ME450, Team 25, Winter 2007

LAPAROSCOPIC TOOL WITH ENHANCED DEXTERITY

Final Report

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ABSTRACT

In the field of laparoscopic surgery there is room for improvement in tool technology. Development of robotic devices has led to sophisticated motion capabilities; however, these systems lack several desired functions seen in more simple purely mechanical devices. Surgeons therefore desire a laparoscopic tool that utilizes the advantages of robotic devices while retaining those seen in purely mechanical systems. These advantages are motion scaling, intuitive master/slave motion, force feedback, tremor reduction, and a minimum of four degrees of freedom. Based on analysis of current technology and customer requirements, we designed and prototyped a purely mechanical, hand-held device that integrates these capabilities.

INTRODUCTION

Laparoscopic surgery is a minimally invasive technique during which a procedure is conducted through small incisions in the abdomen. Based on specified customer requirements and an information search we found that the design of a novel laparoscopic tool with enhanced dexterity would satisfy a need for improvement in modern surgical instrumentation. We therefore developed a project with the ultimate goal of creating a device that will eliminate the current limitations. A Gantt Chart detailing the project timeline can be found in Appendix B. Our sponsor for this project was Professor Sridhar Kota, from the University of Michigan Department of Mechanical Engineering. Our advisor for this project was Professor Shorya Awtar, also from the University of Michigan Department of Mechanical Engineering. We consulted Dr. James Geiger, a pediatric surgeon at Mott Children's Hospital, to address customer needs.

INFORMATION SEARCH

Prior to the design process, we researched existing technology in the area of laparoscopic instruments. We conducted interviews, read patents and publications, and did hands-on experimenting with existing tools. Based on this research, we have broken up pre-existing technology into two categories: Robotic and Traditional.

Robotic

We define a laparoscopic instrument as robotic if it contains computer-controlled electro-mechanical components. The most widely used is the *da Vinci Surgical System* produced by Intuitive Surgical. It was initially introduced in 1999 and a second model was released in 2005 [1]. The *da Vinci Surgical System* is a physician-controlled robot that translates a surgeon's hand motion into robotic arm motion to which laparoscopic manipulators are connected. It is broken up into two stations: the surgeon's station where a 3-D image of the surgery is viewed and the handheld controls are operated, and a separate tableside cart from which the robotic arms protrude and are actuated to mirror the input motions of the surgeon. The translation of the surgeon's motion to robotic motion is done with a computer, which allows for precise control (i.e. motion scaling, tremor reduction). The machine has three tool arms with six degrees of freedom (DoF) and one camera arm. The tool arms have detachable manipulators that can be used for 20 surgeries but then must be replaced. The machine initially costs over $1 million and each replacement manipulator can cost between $20,000 and $50,000 [2].

Based on our information search and our interview with Dr. Geiger, we determined the aspects of the *da Vinci Surgical System* that make it the most successful robotic instrument in this field.

These aspects include intuitive master/slave motion, adjustable motion scaling, an integrated imaging system, six DoF manipulators, and an adjustable fixed reference frame. [3]

Traditional

We define a laparoscopic instrument as traditional if it is purely mechanical in operation. These have been around since the early 20th century and consist of mostly long hand-held tools that operate in the body through small incisions.[5] Traditional instruments include one DoF tools that are operated much like a pair of scissors and multiple DoF tools that use dials or sliders for additional control.

Based on our information search and our interview with Dr. Geiger, we determined the aspects of traditional instruments that have led to their long-term use. These aspects include their lightweight and simple design, cost effectiveness, force feedback, ease of use, mobility during surgery, and disposability.[3]

CUSTOMER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

We determined a set of customer requirements for laparoscopic tools during the interview process with Dr. Geiger, who provided insight on behalf of surgeons using this technology. Using these customer requirements we generated engineering specifications and related the customer needs to the engineering deliverables using a Quality Function Deployment (QFD) diagram. This allowed us to weigh the relative importance of the engineering specifications in our design.

Customer Requirements

The customer requirements specified by Dr. Geiger for the ideal laparoscopic tool were as follows:

- Motion scaling
- Intuitive master/slave motion
- Force feedback
- Mobility during surgery
- Wrist-like range of motion
- A minimum of four DoF
    - Translation (3 directions)
    - Roll
    - Pitch
    - Yaw
- Universality in surgical applications
- Tremor reduction

Of this list he specified that the five most important aspects of an ideal laparoscopic tool are: A minimum of four DoF, intuitive master/slave motion, motion scaling, force feedback, and tremor reduction. Other requirements that we determined would be necessary for a successful product are:

- High durability
- Interchangeable heads
- Sterilizability

- Cost effectiveness
- Light weight
- Standard size ports

These two sets customer requirements can be seen in the left-most column of the QFD in Appendix A. The column on its immediate right weights the importance of each requirement, with 1 being the least important and 10 being the most important.

Engineering Specifications

We developed a set of engineering specifications that describe aspects of a design that could meet the customer requirements. These specifications are listed with their target values for an ideal laparoscopic tool in Table 1.

Table 1. Set of engineering specifications and their target values

Engineering Specifications	Target Values
Tool weight	< 5 lbs (hand-held)
Number of parts	< 30
Diameter of tool heads	5mm and 8mm (scalable design)
Tool head DoF	≥ 4
Material type	Medical grade (Ti, SS, plastics)
Ability to have fixed reference frame	N/A
Number of locking DoF	≥ 4
Range of motion	60°-90°
Disposability/Reusability	Disp. = 1 surgery/ Reuse. ≥ 20 surgeries
System type (mech., electro-mech., etc)	N/A
Motion scaling ratio	5:1 and/or 3:1
Force scaling ratio	1:1
Tool length	6”-18”
Tremor reduction ratio	1:2
Center of mass location	Balanced position

These engineering specifications are listed in the top of the QFD. In the center of the QFD, there is a grid that correlates the customer requirements with the engineering specifications. Their relationships are quantified with a 1, 3 or 9 rating. A “1” represents a weak correlation, a “3” represents a moderate correlation, a “9” represents a strong correlation, and a blank space represents no correlation.

To determine the relative importance of technical requirements, we multiplied the correlation rating by the customer requirement rating. These resulting values are found in the “Total” line at the bottom of the QFD. A subsequent importance rating was given based on the “Total” value with respect to all engineering specification “Total” values (Rank from 1 to 15). In reviewing the importance ratings, we have found that system type, tool head DoF, force scaling ratio, and motion scaling ratio were the most important aspects of design in order to fulfill the customer requirements.

We indicated correlations between the technical requirements using the triangular matrix at the top of the QFD. The relationships were represented with the following symbols: -- (very weak), -, +, ++ (very strong). The results of this analysis indicate that most of these specifications have at least a "strong" correlation with the choice of system type.

Benchmarking

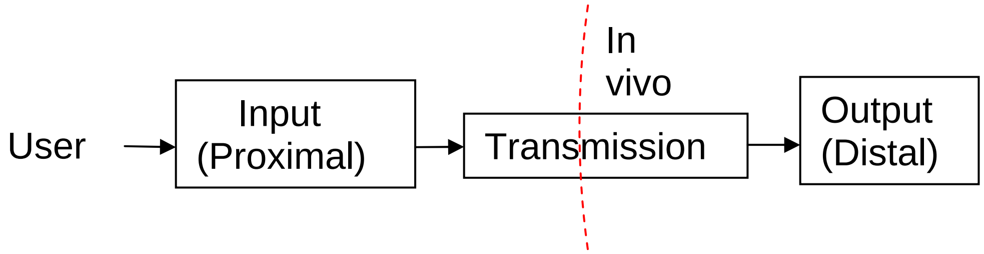
The two existing technologies (traditional and robotic) were evaluated with respect to the customer requirements in the rightmost part of the QFD. It can be seen that neither of the current technologies meet the customer requirements in full. We have determined that there is a need for improved design since neither existing technology satisfies all of the five most important aspects as specified by Dr. Geiger.

Traditional and robotic instruments were also evaluated with regards to the engineering specifications at the lower section of the QFD diagram. We have generated quantitative objectives for the specifications of our design based on these existing technologies, which can been seen in the QFD diagram in Appendix A.

CONCEPT GENERATION AND EVALUATION

In order to design a tool that satisfies the technical requirements set forth, we generated and evaluated concepts that represented aspects of a possible tool. In performing our evaluations we broke our instrument up into three main subsystems: the user input mechanism (proximal end), the transmission, and the tool tip (distal end) (see Fig. 1).

Figure 1. General layout of tool function/control



The ideal laparoscopic tool mimics the surgeons arm, wrist and hand motion inside the patient as it would occur in open surgery. During open surgery the surgeon has pitch and yaw about the wrist. Axial rotation and translation degrees of freedom are supplied by the arm. See Appendix C. [11]

Based on the degrees of freedom needed by the surgeon, as well as the structure of traditional laparoscopic tools, we divided the motion requirements of the tool into the three subsystems seen in Figure 1. We decided that the input subsystem will directly provide translational DoF and roll (axial rotation) while also controlling the degrees of freedom of the output subsystem. The output subsystem will provide pitch, yaw and gripping motion.

Our strategy in weighing possible design concepts was as follows: After defining the main functions of each subsystem, we then generated requirements that the subsystem components must achieve in order to successfully carry out their functions. After defining these, we considered the effectiveness of several types of mechanisms in meeting these requirements. We eliminated mechanism concepts that could not feasibly meet these requirements and further analyzed those that could.

Tool Tip

The tool tip contains the gripping mechanism used for manipulation within the patient's body. The main function of the tool tip is to provide gripping motion (1 DoF) with force feedback. Also, the mechanism must provide 2 rotational DoF (pitch and yaw) used to adjust the position of the gripper.

The input to this system could either be mechanical motion (linear or rotational) or electrical signals. The output is defined as mechanical motion by virtue of its function. If we chose an electrical input, we could use either motors or piezo stacks to translate the signal into mechanical motion. The use of motors was ruled out due to spatial and weight constraints and since piezo stacks wouldn't allow for the range of motion we were looking for, we disregarded their use as well. Therefore the input to the tool tip must be mechanical (linear/rotational motion). Since rotational motion requires more components and increases system complexity, we assumed that the input would be linear. Therefore, we determined that to provide two rotational DoF we could use any of the following joint types: ball joint, a compliant U-joint [6], a pulley system [9], or a system of joined compliant disks [8]. Because a ball joint contains a third unneeded degree of freedom (axial rotation) it was eliminated as a possibility. For a graphical representation of these joint types, see Appendix D. Since it was not clear which of the remaining ideas would work best for our application, they were further evaluated.

A comparison of the use of a compliant U-joint [6], pulley system [9], and compliant disk [8] in the tool tip mechanism can be seen in Table 2. As previously mentioned we generated requirements that the joint must achieve in order to successfully carry out the subsystem functions. The effectiveness of each of the three joint types was therefore evaluated based on how well they met these requirements. We analyzed each joint type in reference to patents and other prior art publications ([6], [9], and [8]).

For each requirement, we gave every joint option a rating of --, -, + or ++ to represent how well they meet the requirement ('--' = very poor, '++' = very well).

Table 2. Comparison of joint types for use in tool tip

	Compliant U-Joint [6]	**Pulley System [9]**	**Compliant Disks [8]**
2 Rotational DoF	++	++	++
Transmit off-axis rotation	++	-	++
Scalable to 5mm/8mm	++	-	++
Adequate range of motion (60-90 deg.)	+	++	+
Minimal radius of curvature in tip deflection	-	+	--
Inert material	++	-	++

From the ratings in Table 2, we could see that the compliant U-joint had more positive qualities than both the pulley system and compliant disk options. While all three options share the ability to allow two rotational degrees of freedom, the compliant U-joint and compliant disk options do not have the problems that are associated with the pulley system (difficult to scale down and difficult to transmit off-axis rotation). The compliant U-joint and compliant disks both meet most of the requirements set forth very well; however, achieving a minimal radius of curvature is done more easily with a compliant U-joint. Based on this evaluation the compliant U-joint is the best option for use in the tool tip.

