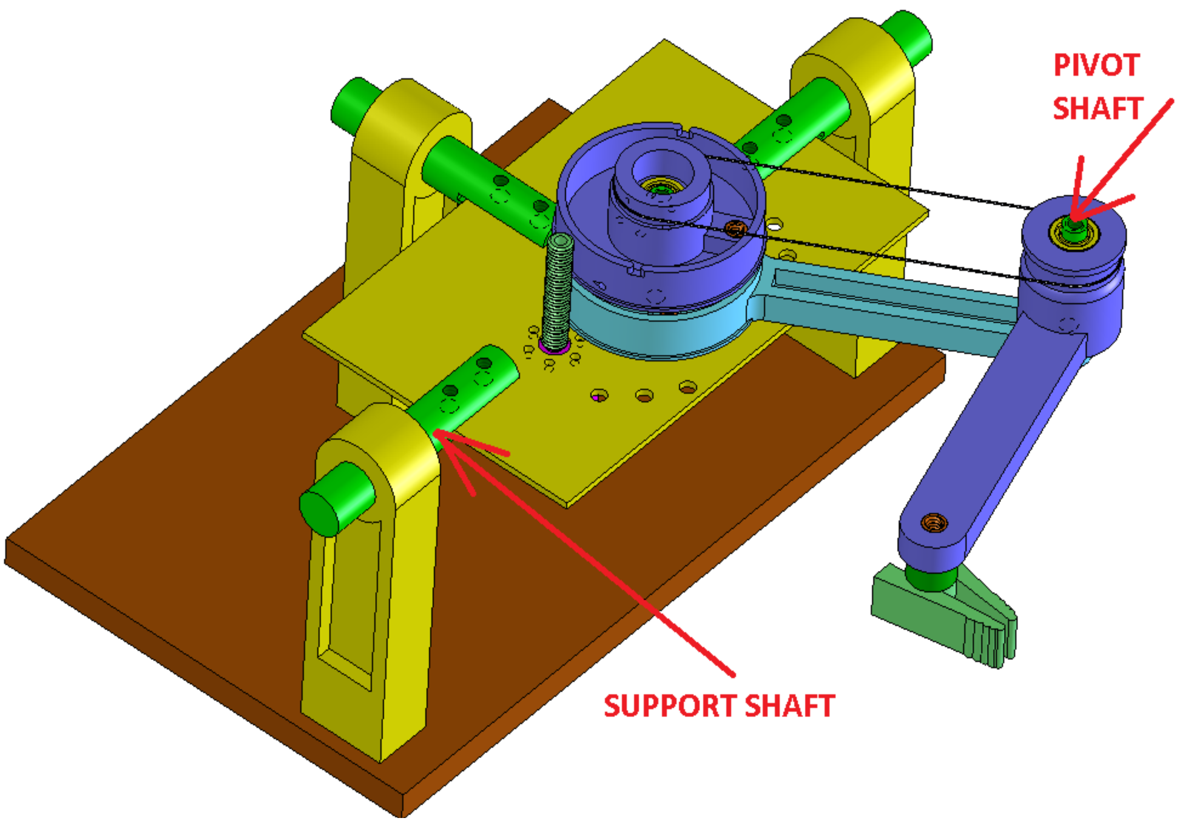


Figure 10. Shafts Used in the Micro-Motion Device

3.4 Team and Project Management

The team consists of three undergraduate bioengineers. The division of labor was equally portioned based on the individual team member's confidence in the specific task. Karan Kapoor was responsible for modeling, drawing, and printing the parts, Cameron Chu was responsible for research on electronic devices, procuring purchased parts, and some programming, and Sandeep Adem was responsible for research on the necessity for micro-motion controllers in surgical procedures.

3.4.1 Project Challenges and Constraints

The team came across many challenges and constraints which included budgeting, temporal planning, part design and assembly, appropriation of expertise, reevaluation of functionality, and finally team management.

3.4.2 Budget

In designing the micro-motion controller the primary constraint was funding. Our budget was limited to $1500 granted by the SCU Senior Design Grant fund application. In order to remain within the apportioned budget it was imperative to obtain donated parts from Intuitive Surgical.

Prior to physically machining or assembling a micro-motion controller prototype, the team devoted attention to ensuring a Computer Aided Design model is fully functional and stable. Upon completion of this step, the team was able to proceed in determining the most cost effective method of producing custom-designed parts. Intuitive Surgical allowed usage of the 3-D printer which prints using ABS plastic material. Additionally, by submitting drawings to the machine shop at Intuitive Surgical, parts such as baseplates and stands were machined at no-cost from aluminum. Through donations as described thousands of dollars were eliminated from the project expenditure in developing a functional prototype and the final cost was $704.13 (See Appendix D2).

3.4.3 Timeline

While the team was able to solve complications that arose in financial planning of the project, another main complication arose in temporal planning. As the parts were being donated by Intuitive Surgical's 3-D printers and it took time as well as scheduling for parts to be returned in their completed state. In situations where parts would break, it was necessary to immediately request additional printed parts. Furthermore, the original request for one copy per printed part was adjusted to three copies.

3.4.4 Design Process

As described above, timing the production of parts was a complex issue and for this reason the development of parts was designated according to assembly order. The primary parts including the stand, baseplate, and motor plate were requested first, see figure 11. This allowed for time to test the electronic equipment which would later be used once the prototype was fully assembled. Electronic testing and part design were delegated to respective teammates and allowed the processes to run in parallel (See Appendix B). Upon completing the base structure of the design time permitted for the development of individual pieces for the user functionality of the device. This included the development of drums, arms, and capstans.

Figure 11. Baseplate Assembly from Initial Parts

Figure 12. Threaded Capstan

Initial capstans were developed from threaded screws, see figure 12. The general principle of capstans does not involve helical threads however due to cost limitations and machining times, threaded screws seemed most appropriate. The threaded screws were not functional as the tungsten wires that were wrapped around the capstans entangled and cut along the intersecting threads. A quick modification was made, and the threaded capstans were replaced with smooth surface cylindrical rod (also machined).

Upon placing capstans upon motors and solving the issue of intertwining threads, another issue was encountered when decreasing the length of tungsten wire, the wire unraveled. This presented a major issue because the anchors of the tungsten wire were dependent on the ends

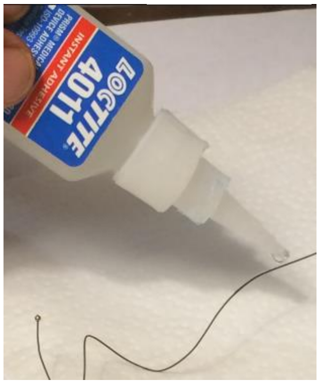


Figure 13. Loctite 4011 Placed on Tungsten Wire

of the wire remaining intact. The solution was simple – an adhesive was able to bind the individual wire threads together. See figure 13.

Further complications were not encountered in the assembly of the device.

3.4.5 Risks and Mitigations

Ironically, further developments and additions to the device were the biggest risks posed to the device. Initially, the device was planned to be 3-axis based however it was later changed to 2-axis based to permit the elimination of dampers. Since there were only two degrees of freedom, dampers to eliminate tremor from user's hands were not necessary as it was discovered tremor was generally in the z-plane and the functional axes of motion were in the x and y- planes. The reason why the dampers posed a risk to the device was due to the fact dampers would not permit the possibility of haptic feedback. Since dampers would eliminate some of the force transferred, it would be too complex to incorporate an accurate measurement of feedback to the device.

3.4.6 Team Management

As described in the initial introduction of this section, the delegation of tasks was appropriated to the team member with expertise and schedule availability. Many times team members conducted tasks in parallel and if complications arose in one task, the other task would have to be temporarily suspended to avoid further complications in device assembly. The majority of these issues arose from part failure when assembling the device as the specific mechanical tools were not always available since only one copy of each tool was provided while multiple members may have required them to complete the assigned task. For this reason the team was able to assign a schedule to avoid parallel task completion on tasks which required the same materials. In the final stages, work was completely divided into unrelated sections, mechanical assembly, computer modeling, and electronic assembly to completely avoid conflict.

4. Electronics

The main concern with electronic components included was the final resolution of the microcontroller. Based on extensive research four electronic components were included, two motors, a motor controller, and an encoder.

Motor: Several micro motor options were considered. The considerations were based off resolution, voltage, and cost. Future uses include haptics capabilities. Based on budget and precision, "FAULHABER® Coreless Technology series 1724_SR, 17 mm dia. brush DC micro motor" was used. The micro motor is capable of 12V winding voltage and possesses a 3.0 mm shaft. The motor controller output would be fixed at 5V which allowed a large tolerance for future adjustments in output voltage.

Encoder: As further development of the micro-motion controller is expected to expand to three axes, it is important that encoders used are capable of multiple motors. Produced by Phidgets, **"**1047_1 - PhidgetEncoder HighSpeed 4-Input" was selected as the encoder for the micr- motion. It allows 4 inputs which will permit further expansion to three axes. One input for each axis. An additional input may be utilized in grasping mechanisms of the controller.

Motor Controller: The motor controller used will be defined by future teams who further develop the microcontroller as the purpose of the Motor Controller is to add haptics to the controller. With capabilities of an output from 6V to 18V "Phidgets Motor Control HC USB Dual 14A 6V-15V Motor Controller" was selected.

5. Experimentation

5.1 Mechanical Experimental Protocol

In order to meet requirements listed in Appendix A, mechanical testing of the microcontroller device focused on the important functionality of the device, which is resolution and tracking (encoder functionality). Since haptics are not required, the motors were simply verified to be working. Using a digital angle caliper the calculated total range of motion for each arm of the micro controller was fixed at 60°. However, encoders attached to both motors and the encoder values at each endpoint were assessed. Without the mechanical stops it is possible to obtain approximately 107.2 degrees of motion per axis.