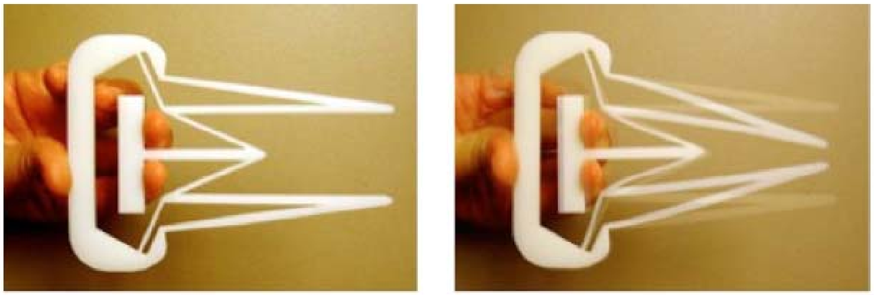
After we selected the optimal joint type for use in the tool tip, we decided what type of force feedback system to employ in the gripper (addressing function 2 of the tool tip). We evaluated the mechanical (rods or cables) and electromechanical (sensors) options to see how well they met the force feedback requirements. Table 3 shows a comparison of the abilities in mechanical and electromechanical systems to meet force feedback requirements. It is important to note here that we have not considered the design of the gripping mechanism yet, only the force feedback system.

Table 3. Comparison of force feedback systems for use in gripping mechanism

	Mechanical	**Electromechanical**
Provide force feedback in gripping motion.	++	++
Accurate	+	++
Scalable to 5mm/8mm	++	-
Inert material	++	+
Satisfy minimal size constraints	++	+

From Table 3, it was shown that the mechanical option meets all of the requirements set forth more effectively than the electromechanical. Both options hold the ability to relay force feedback accurately, however, the electromechanical system is more difficult to scale than the mechanical system because it requires additional components (sensors), which may interfere with the gripper function. Because the mechanical feedback retains the positive aspects of an electromechanical scheme while eliminating the problems, the mechanical system is best for our application. Based on the decision that the system is purely mechanical and because the compliant U-joint design was selected, a simply linearly actuated gripping mechanism can be easily integrated to achieve the gripping motion. An example of a compliant type of this gripping mechanism can be seen in Figure 2. In weighing the option to use a compliant gripper, it is clear that integrating compliance in this case will yield benefits (reduce part count, no friction) without significant drawbacks, when compared to a noncompliant gripper. We therefore decided to use a compliant 1 DoF gripper mechanism similar to that seen in Fig. 2.

Figure 2. Compliant gripping mechanism [6]



Transmission

The transmission contains the shaft that passes through the port from outside the patient (in vitro) to within the patient (in vivo). The function of the transmission is to relate the proximal output to distal input, while providing motion scaling (5 DoF transmission). It is important to note here that this shaft must be scalable to 5mm/8mm diameter for optimal function and the transmission must occur over a relative long distance.

Input to this subsystem could either be mechanical motion (linear or rotational) or electrical signals. Because we determined that the input to the tool tip must be mechanical, the output of the transmission system must be mechanical (motion) (see Figure 1). If the input is electrical and the output is mechanical, either motors or piezo stacks must be used to translate the motion electromechanically. Piezo stacks are not suited for this application because of limited range of motion. This leaves motors as our only feasible electromechanical option. If the transmission simply needs to translate motion-to-motion (purely mechanical) three options were considered: cables, push rods, and hydraulics. Hydraulics were ruled out due to their complex nature and apparent sizing constraints. Therefore we were left with three possible choices for the transmission system: Mechanical (1-cables, 2- rods) and Electromechancal (3- motors). We first analyzed the effectiveness of mechanical vs. electromechanical components in meeting the requirements necessary to achieve the transmission functions, the results of which can be seen in Table 4.

Table 4. Comparison of mechanical and electromechanical transmission systems

	Mechanical (cables or rods) [7] and [10]	**Electromechanical (motors)**
Motion scaling (trem. red.)	+	++
Relating prox. to distal…	++	++
Scalable to fit in 5mm/8mm tube	+	-
Minimal components	+	-
Manufacture-able	+	+
Durable components	++	+

The results shown in Table 4 indicated that the mechanical system had more positive qualities than the electromechanical system. The mechanical option is able to achieve all of the requirements of transmission with minimal difficulties. Although the electro-mechanical system can provide motion scaling with less difficulty, it would be harder to design an electromechanical system that is scalable to 5mm/8mm. An electromechanical system would also require the same components found in a purely mechanical transmission system in addition to the motor and related components. Therefore, in an effort to keep the design simple, efficient, and effective we chose to use a purely mechanical transmission system.

After making the decision to use a mechanical transmission system, we focused next on the specific mechanical means of motion transmission. We evaluated the two mechanical options possible, rods and cables, more critically. We applied the same requirements as seen in Table 4 to cables and push rods, which can be seen in Table 5.

Table 5. Comparison of cables and rods for use in transmission system

	Cables [7]	**Push Rods [10]**
Motion scaling (tremor reduction)	+	+
Relating proximal output to distal input	++	-
Scalable to fit in 5mm/8mm tube	+	-
Minimal components	+	+
Manufacture-able	+	-
Durable components	++	+

The results in Table 5 indicate that the cables had more positive qualities than the push rods in this application. Cables are able to achieve all of the requirements to provide the main functions of transmission with minimal difficulties. The push rod system has no advantage over cables when it comes to achieving our main function for transmission. Cables allow direction of input to output motion to be changed, where push rods are unidirectional in nature. Because of these facts use of cables makes adaptation to the proximal input system and distal tool tip much easier than rods. Cables are also more easily scalable to fit in 5mm/8mm tube, easier to manufacture, and are more durable than rods (can withstand more local strain before failure). Based on this evaluation we determined that a purely mechanical transmission system using cables was the best option for our design. Note that two degrees of freedom (roll and translation) are achieved in the physical motion of the transmission shaft and the other DoF (pitch, yaw, gripping) are transmitted via cable to the tool head through the shaft.

Input

The input contains the handle that the surgeon uses to manipulate the tool head and ultimately perform the procedure. The function of the input mechanism is to relate user input to transmission input (5 DoF). As mentioned earlier, the input subsystem will directly provide three translational DoF and roll while also controlling the DoF of the output subsystem. In order to achieve this, the translation and roll DoF must be separated from the output control. We chose to attach the mechanism rigidly to either the surgeon’s arm or a support mechanism, while leaving the output control DoF free. Therefore, the surgeon’s arm will provide roll and translation while his wrist provides pitch and yaw.

The user input is mechanical by definition (surgeon holds tool in hand). The output must also be mechanical because we determined our transmission system will be a cable driven mechanical system. We determined therefore that the input mechanism must be purely mechanical in nature, since it would only add extra parts, weight, and complexity to the tool if electromechanical conversion was used. The input motion must have 4 DoF plus a gripper actuation for successful operation. We consider here the options for the 4 DoF input and address the gripping input in a later section. For two of the possible designs, two of the DoF (roll and translation) exist between the tool and the proposed arm cuff, as previously mentioned. For the remaining DoF (pitch and yaw) the three possible designs are 1) universal joints 2) a series of two curved slider joints 3) 3D 5-bar input mechanism. For graphic representations of these designs, see Appendix E. The main idea of use of the U-joint would be to mimic the joint in the tool tip so operation would be straight-forward (parallel mechanism machine). The user would simply impart the rotation and through cables and pulleys this motion would enter the transmission system. The series of two curved slider joints achieves the same motion but allows for different mechanism architecture. The user would slide the scissor type input in the two tracks (vertical and horizontal) and attached cables would create relative motion. In this case motion would always be centered at the surgeon's wrist. The 5-bar mechanism concept would create an instantaneous, purely rotational motion that is located at the surgeon's wrist. Cables attached to the floating link of this 3D 'double-rocker' design would be pulled/released during rotation of the plate creating relative motion. Since it was not immediately clear which one of these joints would function the best in our application, we compared the effectiveness of each in meeting requirements needed to satisfy input mechanism function, seen in Table 6.

Table 6. Comparison of U-joint, Series Sliders and 5-Bar for input mechanism

	U-Joint [6]	**Series Slider System**	**3D 5-Bar**
1st and 2nd DOF (pitch/yaw)	++	++	++
3rd DOF (Roll)	++	++	++
4th DOF (Translation)	+	+	++
Rotation centered at wrist	--	++	++
Low friction	+	-	+
Low weight	+	-	+
Resistant to binding	++	-	+

The ratings in Table 6 show that the U-Joint, Series Slider System, and 3D 5-Bar allow for two DoF with few challenges. U-joints require that rotation is centered in the middle of the joint, which does not allow the rotation to be centered at the user's wrist. The spherical track system and the 3D 5-bar mechanism allow for this ergonomic rotation center. Translation of the joints is also independent of type and none of the input choices induces any trouble in this motion direction. A well designed traditional universal joint would have low friction and a compliant joint would have even less due to reduced number of surface interactions. A 3D 5-bar mechanism with ball joints would have minimal friction, and with the integration of compliance, friction would be eliminated completely. The track system has two tracks in series to each other which creates a lot of surface interactions and thus friction, which could be a problem for smooth function. When analyzing weight, it was noted that U-joints have few parts and are small compared to their prescribed range of motion. The track system is bulky compared to the motion it allows and has many parts making it the heaviest option. Our 3D 5-bar mechanism would have multiple parts as well, but it would be lighter weight than the track system due to the materials being used. Binding is a foreseen problem with the track system as well since moments are created on sliding joints during off-axis rotation. U-joints lessen this problem by only transmitting moments onto pin joints.

Although there are many advantages to the three input systems considered, the 3D 5-bar mechanism retains the most advantages while achieving the necessary requirement of rotation about the wrist. In order to achieve the gripping degree of freedom in the output, a gripping input mechanism can be integrated into the 3D 5-bar design simply by adding a 1 DoF scissor-like structure.

DETAILED DESIGN

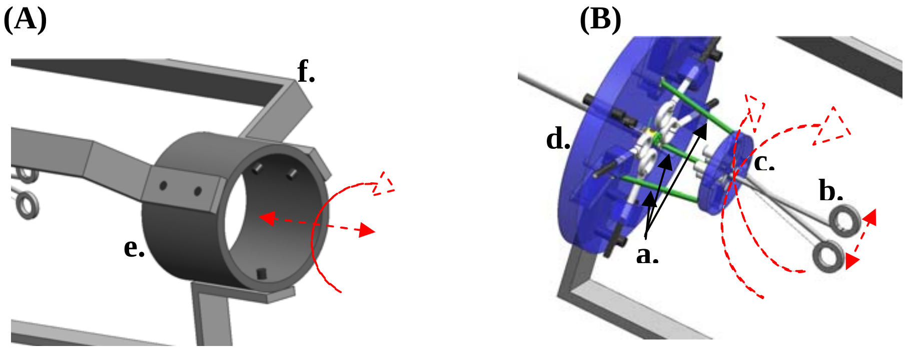
After evaluating many different concepts that form aspects of our tool design, we generated a final tool concept that incorporated the concepts that were successful in achieving each subsystem function. We then evaluated our design with respect to the engineering requirements generated from our customer needs.

User Input

The user input to the system is a 3D 5-bar mechanism consisting of 3 bars (a.) attached to a plate on either side, with one plate moving (c.) and the other stationary (d.) (see Figure 3) with ball joints at each interface. The instant centers of the three bars represent the point of rotation at the wrist. A rigid cuff (Fig. 3A) meant for the surgeon's lower arm will be attached to the stationary plate. This will allow for translational motion, which can be combined with axial rotational motion with this design. As previously mentioned, to generate pitch and yaw motions of the tool tip the surgeon will rotate his hand about his wrist while grasping the input scissor. The user will grasp a gripper input mechanism attached to the moving plate on the five-bar mechanism and using a pinching type motion will actuate the gripping at the tool head. The gripping actuation will occur through a cable/sheath apparatus which would also give mechanical gripper force feedback. The motion of the user's hand (rotation about the wrist) will be related to linear cable motion that is fed into the mechanical transmission system.

The arm cuff structure will consist of a hollow cylinder (e) with three support bars (f) attaching it to the stationary plate of the 3D 5-Bar mechanism. Inside of the cylinder there will be foam or some other form of adjustable filler that will ensure a tight and comfortable fit.

Figure 3. (A) The cuff that on the surgeons arm (B) 5-bar input mechanism



Transmission

The transmission of the system will consist of a hollow shaft containing cables for mechanical motion transmission (see Figure 4) between the input and output mechanisms. Cables will be attached to the moving plate of the 3D 5-bar mechanism (plate seen in Figure 3B). When a motion is imparted on this link from the user, the cables attached to it will be pulled and released according to the displacement of the link. The cables will be routed through individual spring loaded eyelets (a.) that will tension the lines and allow for slack release if needed. The cables are then routed through a low-friction washer (b.) into the tool shaft (c.).

Figure 4. Transmission system

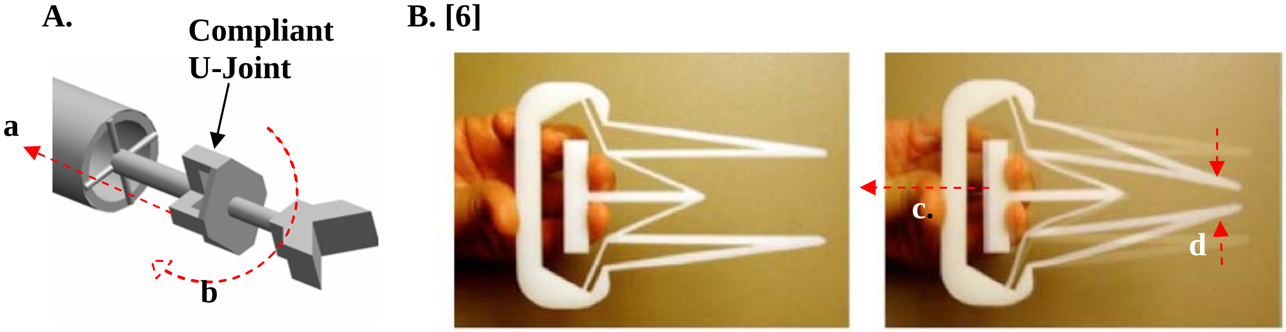
End Effecter

The end effecter of this tool design will consist of a compliant U-joint (see Appendix D.), providing the pitch and yaw DoF, with an integrated one DoF gripping mechanism (see Figure 5.A). The gripping mechanism will be a compliant linearly actuated gripper, similar to what is seen in Figure 5.B. Due to time and resource limitations we were not able to complete design of the compliant gripping device ideal for surgical applications, but the actuation and general function are the same as the design seen in Figure 5.B.

The U-joint will be actuated by relative linear cable motion (a), from the four transmission cables which are attached to the four sides of the U-joint. When the user imparts a rotation on the input plate, one cable is pulled (a) and the opposite relaxed. The pulling cable motion is then imparted on one side of the U-Joint which causes deflection in the desired direction of motion (b). Axial rotation and translational DoF of the tool tip are achieved through connection to the transmission shaft. Since the user imparts axial rotation (roll) and translation directly to the entire mechanism through the arm cuff, the rigid connection between the U-Joint base and the transmission shaft mean that this axial rotation and translation is also transferred to the tool tip.

The compliant gripper is actuated by linear cable motion, which is imparted on the mechanism at (c). This linear motion causes the gripper ends to deflect together (d). The linear input motion for gripping is the result of the 1 DoF scissor type input in the 3D 5-bar mechanism. When the scissor type actuator is closed the cable is pulled, causing the gripper to close.

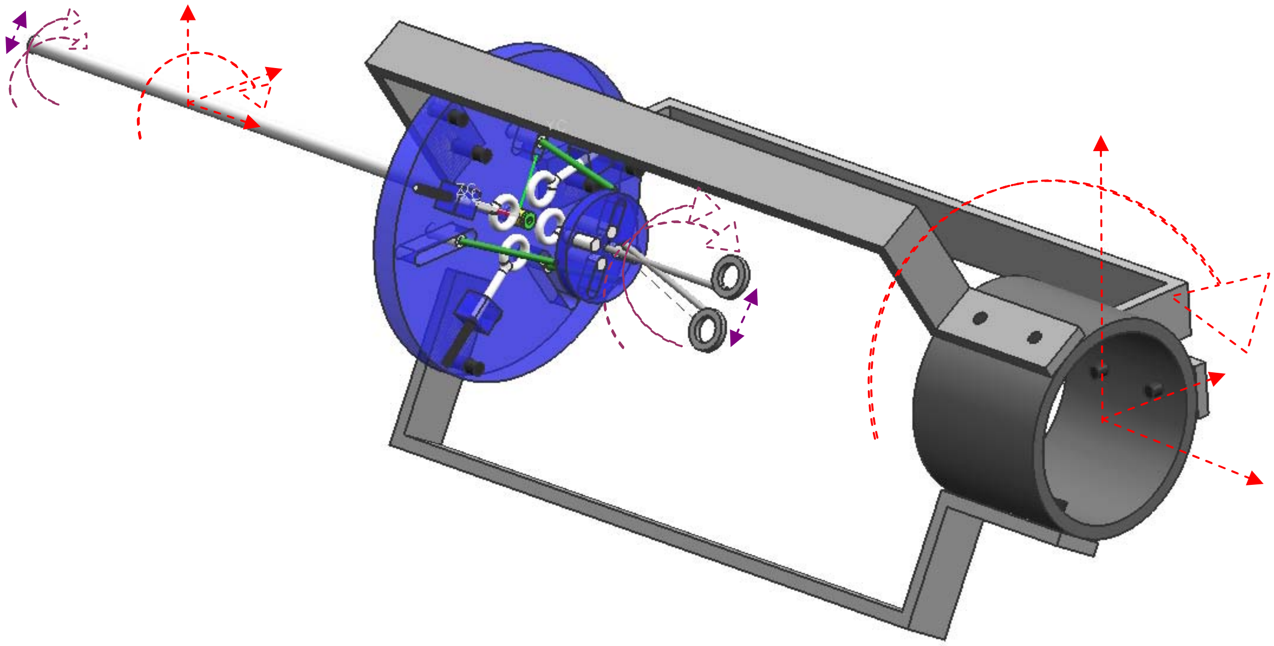
Figure 5. Rendering of compliant U-Joint tool tip and compliant gripper mechanism



Overall Design

A final 3D CAD drawing can be found in Figure 6. Appendix F shows the engineering drawing for the tool along with the dimensions of the major components.

Figure 6. Overall 3D design of tool. (Red = arm motion, Purple = wrist/hand motion)



ENGINEERING ANALYSIS

For our tool design, we analyzed a possible iteration of concepts using mainly a trial and test method. For our scope we were limited to doing a proof of concept. A more deterministic design that includes optimization of components will be investigated in the future.

Input Analysis

Components. The input to the system is a 5-bar mechanism with a scissor-type gripping input. The 5-bar mechanism is made by 3 links that are attached to the base by ball joints and the stage (see Figure 2b).

Geometry. To determine the geometry of our input system, we first generated a CAD model of the 5-bar mechanism to visualize a possible spatial relationship between the links. The links are all of uniform length and are spaced 120 deg. apart. This CAD model can be found in Figure 5.

We then imported the CAD model into MCS.ADAMS for dynamic modeling. We applied a rotation to the scissor input and mapped the displacement of the 5-bar mechanism. The motion data was then exported to Matlab for analysis. We assumed that the motion was independent in each plane, so they could be analyzed separately. It is important to note that the analysis for this assumed geometry was done to investigate a proof of concept (optimization and analytical solutions may be done at a future time).

We mapped the instant center location of the 5-bar mechanism, which represents a point of rotation. In future optimization, we would aim to keep the location of the instant center at the surgeon's wrist for a large range of angular deflections. We projected the motion of the instant center in the horizontal and vertical direction on the XZ and YZ planes respectively. We also mapped the input scissor location to determine the range of angles that the surgeon's wrist is allowed to rotate. Appendix G Figure A shows the horizontal motion of the instant center in the XZ plane and Figure B shows the input scissor location for the same horizontal movement. Appendix G Figure C shows the vertical motion of the instant center as the surgeon moves the handle upwards and Figure D shows the input scissor location for the same vertical motion. Appendix G Figure E shows the instant center location when the surgeon moves the handle down and Figure F shows the scissor input location as the surgeon moves the handle down. It is important to note that the horizontal motion is symmetrical while the vertical motion is asymmetrical, which is why there are separate plots for the upward and downward motions in the vertical direction.

The angular ranges measured represent the maximum angles the surgeon's wrist can rotate before non-negligible deflection in the opposite plane occurs. From the analysis, we found that the horizontal angular range was +/- 35 degrees and the vertical angular range was +/- 45 degrees. The horizontal angular range could be optimized to allow for more rotation; however the vertical angular range meets the customer requirements.

We ran tests on the attachment points of our cables to the input plate so that we could analyze cable motion and extract requirements of our spring-loaded eyelet system and the amount of output cable motion we will get. We varied cable attachment points from near the edge of the plate to near the center. We tracked these points through a range of rotational motion of the input tool handle. We used a symmetric configuration of links about 120 degree angles, but the cable attachment points were symmetric about the x and y axis. This causes the x axis measurements to be symmetric for left and right motion, but the y axis measurements were different for up motion and down motion.

Appendix H Figure A shows the trace of the horizontal (x) motion attachment points through the right and left motion; different colored pairs denote different starting locations. Figures B and C show traces of the attachment points for the vertical (y) motion attachment points for up and down motion.

Using these traces, we were able to track the distance from the receiving point of our cables into the transmission tube. From these distances and the changes in these distances through the motion, we could determine the slack created in the lines from the in-plane motion and from the transverse motion.

The in-plane slack comes from slack in the x-axis lines due to motion left and right in the x direction. Figure D in Appendix H shows that there is zero slack in the lines at the starting position (this serves as a reference point for slack measurements) and as time goes on (motion moves from center), the slack in the line grows to a max of 1 inch (largest for all attachment points tested)

Figures E and F in Appendix H show the in-plane slack created from up and down motion in the y-axis lines.

Slack is also created when there is motion out of the plane; in the transverse plane. When the input is moved left and right, slack is needed in the y-axis lines, and vice-versa. Figure G in Appendix H shows the slack created in the y-axis lines from moving left and right.

Note that this slack is independent of the location of any of the attachment points. Figures H and I in Appendix H show the slack created in the x-axis lines from moving up and down.

By adding these found slacks together, we were able to calculate the amount of slack that our spring-loaded eyelets would have to account for. We found that each spring would have to provide a max of one inch of throw. We have designed our system with this in mind.

Also from these traces, we could calculate the amount of relative motion between the lines which will give us the amount of line that is actuating our output. Figure J shows the amount of relative motion (pull in one, slack in the other) in the x-axis cables for x-axis motion of the input.

Figures K and L in Appendix H show the relative motion of the y-axis cables for positive and negative y-axis motion.

In our actual prototype, we will make the attachment points of the cables adjustable so that we can move through this range of attachment points and test whether our simulation is realistic. We can then decide on an optimal location of the attachment points by an actual physical analysis along with our computer generated results.

Materials. Because our design is a proof of concept, the materials selected for the prototype were chosen based on ease of manufacturing and functionality. The materials for the input mechanism are: Plexiglas, plastic tubes, piano wire, epoxy, scissors and bike cable/sheath. Details of these materials can be found in the Bill of Materials in Table 6.

Arm Cuff

The arm cuff is made using a PVC tube and a blood pressure cuff. The blood pressure cuff will be secured inside the PVC tube by strips of Velcro. The surgeon will place his arm in the blood pressure cuff and inflate it until it is secure. The geometry of the cuff is based on CAD and the human arm. The materials for the cuff were selected for the prototype only based on ease of manufacturing and functionality.