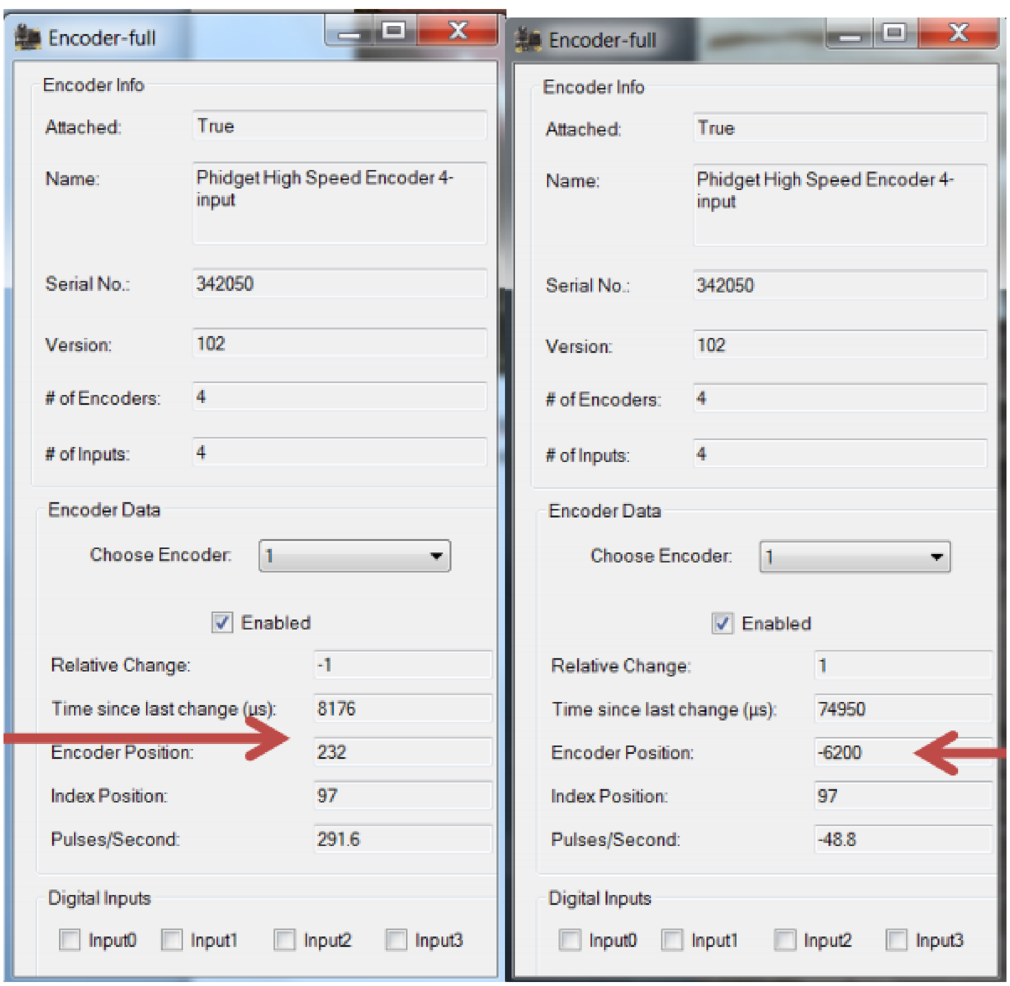


Figure 14. Encoder Output on Phidgets Control Panel (Value depicted shows location of motor and is termed as “Encoder Position”)

5.1.1 Experiment Protocol

A sharp pin was fixed to the pinch portion of the device and it was moved over a metal scale that had graduations in centimeters. It was assumed that over the duration of the tests the room temperature and expansion effects of various materials will be ignored. The encoder counts from the fixed motions in X and Y axis were then correlated to encoder counts. The recorded encoder counts were converted to X &Y values.

5.1.1 Experiment Calculations

The design calculation table is shown in Appendix E. For these calculations a total encoder count change of 6432 units over 60 degrees was observed. Since the drive ratio is 10:1, the post quadrature encoder resolution (1024/rev x 4) is 682.66 for every 60 degrees, and the manufacturing error in expected 10:1 drive ratio = 5.83%

5.2 Results

Each arm of the microcontroller measures 3" in length (theoretical distance). Every degree of encoder motion will equal a cord distance $a = 2\,R \sin(1/2\,\alpha)$ Here "R" = 3" which is the arm of the X and Y axes of the microcontroller "a" is the cord. While there is a manufacturing offset in the capstan to drum drive ratio, this ratio will not affect measurements. The drive drums and the capstan have anchored drive cables or the cables are wrapped multiple times to eliminate slippage. There is not much force being transmitted by the user to move the device, thus eliminating slippage as a cause of concern. Figures 16 and 17 show the difference in expected v/s actual recorded "linear" motion and the small error over 3 cms of test travel.

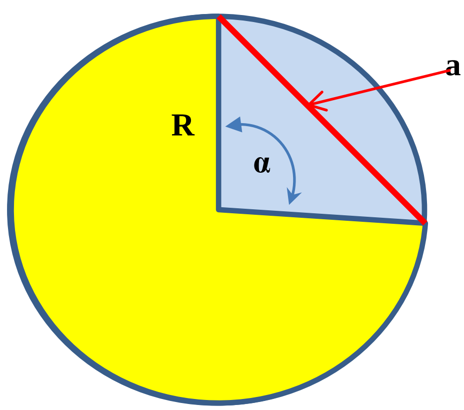


Figure 15. Length of Cord
in an Arc Segment

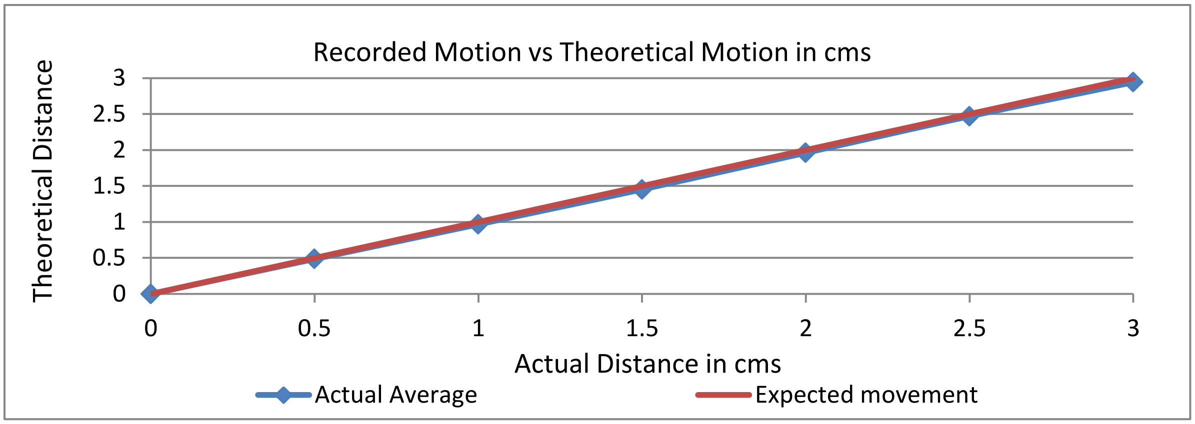


Figure 16. Recorded Motion vs Theoretical Motion in cms

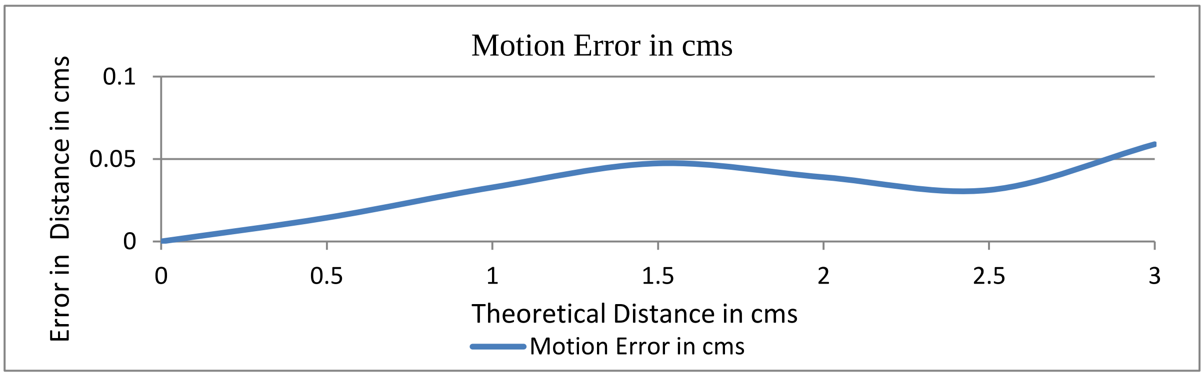


Figure 17. Motion Error in cms

5.3 Interpretation of Results

Motion at the pinch point is converted to motion at the encoder and since the error is not linear, one can deduce that there exists a minor oval shape deformation in the drum structures and out of roundness in the drive capstans. The motion error or lack of linear motion accuracy is affected by low stiffness of the 3D printed parts and by the out-of-round condition in them which is created by cable tension. The device performs reasonably well and its performance can be improved by making the parts out of a stiffer material. All the measurements were taken in a relatively short period of time, so any errors due to dissimilar coefficient of expansion rates in the capstan and the drive drum are ruled out. The encoders move at slow speed, so speed of motion is not contributing to the observed error.

6. Conclusion

6.1 Summary

Micro-motions are small motions and are generally recognized in the range of a few millimeters in surgical applications. Regular handheld surgical equipment requires surgeons to have high stability and low margin of error in microsurgery. However, tremors caused by involuntary hand motion induce stress for surgeons during these operations as manual accuracy**,** may not be precise enough for micro-surgical applications. This is why robotic assisted surgery may be a better alternative as surgeons indirectly use robotic arms remotely with the use of controllers. This greatly enhances the experience for surgeons during microsurgery as it eliminates tremor, improves operational accuracy, leads to faster surgical times, and alleviates stress. Our design project is a micro-motion controller that is a 3-axis capable, expandable device with 2 motor-actuators, 2 encoders, and mechanical linkages. With this device, linear 2-D micro-motion of pinched human fingers in a damped and un-damped state can be studied and analyzed.

6.2 Future Uses

Development of the micro-motion controller opens up the possibilities for future uses and capabilities. The device can be used as a platform for expansion and research in the fields of surgical robotic applications. Research for the micro -motion controller can provide a greater depth and understanding of micro-motion for surgery and in comparing damped motion. Further understanding of motion in robotic applications can help improve speed of surgery and reduce the chance of surgical error.

The device also serves as a platform for further research into devices utilizing haptic technology and providing the surgeon a sense of feel and touch when operating the micro-motion controller. The micro-motion controller also provides a platform for research and development of other future bio-devices including neurological disorder tracking systems and gaming platforms for the disabled. The micro-motion controller can also provide a benefit to Santa Clara University by being used as an expandable research platform that can be used and further built upon by future undergraduate and graduates students.

6.3 Lessons Learned

What we learned in the development and building of the micro- motion controller was the benefits provided by robotic assistance in surgical settings. One of the most significant problems in microsurgical applications is involuntary hand tremor of the surgeon limiting the accuracy and stability of the operation. The micro-motion controller benefits the issue by eliminating tremor and involuntary motion and providing greater accuracy and precision to surgical applications. Added damping provides greater stability to unsteady hands and aids in reducing occupational strain on surgeons. Also learned during this process is the mechanical design process. The steps of computer aided modeling, prototyping, part procurement, and device assembly are important stages in the design process. All these lessons are great building steps that students can use in future applications and endeavors.

7. Professional Issues and Constraints

Professional issues and constraints can arise in any engineering project, and the micro-motion controller is not any different. However, the main issues in ethics, science, technology, health& safety, manufacturability, usability, and environmental impact are primarily found in the production stages of this kind of product rather than end use.

7.1 Ethical Complications

The procedures conducted by micro-motion controllers are intended to be medical procedures and involve complications when appropriately testing the device. The primary concern is specimen testing to ensure the new device works and fulfills the desired purpose. The micro-motion controller is intended for use in micro-motion procedures where precision and accuracy are paramount and this requires a multitude of tests on specimens including live animals and cadavers. When considering these tests, it is most important to understand that the utilization and possible functionality of the device is explored to a maximum so the tests are conducted without wasting live specimens rather than testing incrementally over time. Proper planning allows the amount of live animals and cadaver usage to be minimal.

7.2 Science

Science and technology based complications are limited in the micro-motion controller, however it has a positive impact as this device may be utilized for research stages into neurological disorder tracking, gaming platforms for disabled, and haptic-based evaluation of arthritic hands.

7.3 Manufacturability and Environmental Impact

The micro-motion controller developed remains in prototype stages as it has not been manufactured from industry-grade materials such as aluminum and stainless steel.
There are other functional materials which extend durability and provide aesthetics, and their use on the environment can only be considered during productization. Medical waste accounts for a large portion of landfills and biohazards and extending the usage time of the micro-motion controller allows for a lessened environmental impact. Since the controller will be used for every procedure involving micro-motions, a device with an extended life time lasting the years of the console it is utilized on should be prioritized. Further considerations must be provided for quick disassembly to allow recovery of printed circuit boards and recycling of materials used.

7.4 Usability

Prior to marketing the micro-motion controller for use in clinical procedures, the device must be fully functional and have a versatile user base which allows multiple individuals to use the product. The micro-motion controller has been developed with an adjustable gauge to increase the range of motion. This ensures that the product can be utilized by individuals with varying hand and finger sizes.

Appendix A: Project Specifications

Device Type: Expandable Two Degrees of Freedom Micro-Controller

Device Expandability: Mechanical design provision only. The Computer Aided Design must consider the possibility of allowing the adding of a third motion axis in the CAD design.

Device Input: Motion by human hand

Input Range: Minimum 1 cm in X and Y axis

Device Output: Encoder Values. The device must use DC motors with encoders to allow future possibility of haptics output.

Motion Elements: DC Motors

Motion Control: DC Motor Controller

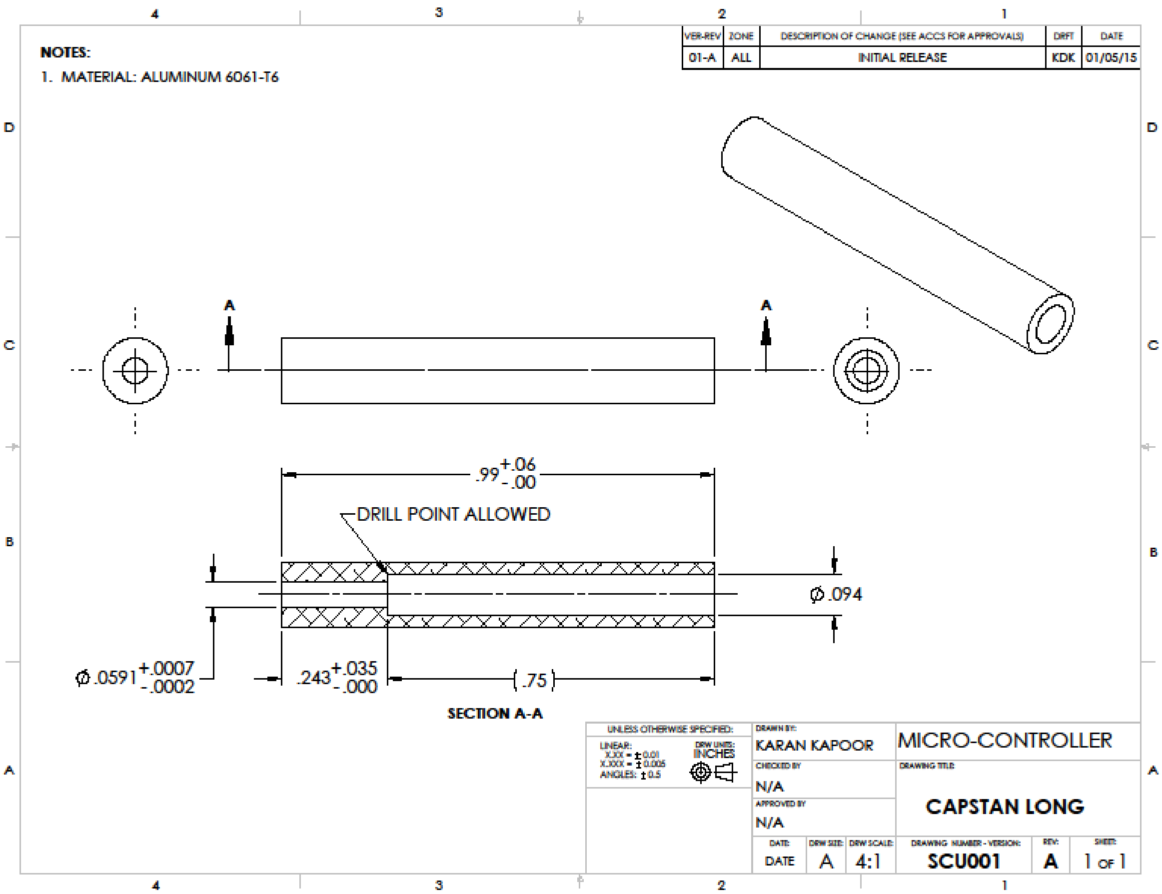
Position Recording: High Resolution Digital Encoders (no potentiometers)

Position Backlash: Near zero (use of gears is not recommended)