Transmission Analysis (Cable pulley system)

The components of the transmission system include the tensioning pulleys, a rod that the cables can run through and spring loaded mechanism. The analysis regarding the transmission system was lumped together with the input mechanism analysis and can be seen on pp. 12-14. As mentioned before the materials for a final design have not been chosen. For our prototype we are using eye hooks, springs, nuts, washers, and Plexiglas. Refer to the Bill of Materials in Table 6 for more details on these materials.

Output Analysis

The output will consist of a compliant U-joint with a gripper that we will rapid prototype. A simple FEA analysis for a future compliant U-joint at the tool tip was used to verify scalability to our working size. A simple T shaped plastic piece can be used as a compliant joint and we chose to analyze a joint of this type for our application. A force is applied at the bottom left edge of the top of the T as shown in Figure A in Appendix I. This is where the actuation cable would imply a force on the joint. Figure B in Appendix I shows the resultant deflection under such a force. Figure C in Appendix I shows the maximum stresses through the mechanism due to the applied force (stresses shown in MPa). We have shown in this analysis that under a load of 5 Newtons, we get a deflection which is in our targeted working range, while the stress induced is 40% less than the yield stress of the material. The material we used was Accura 25 which is a common rapid prototyping material. It has an elastic modulus of approximately 1500 MPa and yield strength of 40 MPa. The maximum stresses shown in our model are around 25 MPa.

Achieving Engineering Requirements

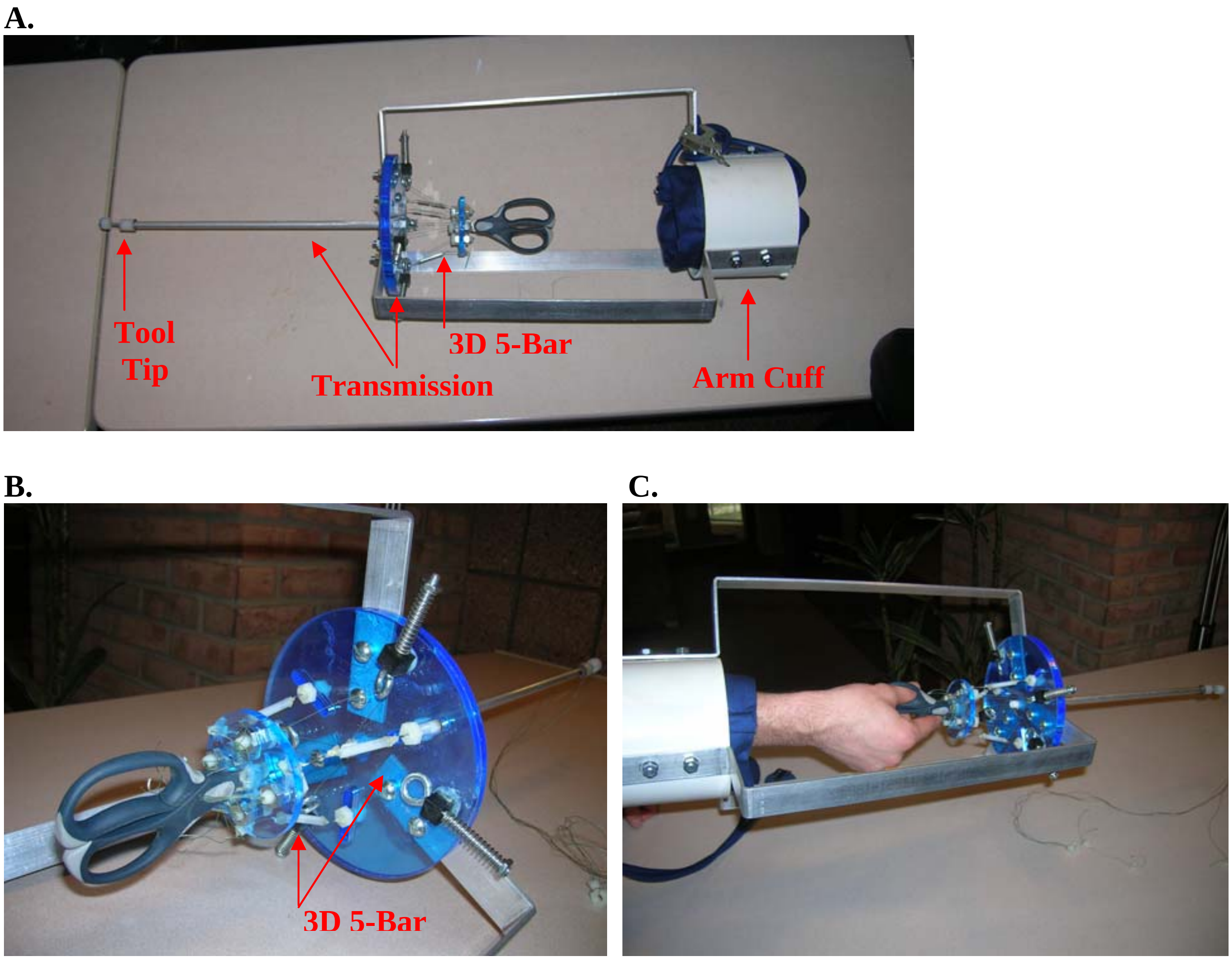
In reviewing this design it is evident that it qualitatively achieves all engineering requirements set forth. We were able to create a mechanism that had 5 DoF, which exceeded our minimum limit of four. Our design allows for intuitive input motion in that it involves 3-D rotation about the surgeons wrist, which is mimicked exactly at the tool head. Motion scaling was achieved in the design through size variation of parallel mechanisms (input 3D 5-bar to output compliant U-joint) and variation in relative cable attachment points. By the same mechanism, tremor reduction was achieved, since as the input motion is scaled down, so are tremors. Lastly, we were able to achieve force feedback in gripping and deflections in the compliant tool tip and cable force feedback. The results are discussed in more detail in the Testing section on pp.19.

It is important to note here that we met these requirements using a tool design that is purely mechanical. Our tool achieves the functions contained in the *da Vinci* robotic system, while retaining advantages of traditional laparoscopic tools.

FINAL PROTOTYPE DESIGN

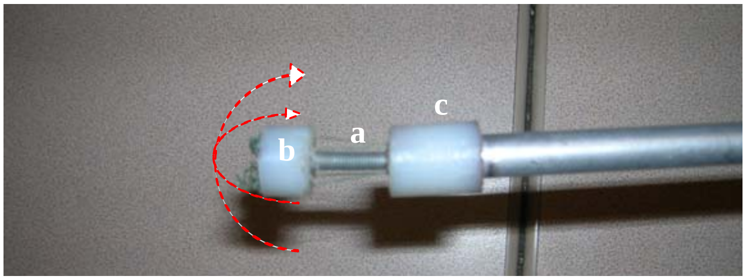
The prototype was manufactured using a slightly modified version of the design described in the earlier section. Because of time and resource constraints these modifications were necessary to ensure the functionality of the highest priority components. Due to their unique and original design, the input and transmission components were considered a higher priority than the tool tip. Our reasoning for this was that the tool tip would not function and therefore could not be evaluated if in the prototype the input and transmission subsystems were not functional. Using this modified design, we completed manufacturing of a prototype, which can be seen in figure 7 below.

Fig. 7 Completed Prototype



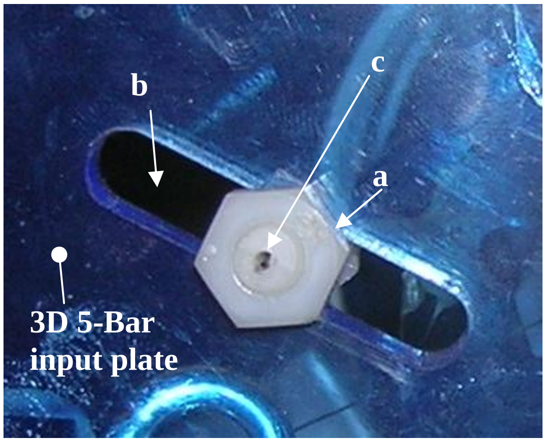
For the output system, the two DoF joint and the gripping mechanism that were used in the prototype differed from that seen in the design described in the Final Design section. Instead of using a compliant U-joint mechanism for the two DoF joint, we decided to use a mechanism similar to that of the compliant disk concept described in the Concept Generation and Evaluation section. See Appendix D for schematic. Seen in Figure 8 is the design we implemented which consists of a tension spring (a) mounted in two plastic disks (b,c). Note however that the actuation is the same as would be in the compliant U-joint design since relative cable motion imparts a couple on the free disk which causes spring deflection. In the manufacturing process, we planned to integrate the compliant gripping in the design, however due to a manufacturing error we were unable to implement this into our prototype. Our prototype therefore lacks a gripping mechanism.

Figure 8. Spring end effecter



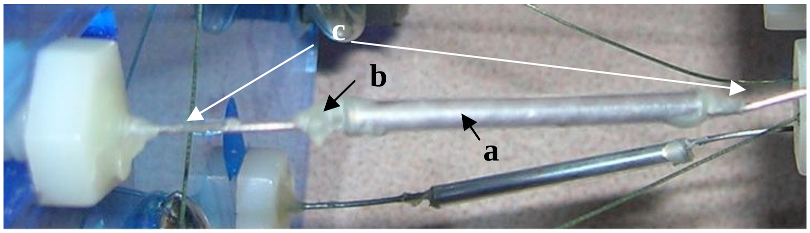
We chose to integrate adjustability into the input and transmission systems of our prototype to allow for robust testing with the intention of verifying results from engineering analysis. One point of adjustability in the prototype was the connection points for the 5-bar links to the stationary plate (see Figure 9a). Each link was attached to a bolt and nut which was held in a radial channel and could be repositioned upon loosening. This same bolt (a) channel (b) design was used to allow for varying attachment points for the cables (c) to the moving plate (see Figure 9).

Figure 9. Cable connection points



Because of size constraints, implementing traditional ball joints in the 3D 5-bar mechanism was difficult. Therefore, we chose to use 2 DoF flexure joints created by attaching a rigid sleeve (a) around a flexible wire (b) to isolate flexure of this wire to the joint areas (c) (see Figure 10). The wire ends were then attached to the moving plate and adjustable bolt of the 5-bar mechanism.

Figure 10. Flexure joint links



As mentioned earlier the arm cuff component requires an adjustable interior size for user comfort. This was achieved in the prototype by using a blood pressure cuff inside a rigid cylinder, which can be inflated or deflated according to the users needs.

A Bill of Materials listing the parts we needed to build our prototype, where they were purchased from and their price can be found in Table 7. Most of the materials were purchased from hardware stores, however smaller objects were provided to the group from the ME 450 machine shop.

Table 7. Bill of Materials for Prototype

Quantity	Part Description	Purchased From	Part Number	Price (each)
1	4" PVC schedule 40 coupling	Lowe's		$1.92
1	2" x 2" x 3/8" Acrylic plate	ALRO		$2.25
2	6' x 1" x 1/8" 6061 Aluminum flat stock	ALRO		$17.58
1	6" x 6" x 3/8" Acrylic Plate	ALRO		$4.50
1	5/16" x 3' Aluminum tube	ALRO		$2.59
1	1' x 1" x 1" Acrylic L-Stock	ALRO		$2.25
5	Araldite Epoxy	Home Depot	SY-IN	$14.60
1	Piano Wire 5’	King’s Keyboard		$5.00
4	Small plastic tube (piano wire OD = ID)	Stadium Hardware		$0.92
1	Fishing Line (high quality)	Sporting Goods Store / Awtar		$0.00
2	10” Adhesive Velcro strips	Home Depot		$3.00
1	Scissors	CVS	4110	$2.99
1	2’ Bike Cable Sheath	Andy		
1	Pack Nylon Hex Head Cap Screw 1/4"-20 Thread, 3/4 Length, 100/pack	McMaster/Carr	91244A540	$11.56
1	Pack Wire Eyebolt with Nut, Zinc-Plated, 3/16"-24, 2" Shank, 10/pack	McMaster/Carr	9489T49	$2.42
1	Pack Nylon 6/6 Hex Nut 1/4"-20, 7/16" Width, 1/4" Height, 100/pack	McMaster/Carr	94812A116	$5.71
3	Rapid Prototyped Compliant Gripper	Rapid Prototyping		$300.00
1	Blood Pressure Cuff	CVS		$16.99
			Total	$394.28

MANUFACTURING

The prototype was built in three subassemblies which were then connected: arm brace, base plate, and input stage.

The arm brace includes the rigid PVC ring that goes around the user’s arm, the inflatable blood pressure cuff that lies along the inside of that ring, and the 3 aluminum support arms that link this arm brace to the base plate. Holes were drilled in the PVC and the aluminum support arms and attached with bolts. The blood pressure cuff was attached to the inside of the PVC with Velcro strips. The support arms were bent to create the shape as prescribed by our CAD model.

The base plate includes the acrylic ground plate, transmission tube, and spring-loaded eyelets. The eyelets were attached with support blocks that are glued to the ground plate. Holes for all support arm attachments along with slots for adjusting location of leg bases were laser cut. The transmission tube and a bushing to guide the cables were glued into a hole in the center of the plate.

The input stage includes the acrylic input plate, the attached legs of the 5-bar mechanism, the input handle, the actuation handle, and cable attachments. The slots and holes needed in the input plate were laser cut. The legs of the mechanism were made by gluing a thin wire through an aluminum tube (to provide rigidity in the middle section) and fixing it to nylon bolts at both ends to attach to the base plate and the input plate. The input and actuation handles were made out of a pair of modified scissors. The blades of the scissors were cut off, and a hole was drilled in the bottom handle. The actuation cable attached to the hole in the bottom handle and the top handle was glued to the input plate.

To assemble these pieces, we first connected the legs of the mechanism between the input plate and the base plate with the nylon bolts on the ends of the legs. We then ran all of the appropriate cables from the input plate, through the spring-loaded eyelets, and through the transmission tube. The support arms were then bolted to the base plate and the arm brace.

TESTING

Because of limited time we were unable to carry out quantitative testing of the effectiveness of our prototype in meeting the target values of the engineering specifications seen in Table 1. However it was qualitatively evaluated to determine if it met the engineering specifications to any degree. We found that our prototype satisfied the five key engineering requirements as seen on page 2. This was determined by manually operating the tool and observing its function.

Table 8. Testing results indicate all engineering requirements are met

Engineering Requirement	**Achieved?**	**Comments**
4+ DoF	Yes	Range of motion for end effecter deflection seemed reasonable compared to input plate motion. Note that the gripping cable motion was achieved, however, it was not tested using the gripper device itself.
Intuitive Master/Slave Motion	Yes	Energy storage in flexure joints caused undesired resistance to motion.
Motion Scaling	Yes	In adjusting the cable attachment points it was seen that the relative motion of the end effecter with regards to the input plate was changed.
Force Feedback	Yes	Increased resistance to motion was felt

		when the end effecter was held stationary and the input plate was moved.
Tremor Reduction	Yes?	As mentioned earlier tremor reduction is achieved in motion scaling. Since, motion scaling was achieved it was assumed that tremor reduction was as well.

FUTURE IMPROVEMENTS AND RECOMMENDATIONS

With respect to achieving the five key engineering specifications we recommend that quantitative testing be carried out to evaluate the effectiveness of the design in meeting the target values. We recommend that the motion scaling ratio, tremor reduction ratio, force feedback scale, gripping force, and required force input for the 3D 5-bar mechanism be the focus of this analysis. With these results optimization of the tool components can be carried out to improve their function. The motion scaling ratio, tremor reduction ratio, and force feedback can be tuned to optimal settings (target values of engineering specs.). Also, the 5-bar mechanism (including links and joints) can be optimized to reduce the resistance to motion while retaining positive features that result from compliance (reduced part count, equilibrium position, no friction).

As previously mentioned due to time and resource constraints we were unable to design a unique compliant gripping mechanism ideal for surgical applications. Future improvements should therefore include designing a unified compliant tool tip that consists of a U-Joint and gripping mechanism.

In moving from a prototype to an actual product, several improvements would be necessary to satisfy ergonomic, aesthetic, manufacturing and environmental requirements. These include but are not limited to: weight reduction, streamlining the arm supports shape, choosing appropriate material type, improving the comfort of the arm cuff and input handle, and improving the overall design for greater manufacturability.

CONCLUSION

Our goal in this project was to create a laparoscopic instrument which has motion scaling, intuitive master/slave motion, force feedback, a minimum of four DoF, and tremor reduction. To do this, we focused on the engineering specifications as set forth on page 3. After considering previous technologies, we created a unique design intended to meet these specifications. After analyzing and prototyping this design, we determined that it qualitatively met the engineering requirements. Further work is needed to optimize the design to ensure that it meets the quantitative engineering specifications before it can become viable as a surgical product.

ACKNOWLEDGEMENTS

We would like to thank Professor Sridhar Kota for providing funding for this project and advising us throughout the design process. We would also like to thank Dr. James Geiger for taking the time to meet with us and provide valuable insight into the needs of surgeons performing laparoscopic surgery. Finally, we would like to thank Professor Shorya Awtar for his continued support throughout the project and valuable engineering insight.

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BIOGRAPHIES

Rosa Abani

Rosa grew up in Ann Arbor, MI and graduated from Huron High School in 2003. After a full year at the University of Michigan College of Engineering, Rosa chose to major in Mechanical Engineering. After taking most of the core Mechanical Engineering courses, Rosa found an interest in dynamics and controls. She has had two internships at Toyota Technical Center, and hopes to eventually work in industry. After her graduation in Fall 2007, however, Rosa plans to stay at the University of Michigan for a master’s degree in Mechanical Engineering. Rosa was a coxswain for the Huron Rowing Team for four years, and since then has rowed and coxed at the Ann Arbor Rowing Club.

Vidi Chavez

Vidi Chavez was born in Mexico and moved to Owosso, Michigan when she was four years old. She graduated from Perry High School in 2003 and started at the University of Michigan, College of Engineering. She plans on Graduating in fall of 2007 with her B.S.E in Mechanical Engineering. She plans on attending graduate school but is undecided on what she is going to pursue. She has worked for the U.S. General Service Administration as a mechanical engineering co-op for 2 years and just recently transferred to a new company so she can gain more experience before graduation.

Andrew Mansfield

Andrew is originally from Rochester Hills in the southeast corner of Michigan. He graduated from Rochester Adams High School in 2004 and began his studies at the University of Michigan, College of Engineering in the following September. He expects to receive his bachelors in ME at the end of Fall 2007 and enter graduate school for Mechanical or Biomedical Engineering the following semester. He has worked in industrial and academic engineering settings in the past and plans to continue this work through graduation. He enjoys playing music, ice hockey, and mountain biking.

Patrick Quigley

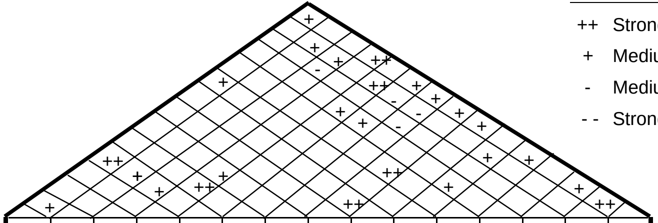
Patrick Quigley is originally from Cassopolis in the southwest corner of Michigan and spent the first 19 years of his life there. He graduated from Edwardsburg High School in 2003 and studied the next 2 years at Southwestern Michigan College. While at SMC, he changed majors from Mathematics to Mechanical Engineering by some inspiration from professors. After completing all math, science, and humanities prerequisites he transferred to the University of Michigan as a junior in the Fall of 2005. Expecting to receive his bachelors in ME at the end of Fall 2007, he plans on doing his graduate work in environmental studies and alternative energy sources. Before graduate school he plans on working and gaining experience in the field and spending some time developing his musical interests. He has been playing drums for 7 years and is currently playing with a touring band when his busy engineering schedule allows.

APPENDIX A

Quality Function Deployment (QFD)

Relationships

++ Strong Positive
\+ Medium Positive
\- Medium Negative
\- - Strong Negative



Benchmarks

	Weight*	Tool weight	# of parts	Diameter of tool head	Tool head degrees of freedom	Material type	Ability to have fixed reference frame	Number of Locking degrees of freedom	Motion scaling ratio	Force scaling ratio	Tool length	Tremor reduction ratio	Center of mass location	Range of Motion	Disposability/Reusability	System Type (mech., electo-mech. Etc)	*Robotic (da Vinci)*	*Traditional*
Customer Requirements																		
Motion Scaling	10								9	9	3	9			1	9	5	1
Intuitive slave/master motion	10	1			9		1	9	1	3		1	1	3		9	4	1
Force feedback	8		1						3	9		3				9	1	3
Cost effectiveness	5	3	9	1		9					1				9	3	1	5
Mobility during surgery	7	9					9	3			3		3	3		3	2	5
High Durability	6	3			1	9					1				1		4	3
Wrist-like range of motion	7			3	9		9	9	3	1			1	9		3	3	1
Tremor reduction	9	3	1			1	3		9	9	3	9	3			3	5	1
A minimum of Four Degrees of freedom	9			3	9		3	3	1			1				3	5	2
Light weight	4	9					1				3		3			3	1	4
Sterilizability	7		9			9					3				9	9	2	4
Interchangeable heads	4		3					1	1	1		1			9	3	4	3
Standard size ports	10			9													5	5
Universality in surgical applications	7				9	3	1		3	3	1	1	1	9	1	3	2	5
Total		124	65	122	234	66	111	142	158	217	75	144	50	114	98	360		
Normalized		0.06	0.03	0.06	0.11	0.03	0.05	0.07	0.08	0.10	0.04	0.07	0.02	0.05	0.05	0.17		
Importance Rating		**7**	**14**	**8**	**2**	**13**	**10**	**6**	**4**	**3**	**12**	**5**	**15**	**9**	**11**	**1**		
Measurement Unit		lb	#	mm	#	N/A	Y/N	#	#:#	#:#	in	#:#	N/A	°	Y/N	N/A		
Benchmarking																		
Robotic (da Vinci)		N/A	N/A	5 & 8	6	N/A	yes	6	3:1 & 5:1	N/A	10 to15	1:3 or 1:5	N/A	180	Yes	EM		
Traditional		1.5	10 - 50	3 to 8	1 to 3	N/A	no	0	0	N/A	6 to 18	1:1	N/A	45 to 180	Yes	M		
Our design goal		<5	<30	5 & 8	>4	N/A	yes	>4	5:1 and 3:1	1:1	6 to 18	1:2	N/A	180	Yes	TBD		

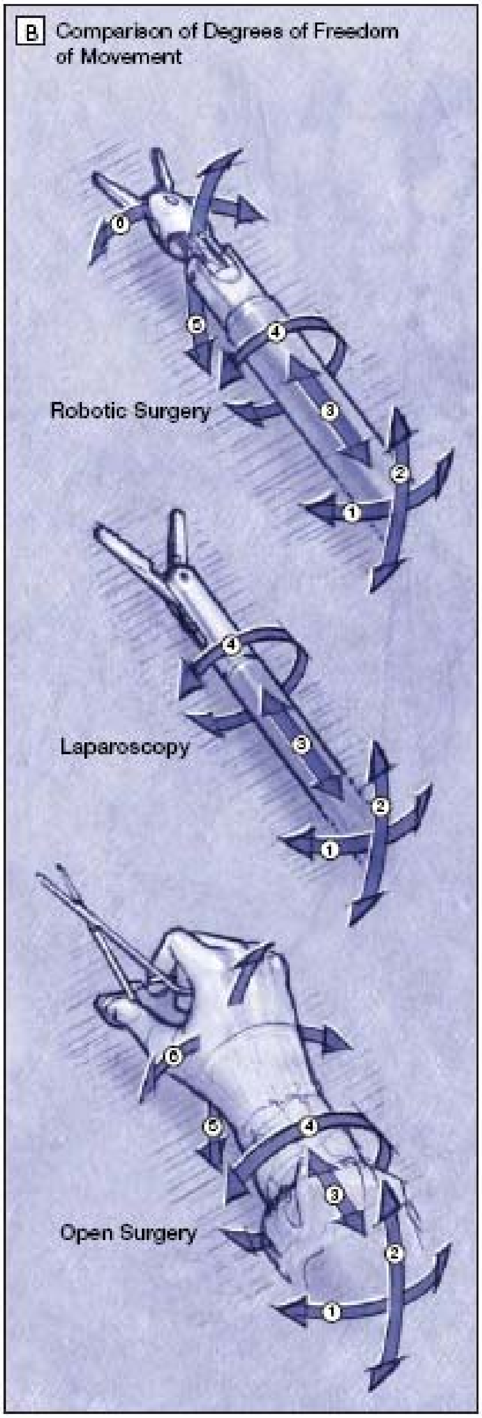
Key for correlation matrix:
9 => Strong Relationship
3 => Medium Relationship
1 => Small Relationship
(blank) => Not Related