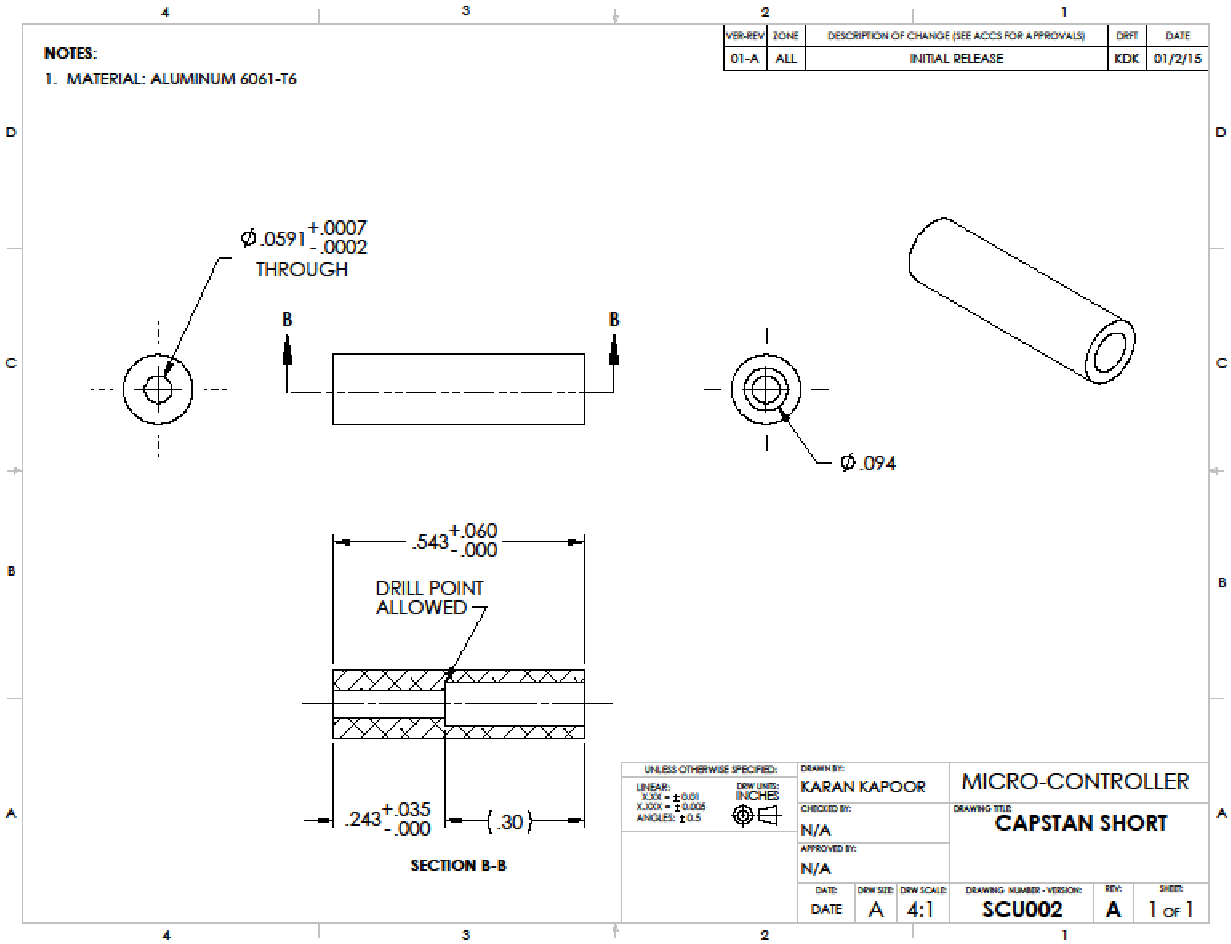
Budget: Under $ 1500

Appendix B: Engineering Drawings

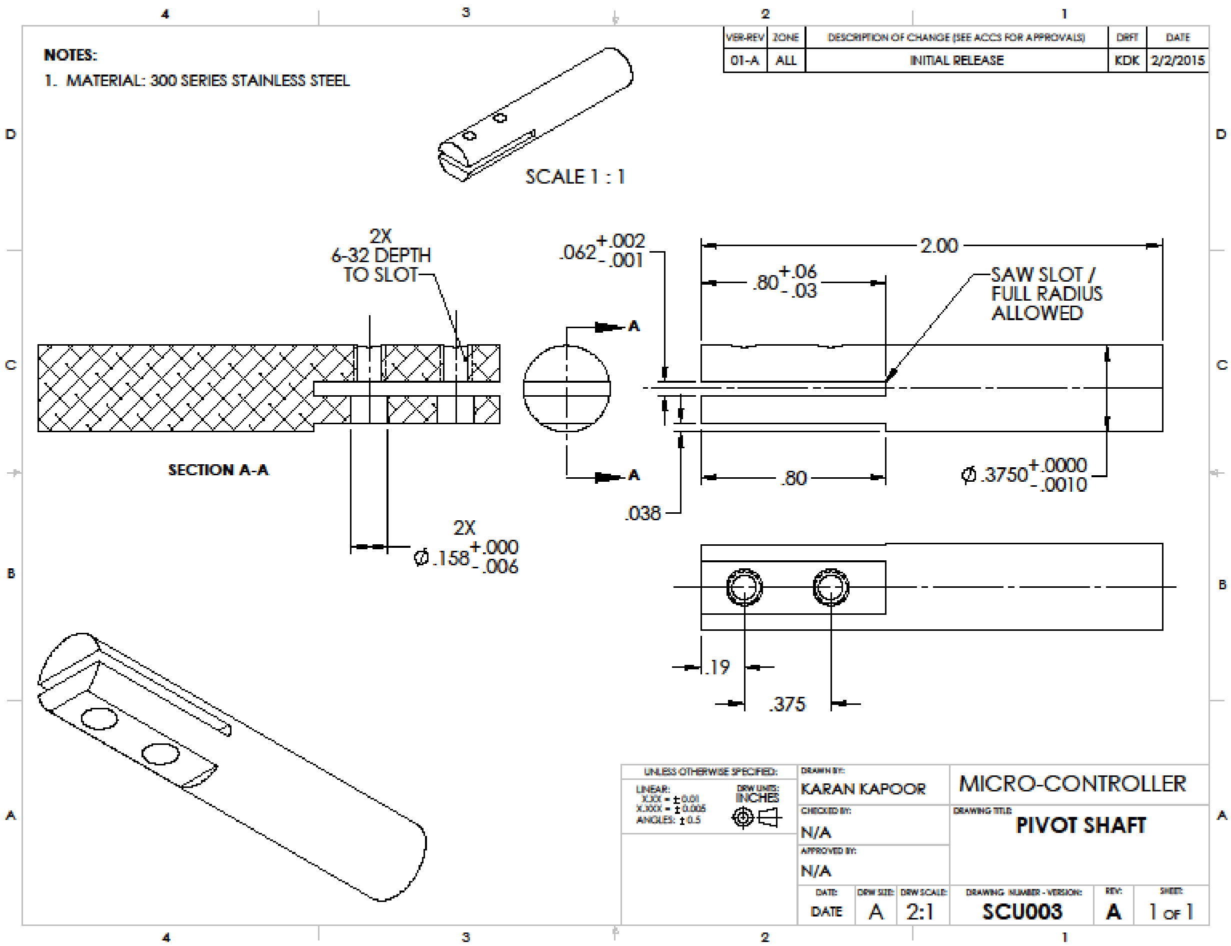
Appendix B1: CAPSTAN, LONG SCU001



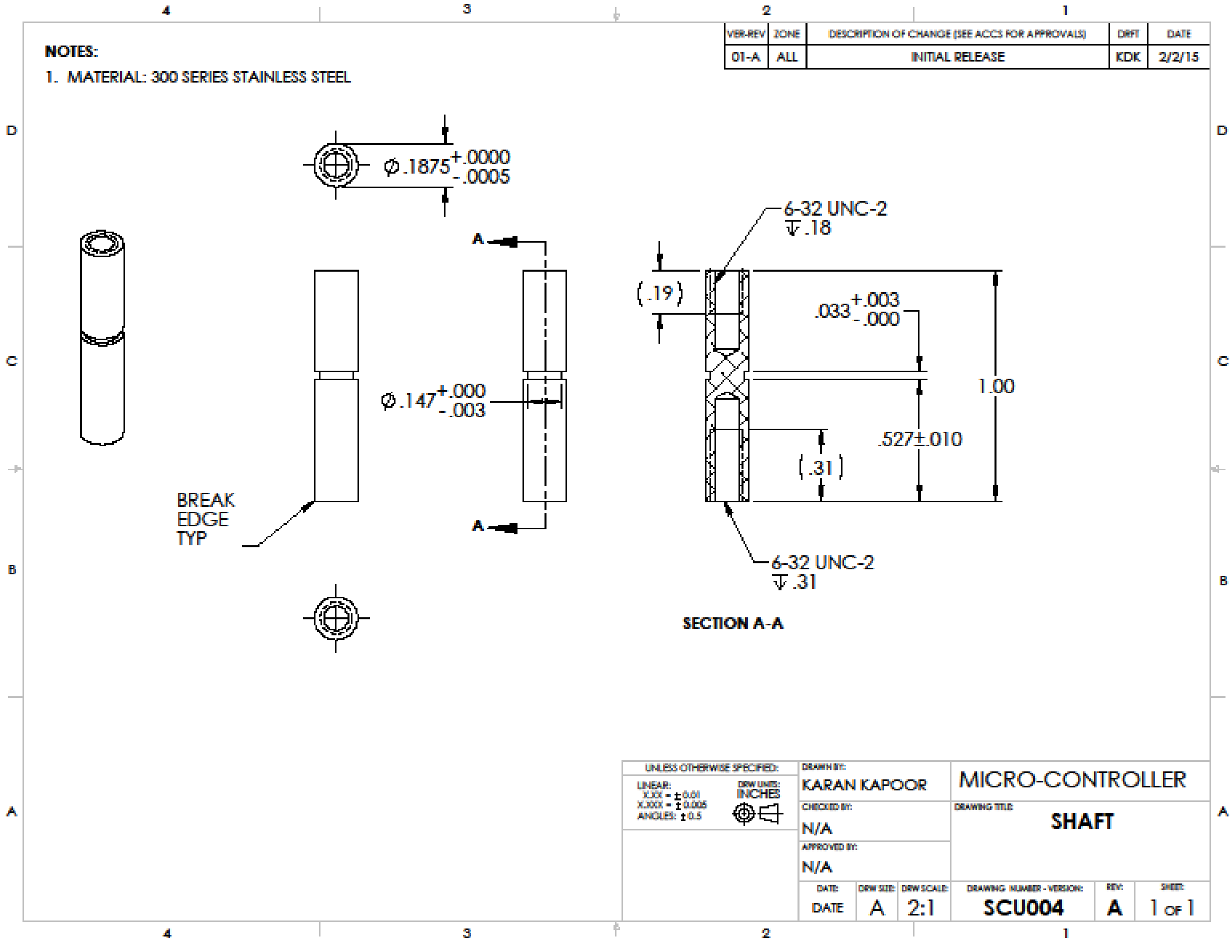
Appendix B2: CAPSTAN, SHORT SCU002



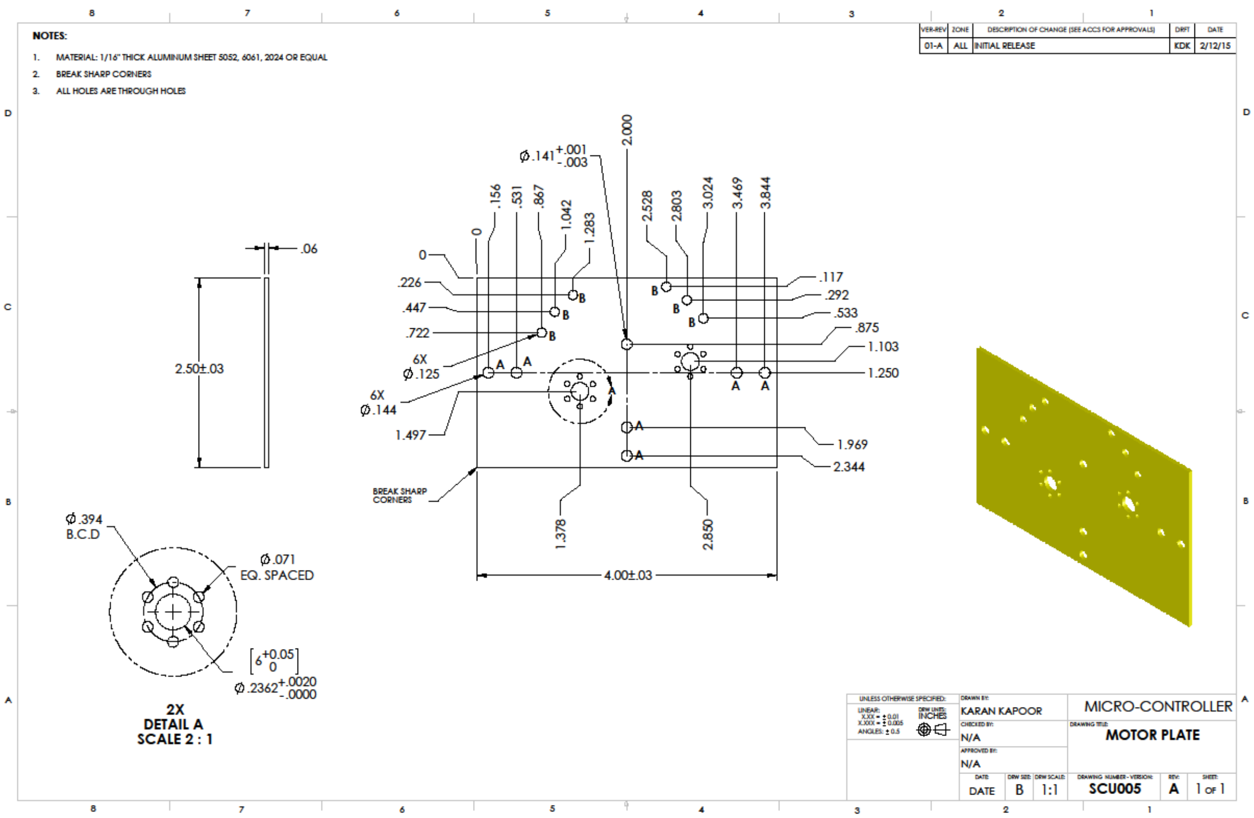
Appendix B3: PIVOT SHAFT SCU003



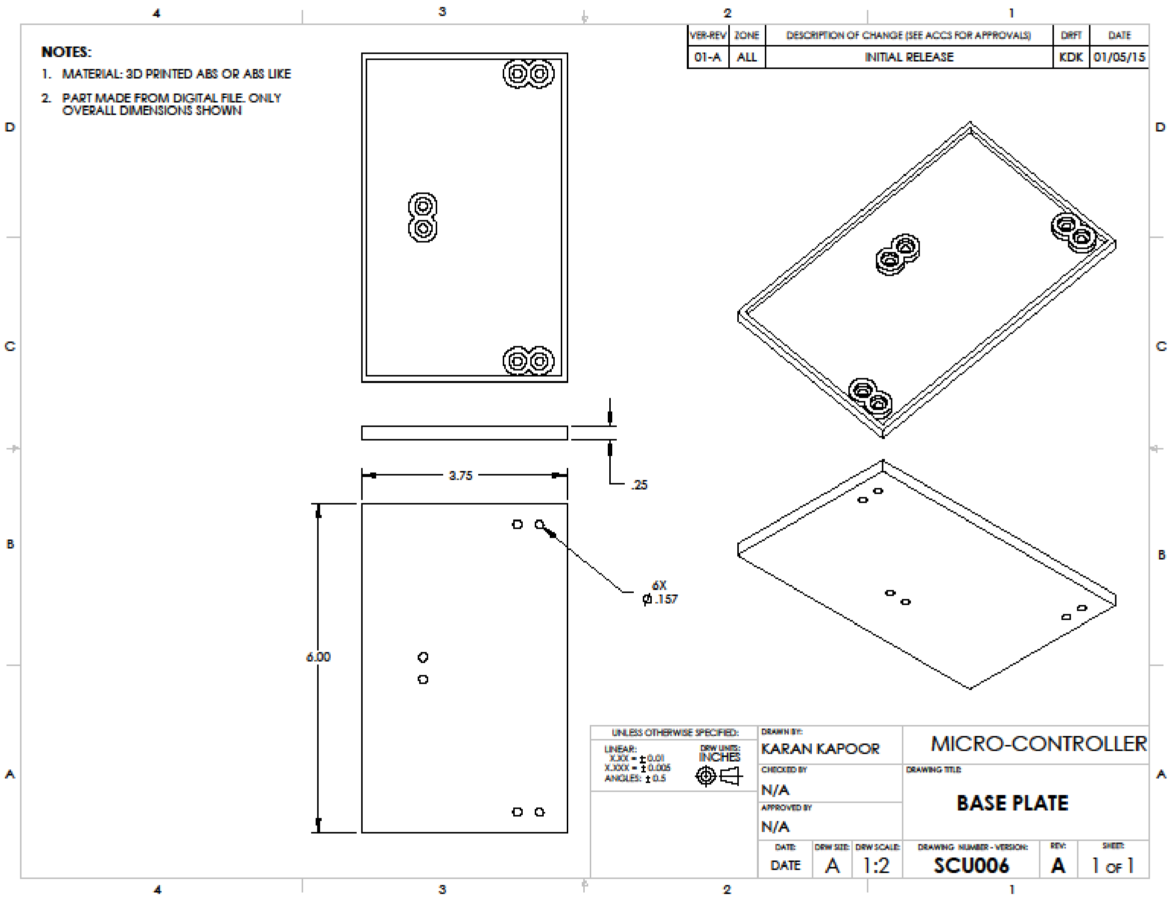
Appendix B4: SHAFT SCU004



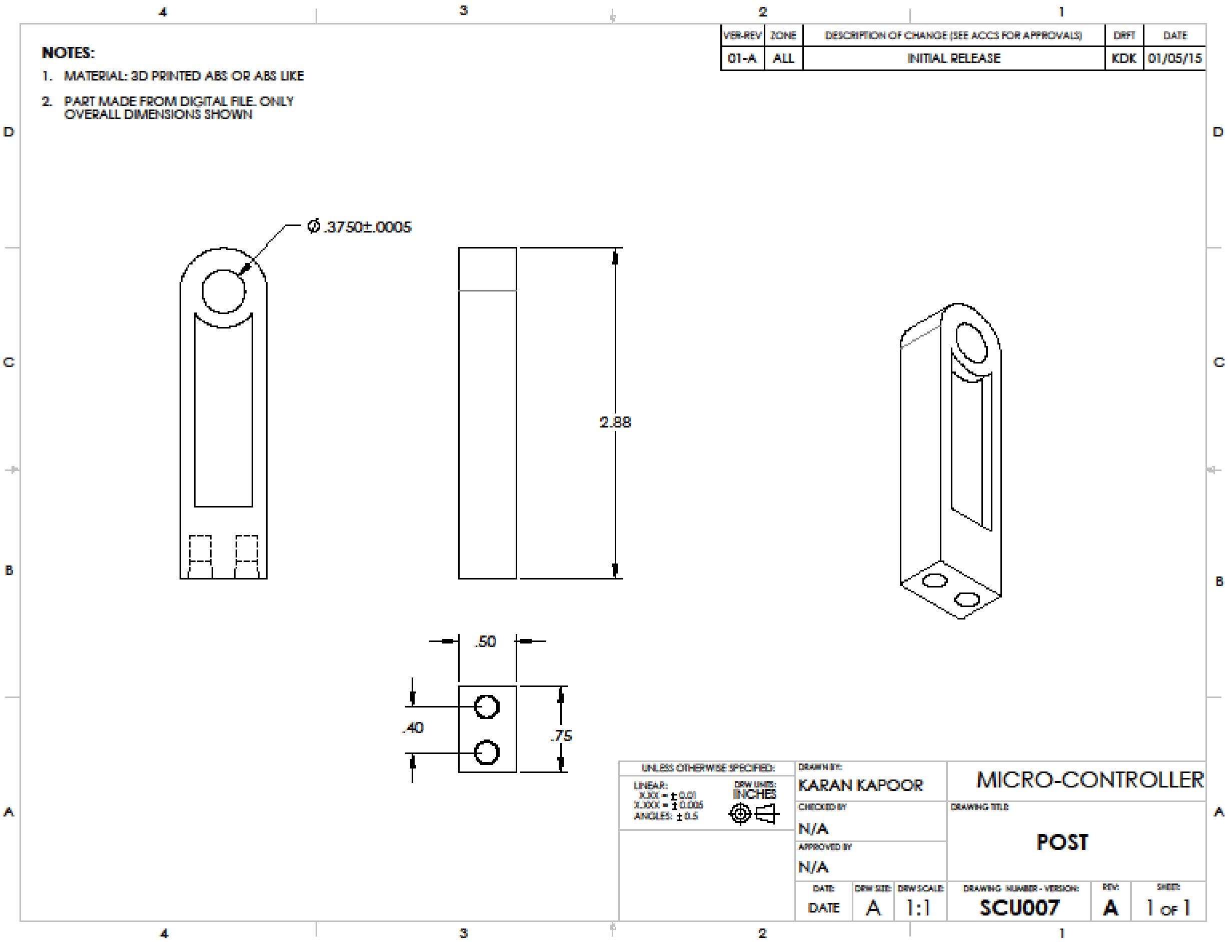
Appendix B5: MOTOR PLATE SCU005



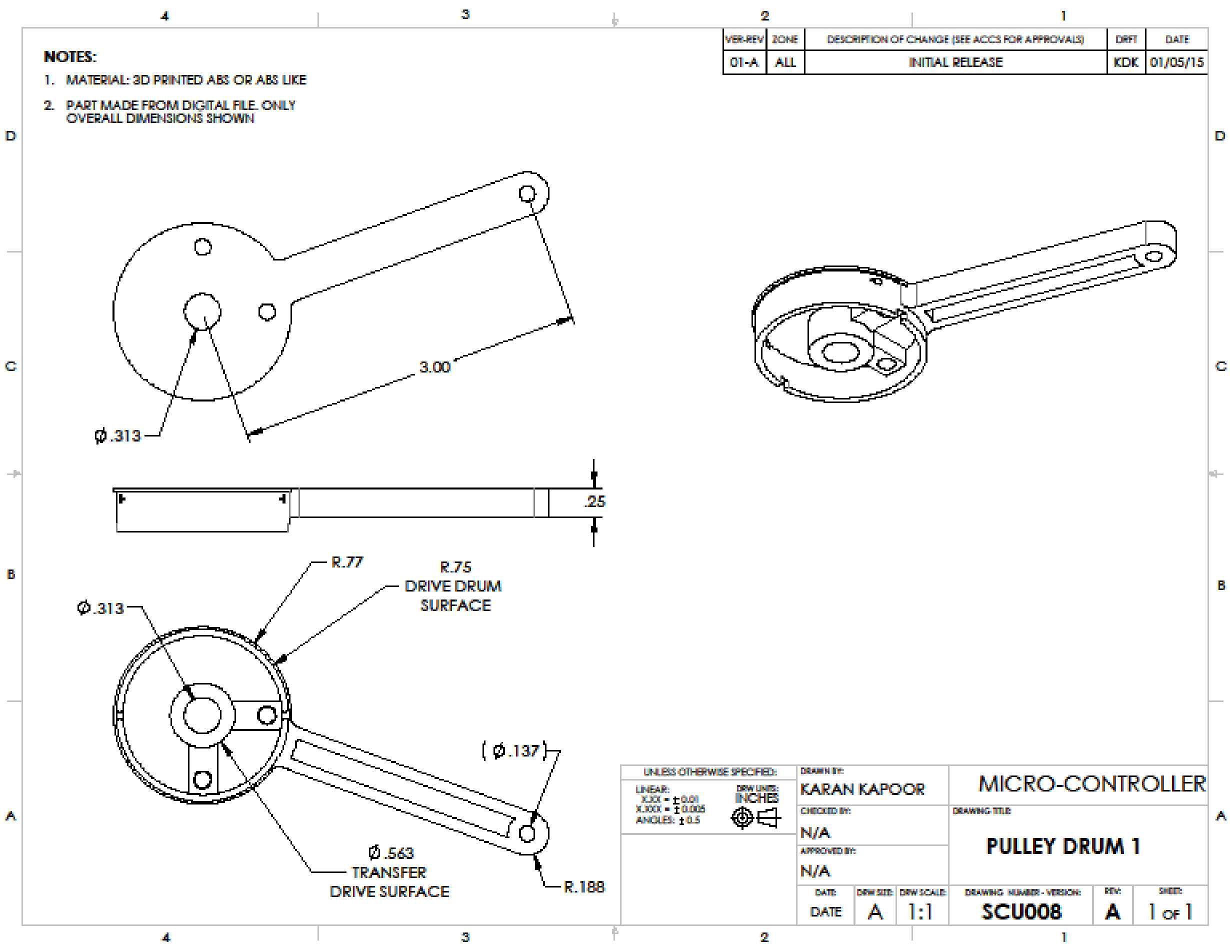
Appendix B6: BASE PLATE SCU006



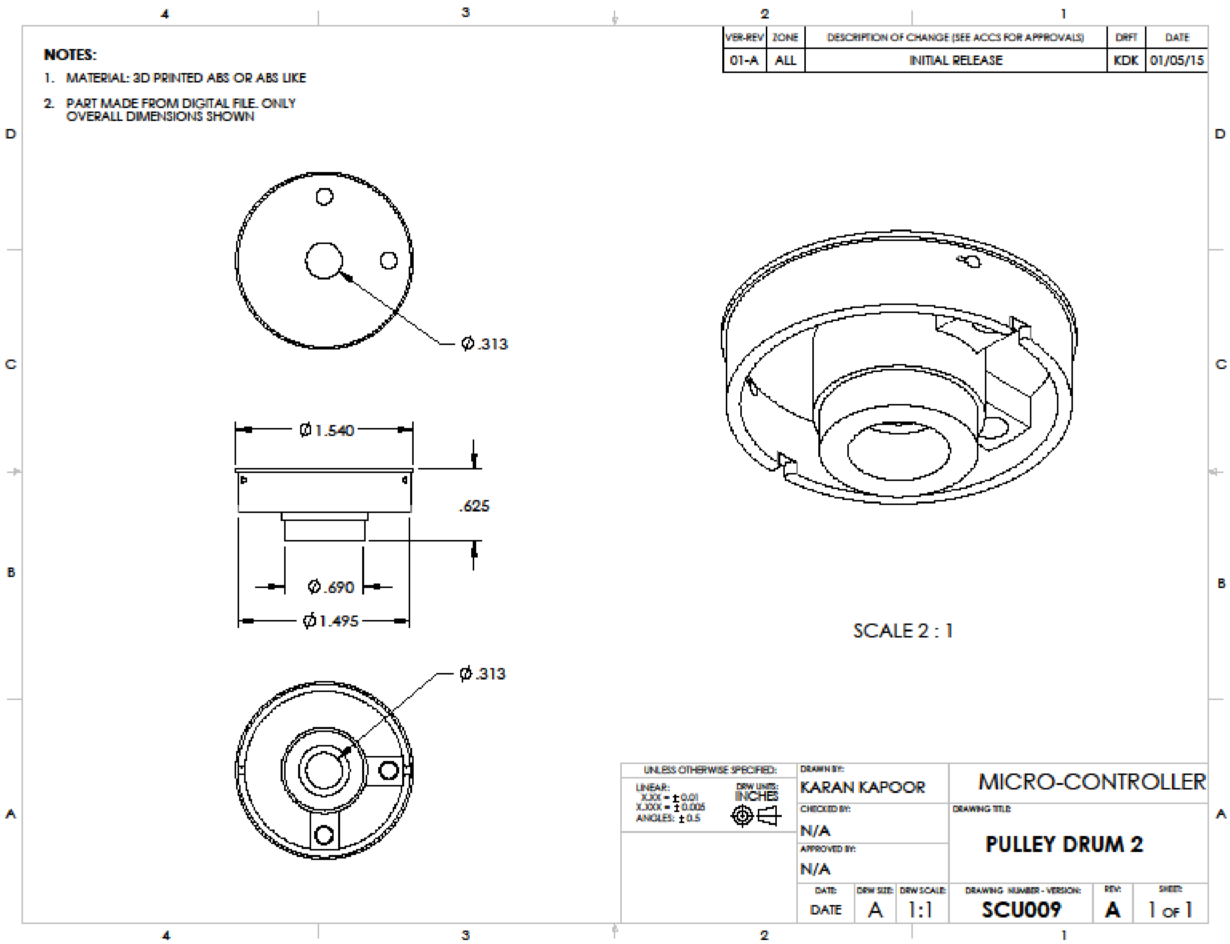
Appendix B7: POST SCU007



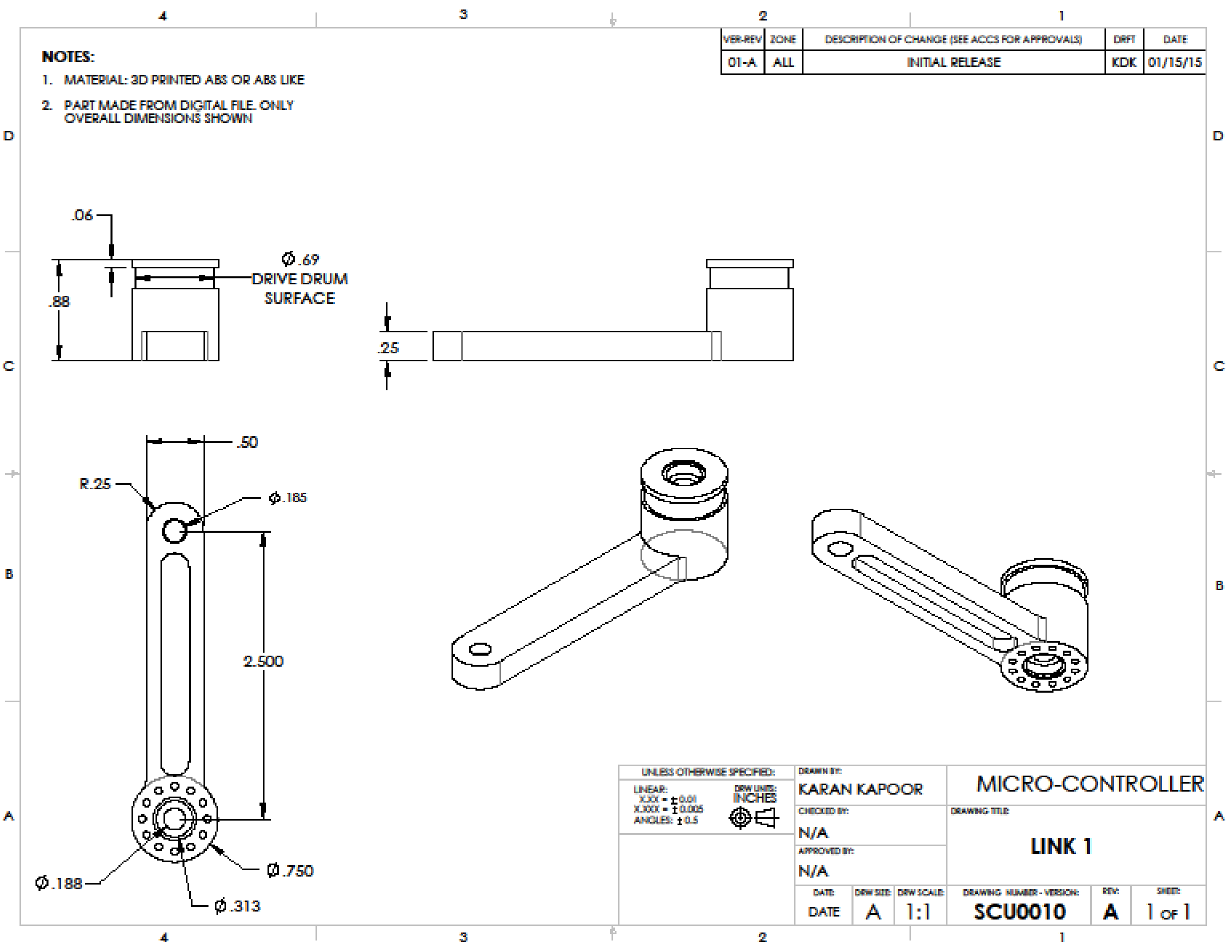
Appendix B8: PULLEY DRUM 1 SCU008



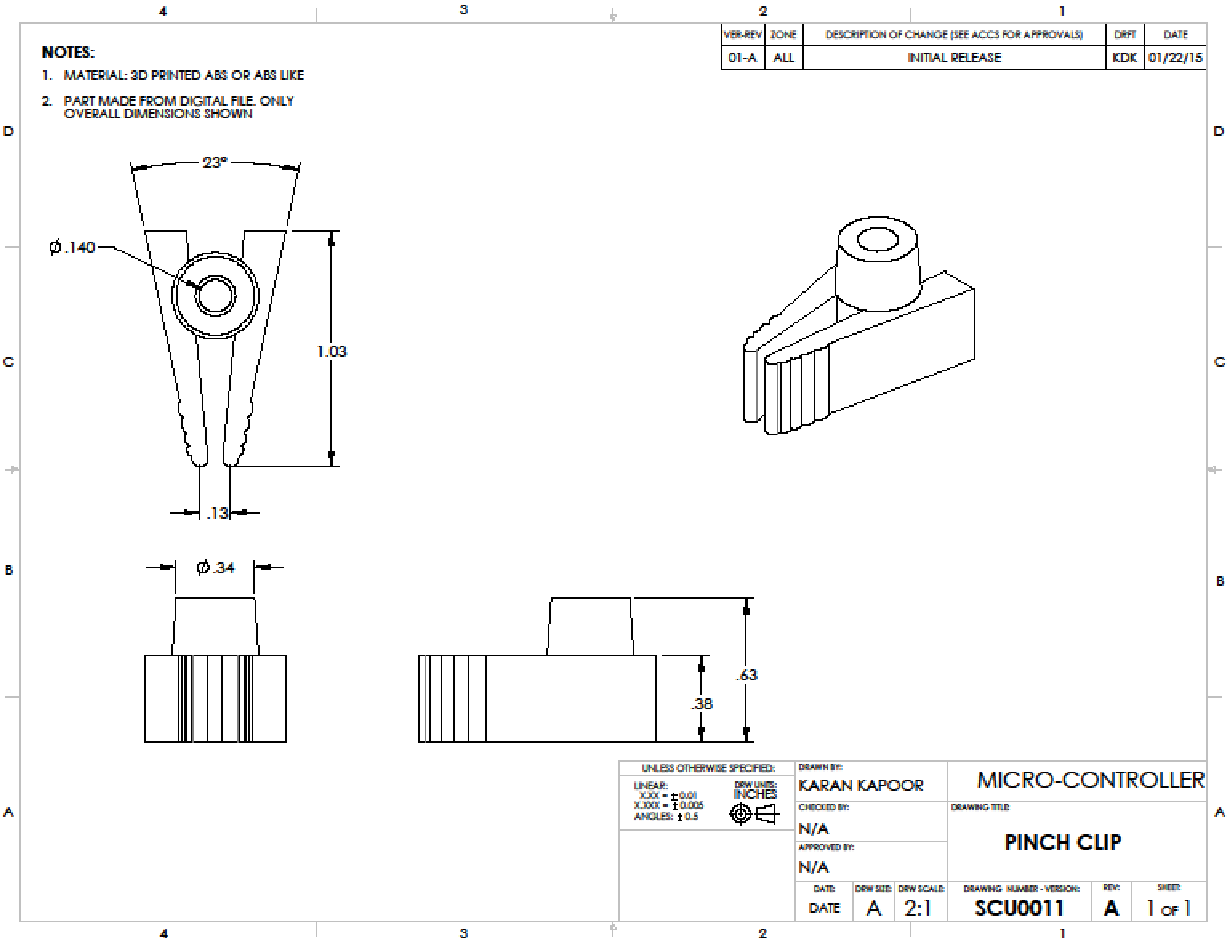
Appendix B9: PULLEY DRUM 2 SCU009



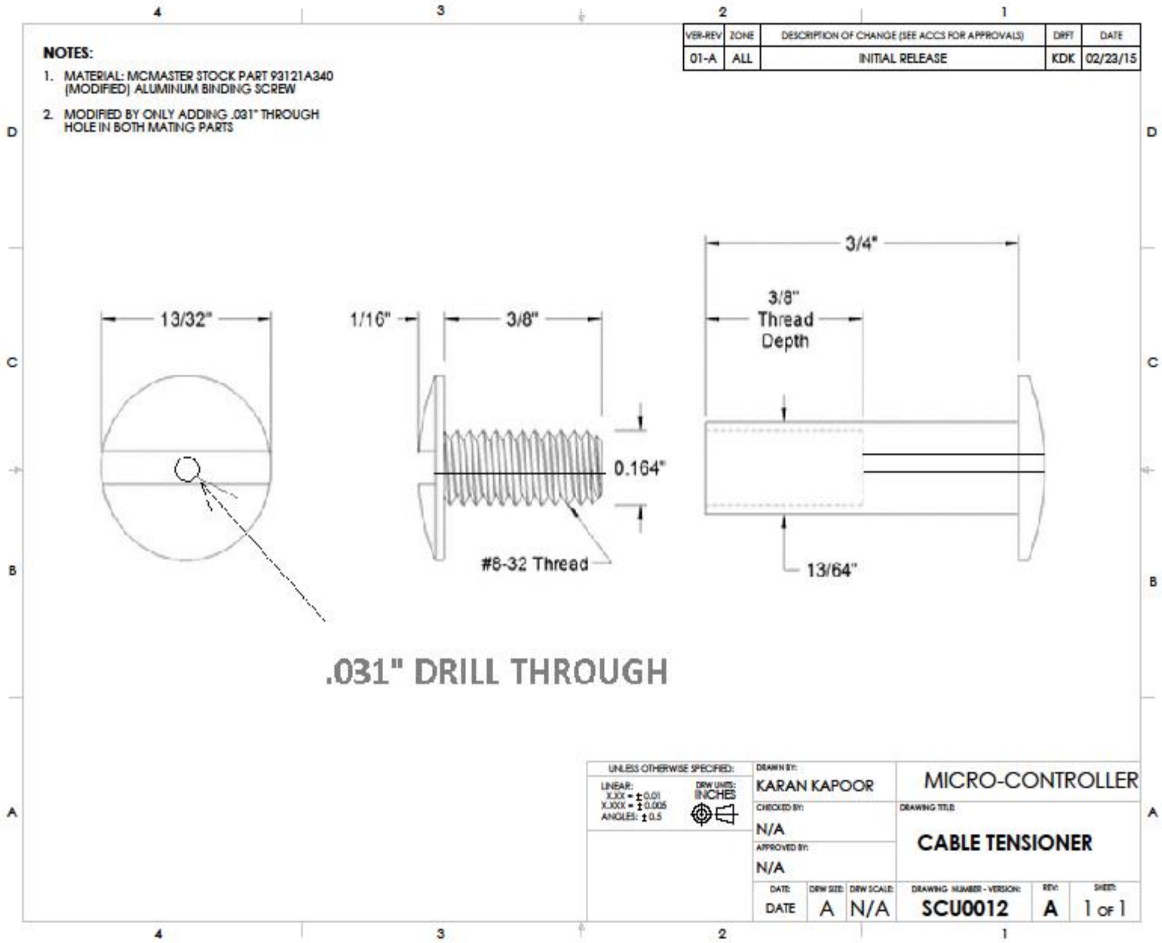
Appendix B10: LINK 1 SCU0010



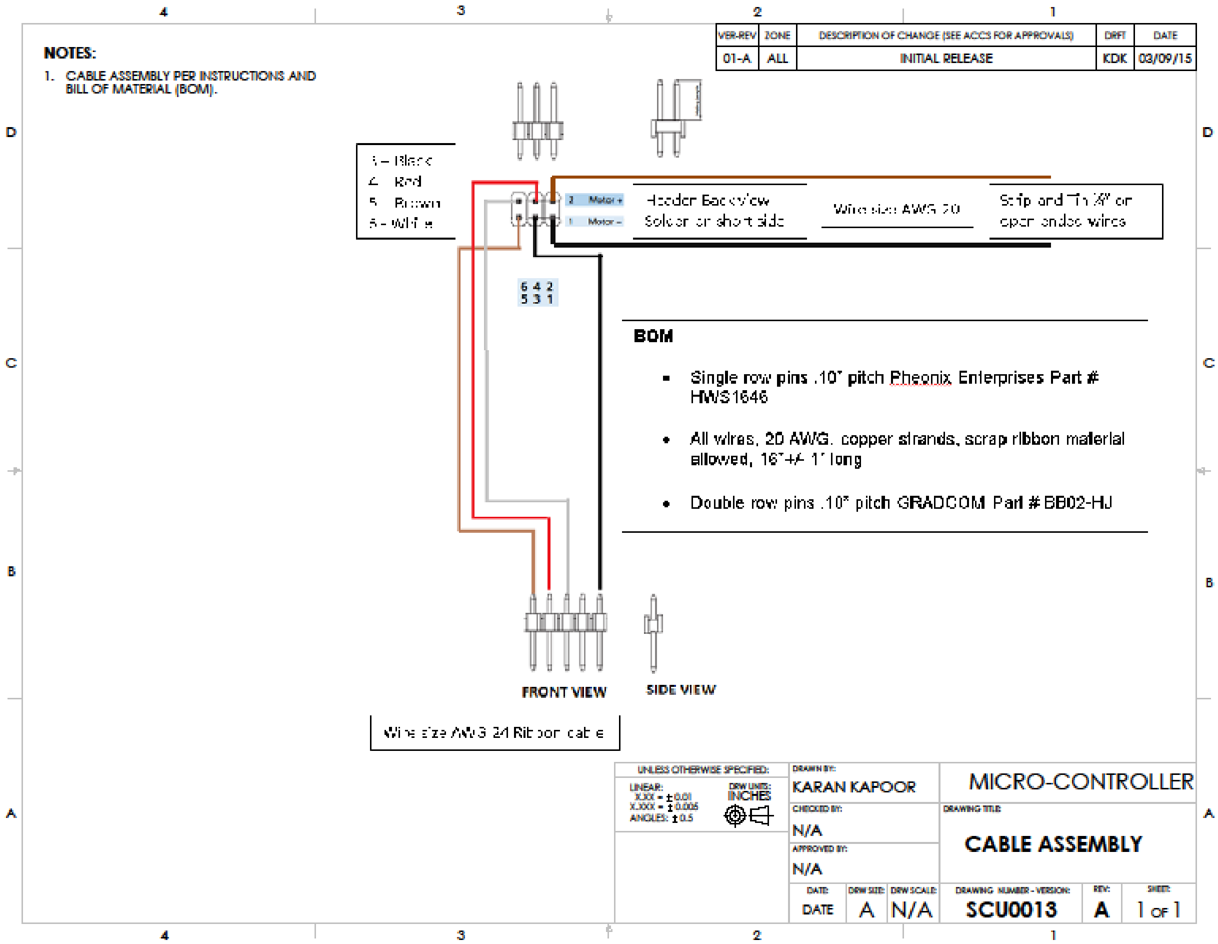
Appendix B11: PINCH CLIP SCU0011



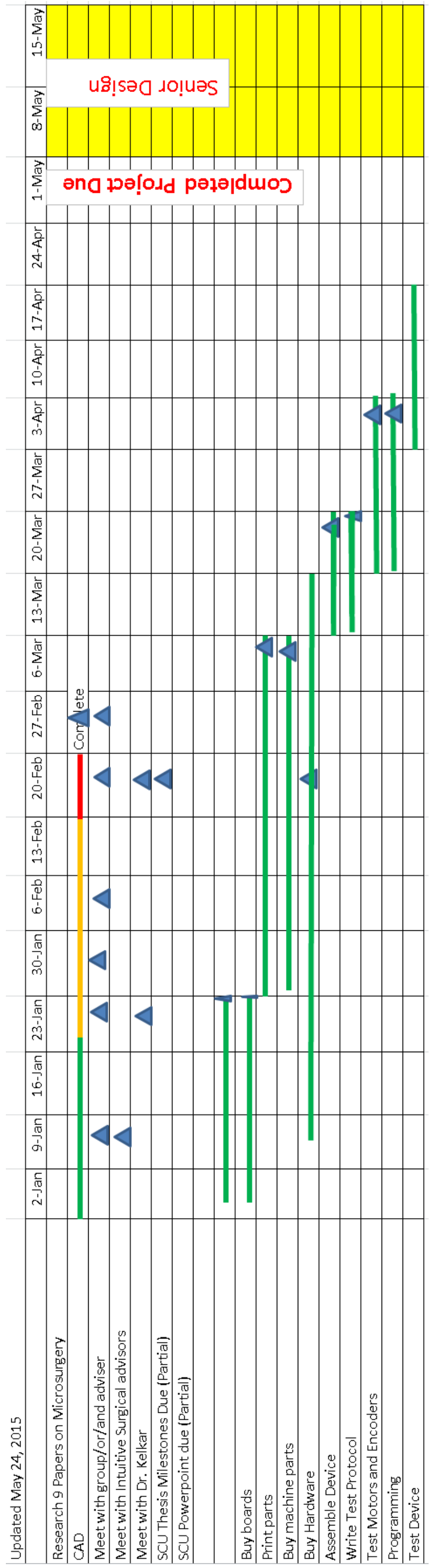
Appendix B12: CABLE TENSIONER SCU0012



Appendix B13: CABLE ASSEMBLY SCU0013



Appendix C: Project Timeline



Appendix D: Bill of Materials

Appendix D1: Parts Material List

ITEM #	Name of Part	Material	Quantity	Manufacturer	Manufacturer Part #