***Weights for customer requirements are figured on a scale of 1 to 10**
(ten being most important)

APPENDIX B

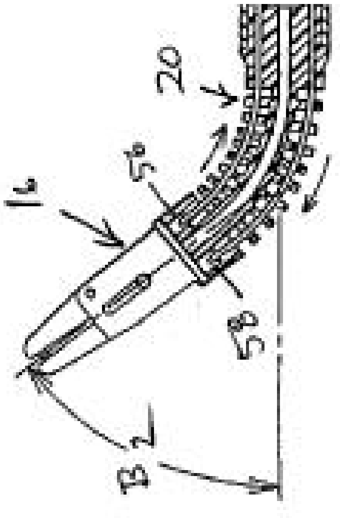
Week of :	**15-Jan**	**22-Jan**	**29-Jan**	**5-Feb**	**12-Feb**	**19-Feb**	**26-Feb**	**5-Mar**	**12-Mar**	**19-Mar**	**26-Mar**	**2-Apr**	**9-Apr**	**16-Apr**
Task/Due:														
Problem/Project definition (meet with sponsors)	■													
Budget meeting with Prof. Kota		■												
Design Review 1: Project definition, info search, engineering specs.		🟦												
Concept brainstorming/generation (consider compliant and traditional mech.)			■											
Evaluation of concepts				■										
Meeting with Jim Geiger and Prof. Kota				■										
Concept selection					■									
Report/ presentation preparation					■									
Design Review 2: Concept generation, evaluation, selection					🟦									
Final concept breakdown (system components)						■								
Scaling, determining dimensions, defining numerical requirements						■								
CAD : Dynamics (ADAMS), modeling (UG)						■	■	■						
Spring Break							🟥							
Integration of compliance review (advise: Kota, Awtar)								■						
Integrate necessary changes into design as the result of visualization								■						
Report/ presentation preparation									■					
Design Review 3: Engineering analysis and final design									🟦					
Decide on full-scale manufacturing or component									■					
Create manufacturing outline and budget									■					
Manufacture!									■	■	■			
Report/ presentation preparation											■			
Design Review 4: Alpha prototype review											🟦			
Design Expo													🟦	
Report/ presentation preparation												■	■	■
Final Report Due														🟦

APPENDIX C

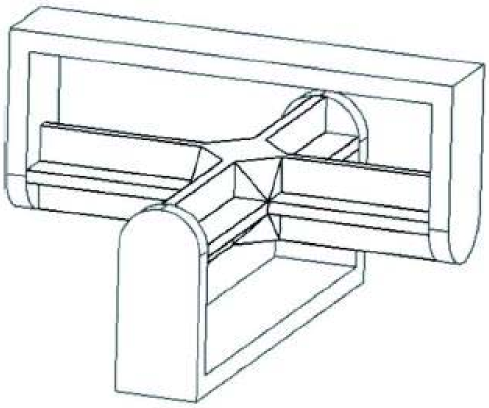

B
Comparison of Degrees of Freedom of Movement
6
5
4
Robotic Surgery
3
2
1
4
Laparoscopy
3
2
1
6
5
4
3
Open Surgery
2
1

APPENDIX D: Output Tool Tip

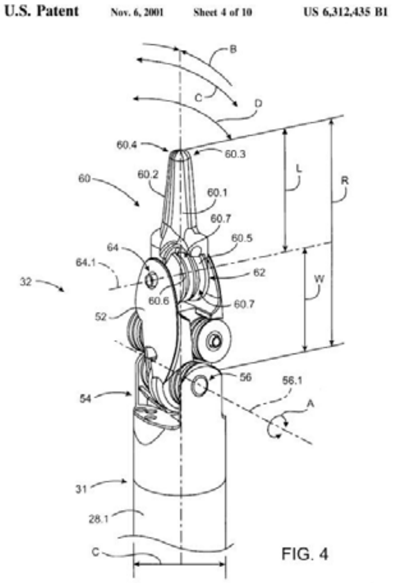
Compliant Disks [8]



Compliant U-Joint [6]

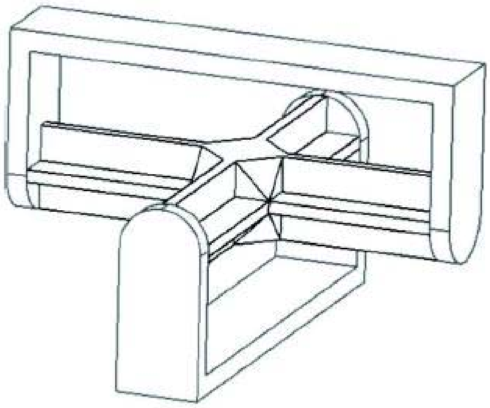


Pulley System [9]

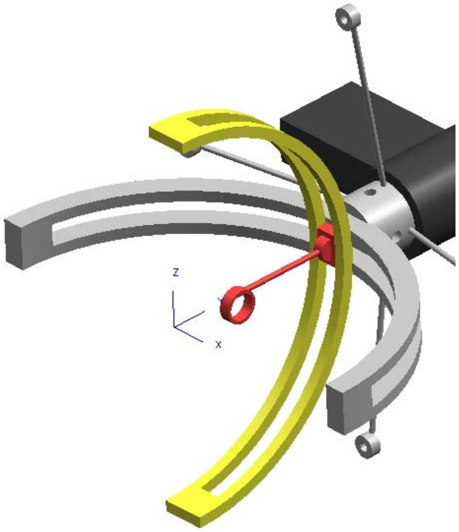


APPENDIX E: Input

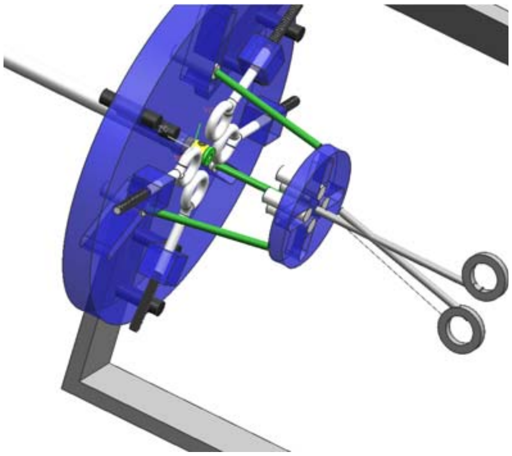
U-Joint [6]



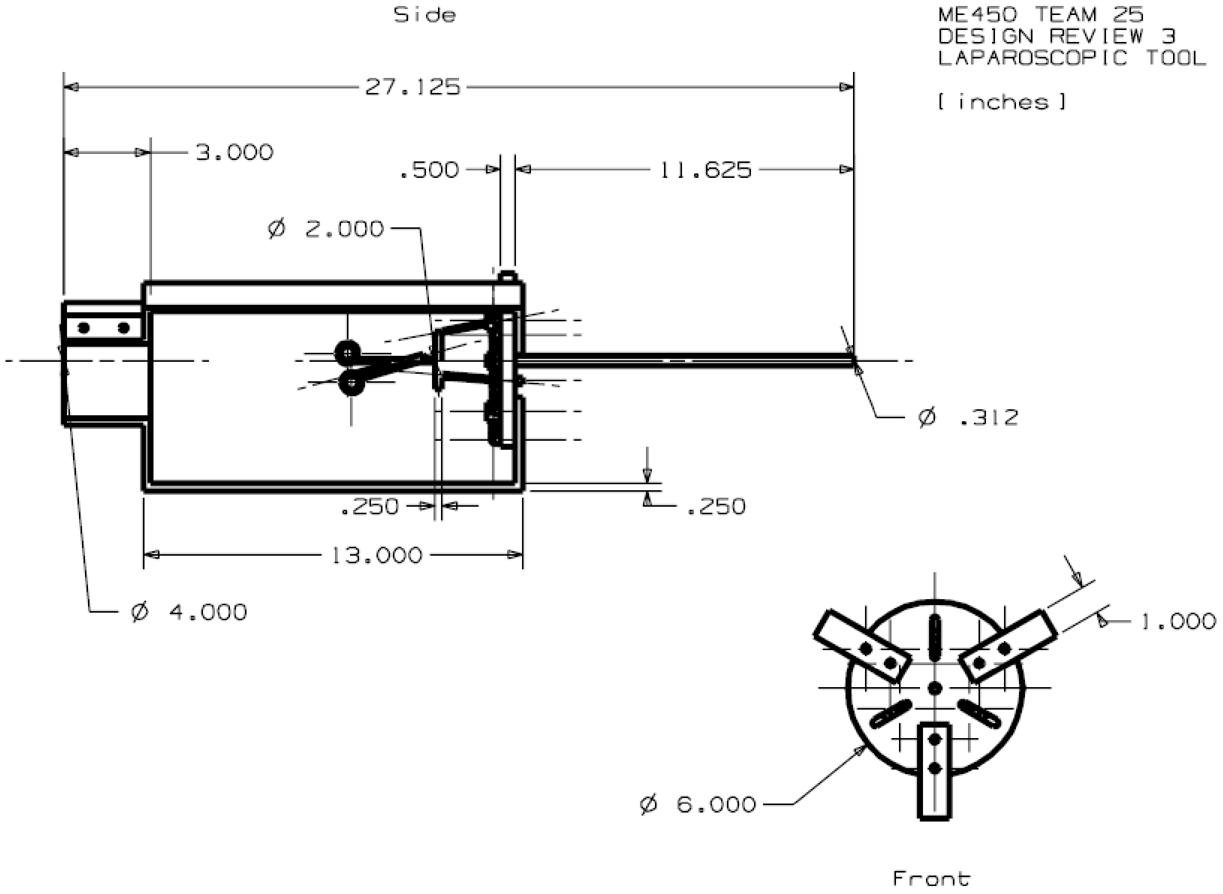
Series Slider



3-D Five Bar



APPENDIX F


ME450 TEAM 25
DESIGN REVIEW 3
LAPAROSCOPIC TOOL
[inches]
Side
27.125
3.000
.500
11.625
Ø 2.000
Ø .312
.250
.250
13.000
Ø 4.000
1.000
Ø 6.000
Front

Appendix G

Figure A

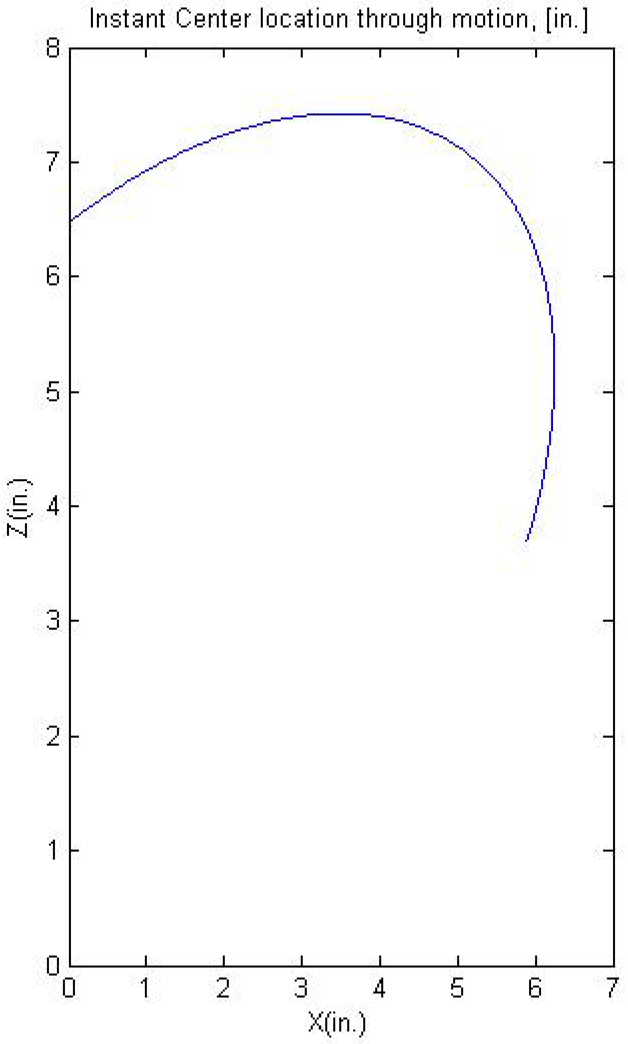


Figure B

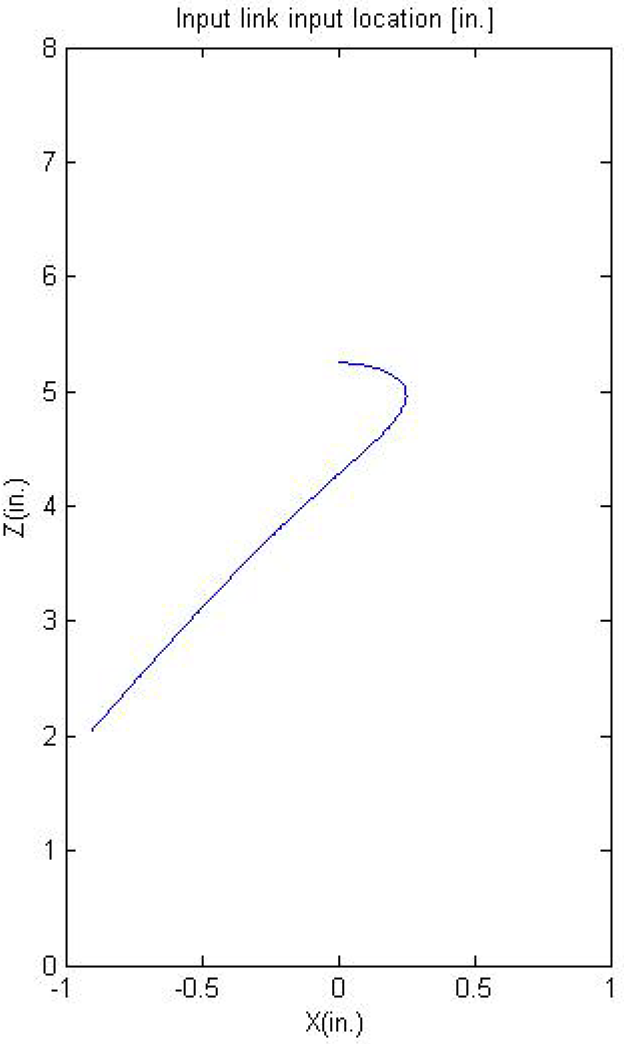


Figure C

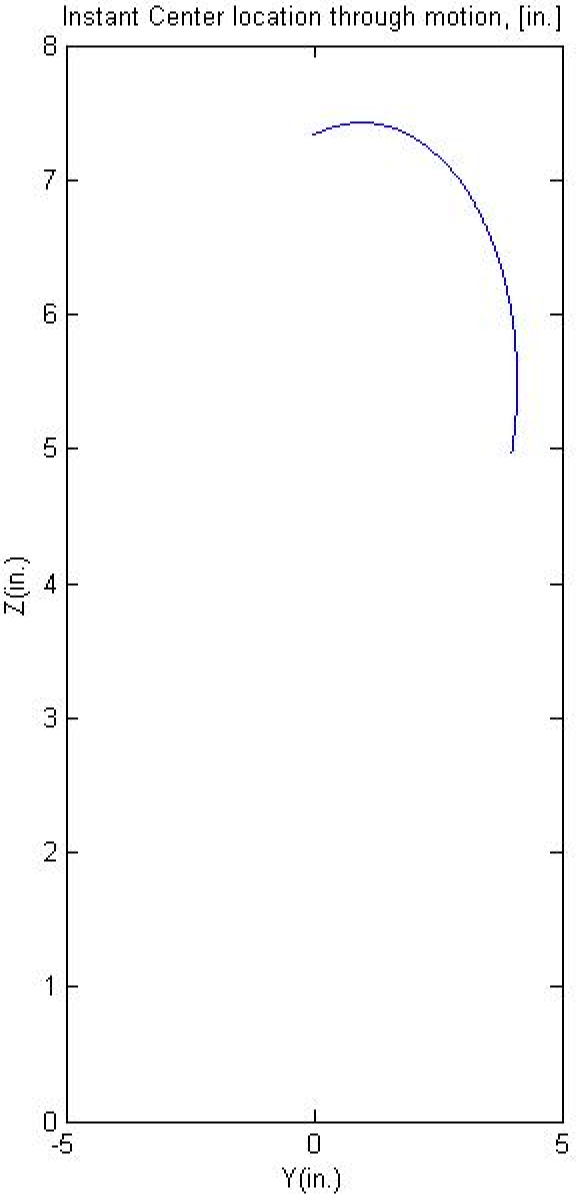


Figure D

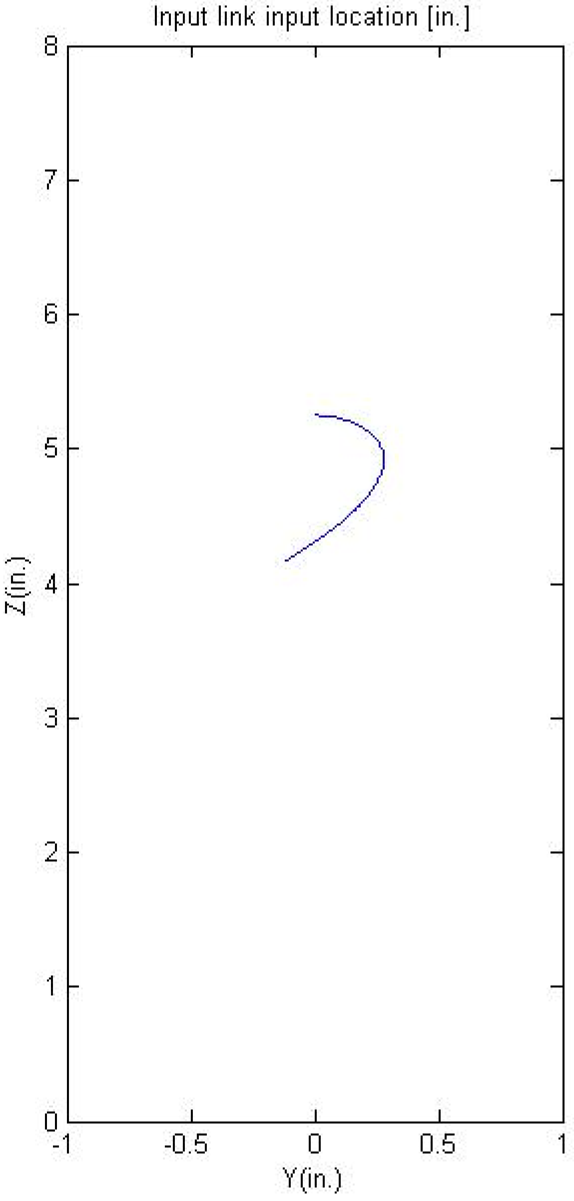


Figure E

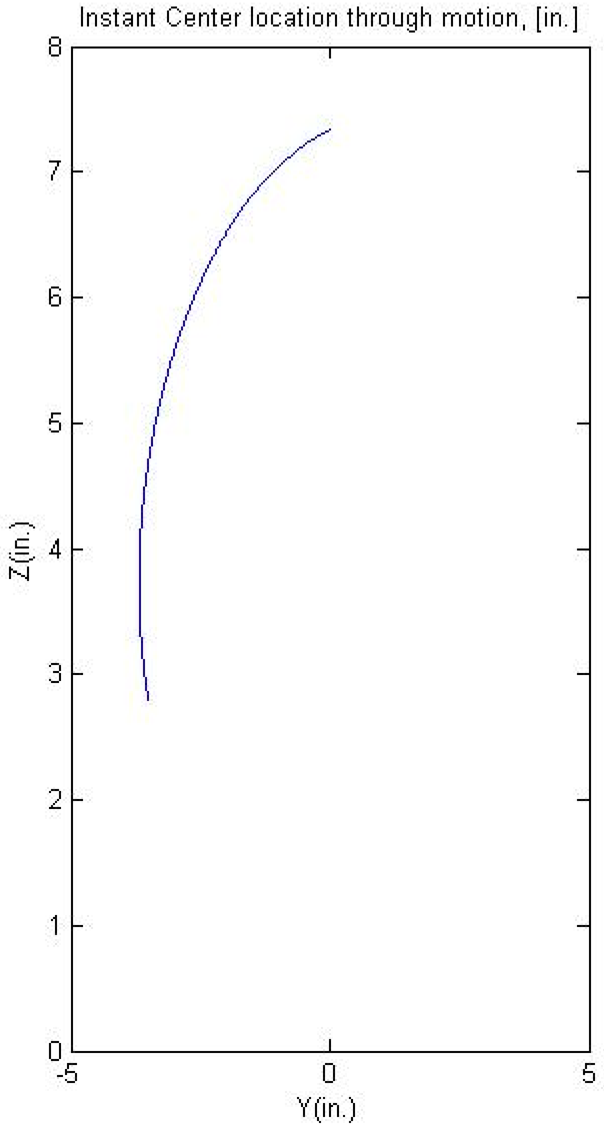
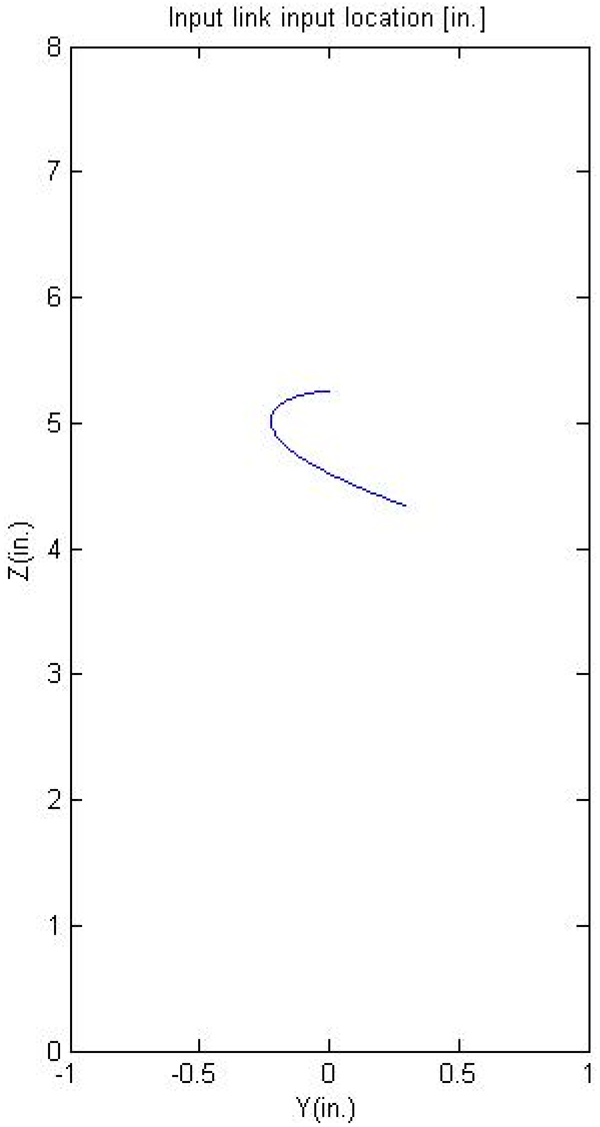