1	CAPSTAN, LONG	ALUMINUM 6061-T6	1	SCU TEAM	SCU001
2	CAPSTAN, SHORT	ALUMINUM 6061-T6	1	SCU TEAM	SCU002
3	PIVOT SHAFT	300 SERIES STN STEEL	3	SCU TEAM	SCU003
4	SHAFT	300 SERIES STN STEEL	2	SCU TEAM	SCU004
5	MOTOR PLATE	ALUMINUM	1	SCU TEAM	SCU005
6	BASE PLATE	ABS	1	SCU TEAM	SCU006
7	POST	ABS	3	SCU TEAM	SCU007
8	6-32 LONG ULTRASERT	BRASS	14	MCMASTER	93365A132
9	PHILLIPS PAN HEAD SCREW 6-32 x 3/8	STAINLESS STEEL	11	MCMASTER	91735A146
10	MOTOR	Proprietary	2	MICROMO	1724T012SRIE2-1024
11	PHILLIPS PAN HEAD SCREW M1.6 x 3mm	STAINLESS STEEL	12	MCMASTER	92000A001
12	680 LOCTITE	Proprietary	0.02 OZ	MCMASTER	91458A121
13	3/16" SHIM SPACER	STAINLESS STEEL	20	MCMASTER	90917A510
14	Retaining Ring (E-Style)	STAINLESS STEEL	2	MCMASTER	97431A280
15	PULLEY DRUM 1	ABS	1	SCU TEAM	SCU008
16	PULLEY DRUM 2	ABS	1	SCU TEAM	SCU009
17	4-40 LONG ULTRASERT	BRASS	4	MCMASTER	93365A122
18	FLANGED BALL BEARING 3/16"X 5/16"	STAINLESS STEEL	6	SDP	A 7Y55 F3118
19	LINK 1	ABS	1	SCU TEAM	SCU0010
20	PINCH CLIP	ABS	1	SCU TEAM	SCU0011
21	CABLE TENSIONER	ALUMINUM	1	MCMASTER	SCU0012
22	MOTOR CONTROLLER	Proprietary	1	PHIDGETS	RB-PHI-54
23	ENCODER INPUT	Proprietary	1	PHIDGETS	RB-PHI-94
24	POWER SUPPLY 18V	Proprietary	2	AMAZON	VFB-85-SP-SP20-01-H01
25	POWER SUPPLY 5V	Proprietary	2	AMAZON	“0835561000325”
26	CABLE ASSEMBLY	VARIOUS	2	SCU TEAM	SCU0013
27	DRIVE CABLES	TUNGSTEN	10 FEET	INTUITIVE	SCRAP ITEMS
28	PHILLIPS PAN HEAD SCREW 4-40 x 1/4	STAINLESS STEEL	4	MCMASTER	91735A102

Appendix D2: Parts List - Costing

ITEM #	Name of Part	Manufacturer Part #	TYPE	METHOD	COST
1	CAPSTAN, LONG	SCU001	CUSTOM	MACHINED	Donated
2	CAPSTAN, SHORT	SCU002	CUSTOM	MACHINED	Donated
3	PIVOT SHAFT	SCU003	CUSTOM	MACHINED	Donated
4	SHAFT	SCU004	CUSTOM	MACHINED	Donated
5	MOTOR PLATE	SCU005	CUSTOM	MACHINED	Donated
6	BASE PLATE	SCU006	CUSTOM	3D PRINT	Donated
7	POST	SCU007	CUSTOM	3D PRINT	Donated
8	6-32 LONG ULTRASERT	93365A132	HARDWARE	PURCHASED	$0.05/ea
9	PHILLIPS PAN HEAD SCREW 6-32 x 3/8	91735A146	HARDWARE	PURCHASED	$0.15/ea
10	MOTOR	1724T012SRIE2-1024	ELECTRONIC	PURCHASED	$182.36/ea
11	PHILLIPS PAN HEAD SCREW M1.6 x 3mm	92000A001	HARDWARE	PURCHASED	$0.15/ea
12	680 LOCTITE	91458A121	HARDWARE	PURCHASED	$16.00
13	3/16" SHIM SPACER	90917A510	HARDWARE	PURCHASED	$0.50/ea
14	Retaining Ring (E-Style)	97431A280	HARDWARE	PURCHASED	$.02/ea
15	PULLEY DRUM 1	SCU008	CUSTOM	3D PRINT	Donated
16	PULLEY DRUM 2	SCU009	CUSTOM	3D PRINT	Donated
17	4-40 LONG ULTRASERT	93365A122	HARDWARE	PURCHASED	$0.15/ea
18	FLANGED BALL BEARING 3/16"X 5/16"	A 7Y55 F3118	HARDWARE	PURCHASED	$9.39/ea
19	LINK 1	SCU0010	CUSTOM	3D PRINT	Donated
20	PINCH CLIP	SCU0011	CUSTOM	3D PRINT	Donated
21	CABLE TENSIONER	SCU0012	HARDWARE	MACHINED	Donated
22	MOTOR CONTROLLER	RB-PHI-54	ELECTRONICS	PURCHASED	$120/ea
23	ENCODER INPUT	RB-PHI-94	ELECTRONICS	PURCHASED	$106/ea
24	POWER SUPPLY 18V	VFB-85-SP-SP20-01-H01	ELECTRONICS	PURCHASED	$13.95/ea
25	POWER SUPPLY 5V	“0835561000325”	ELECTRONICS	PURCHASED	$6.79/ea
26	CABLE ASSEMBLY	SCU0013	ELECTRONICS	ASSEMBLED	Donated
27	DRIVE CABLES	SCRAP ITEMS	N/A	N/A	Donated
28	PHILLIPS PAN HEAD SCREW 4-40 x 1/4	91735A102	HARDWARE	PURCHASED	$0.20/ea
Total					**$704.13**

Appendix E: Design Calculations

Design Calculations	Data/Misc	Values	Units	Remarks
Capstan drive diameter (X and Y axis) "A"		.150	inches	
Driven drum diameter (X and Y axis) "B"		1.5	inches	
Drive Reduction Ratio X axis	B/A	10		Reduction
Drive Reduction Ratio Y axis	B/A	10		Reduction
Rated Motor Torque		4.5	mNm	
Possible torque at pinch tip		45	mNm	
Encoder resolution per revolution	1024		counts	
Encoder resolution post quadrature	4098		counts	
Encoder counts over 60 deg of pinch rotation	683		counts	
Counts with 10:1 theoretical drive ratio	6830		counts	
Actual encoder counts over 60 deg	6432		counts	
Actual counts/expected counts ratio	0.94			
% offset/deviation in drive ratio	5.83		%	
every degree in radians (conversion factor)	0.017453293		radians	
Pich tip movement every degree of drum =	0.0524		inches	3" arm
Pich tip movement every degree of encoder =	0.5236		inches	10:1 ratio
Pich tip movement every degree of encoder =	1.3300		cms	10:1 ratio

Appendix F: Results Table

In cms	In cms	Actual distance recorded by encoder (cms)						
Distance on Scale	Expected movement	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Actual Average	Motion Error in cms
0	0	0	0	0	0	0	0	0
0.5	0.5	0.4980	0.4820	0.4880	0.4810	0.4790	0.4856	0.0144
1	1	0.9920	0.9570	0.9670	0.9500	0.9700	0.9672	0.0328
1.5	1.5	1.4850	1.4270	1.4500	1.4650	1.4360	1.4526	0.0474
2	2	2.0170	1.9270	1.9400	1.9560	1.9650	1.961	0.039
2.5	2.5	2.4860	2.4660	2.4840	2.4680	2.4400	2.4688	0.0312
3	3	2.9800	2.9480	2.9640	2.8980	2.9150	2.941	0.059

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