Figure F



Appendix H

Figure A

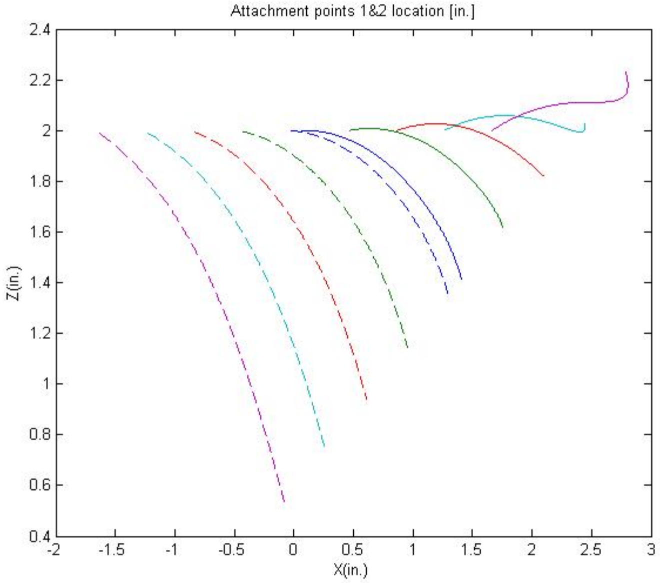


Figure B

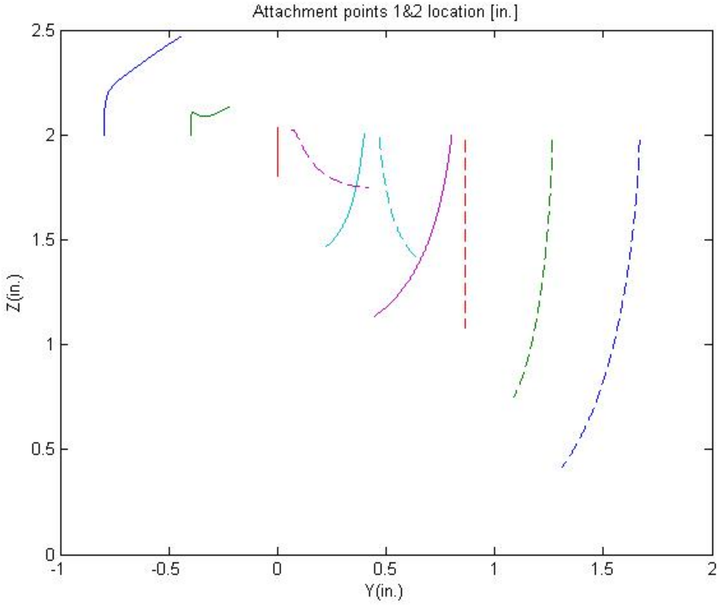


Figure C

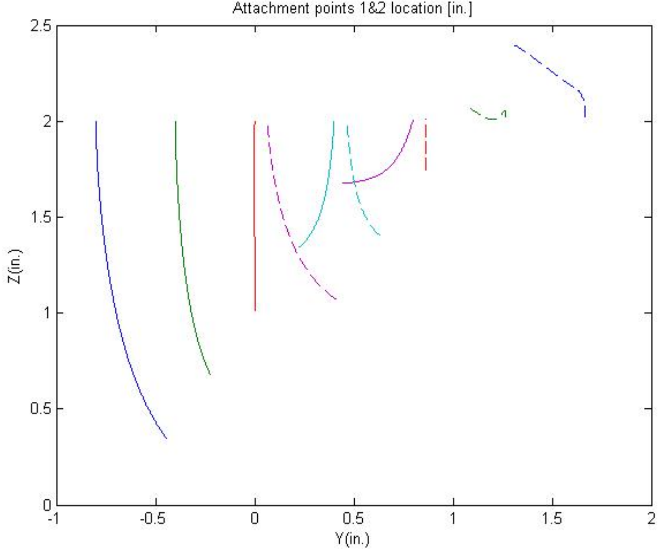
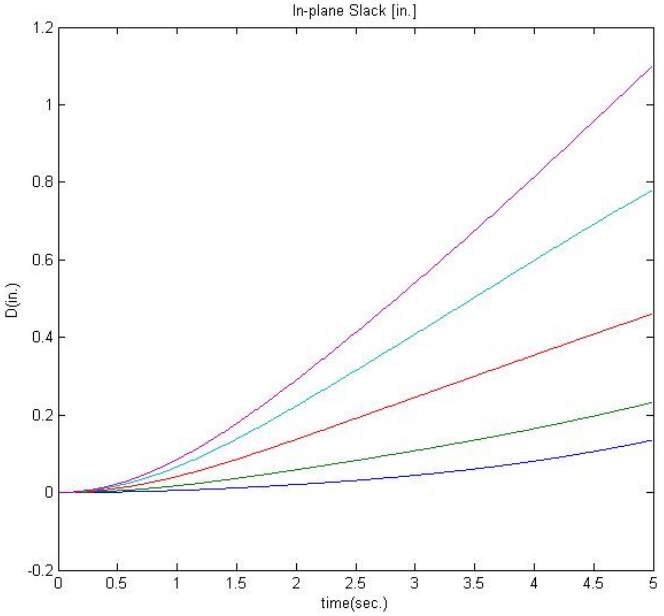


Figure D



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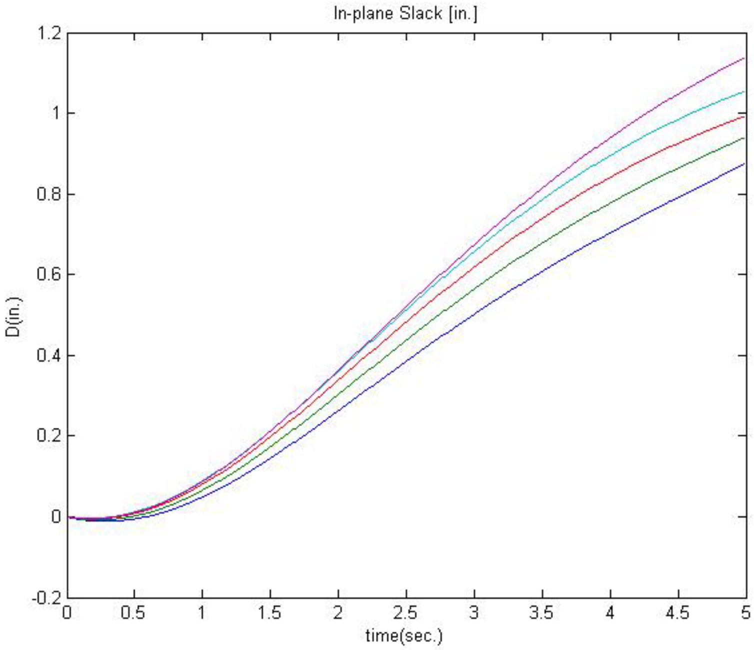


Figure F

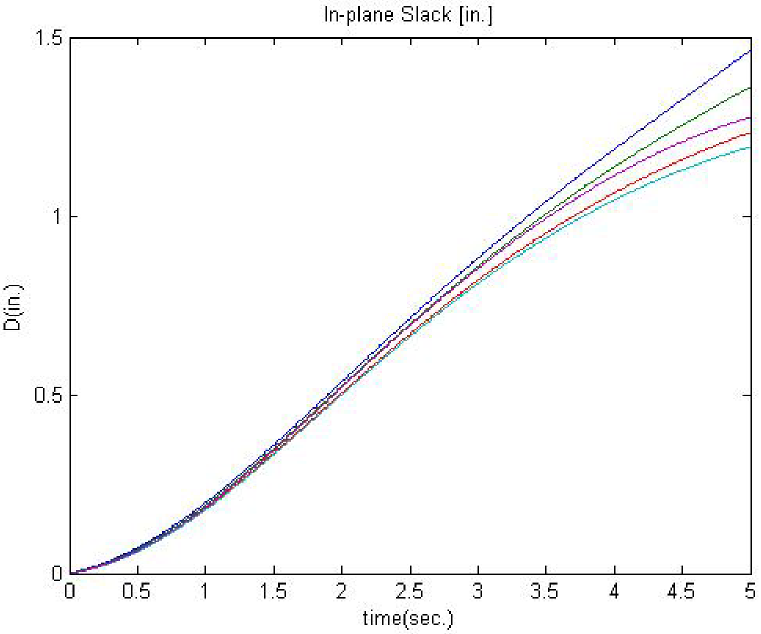


Figure G

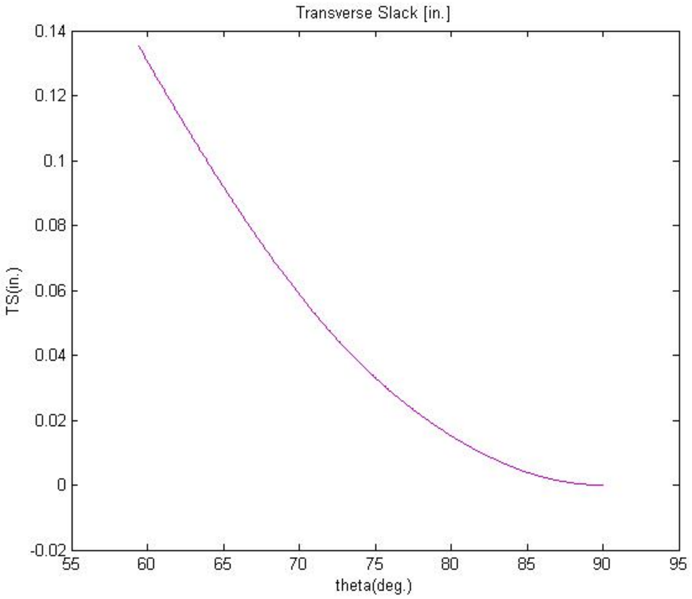


Figure H

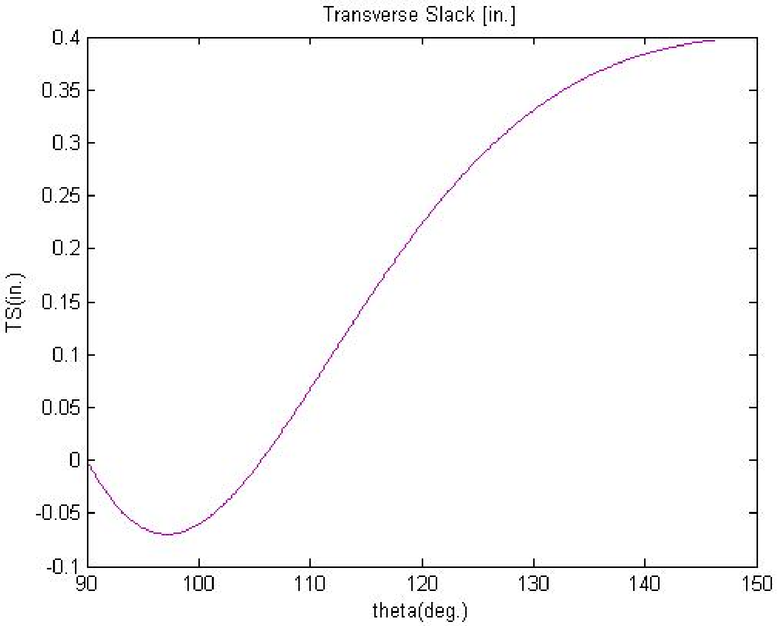


Figure I

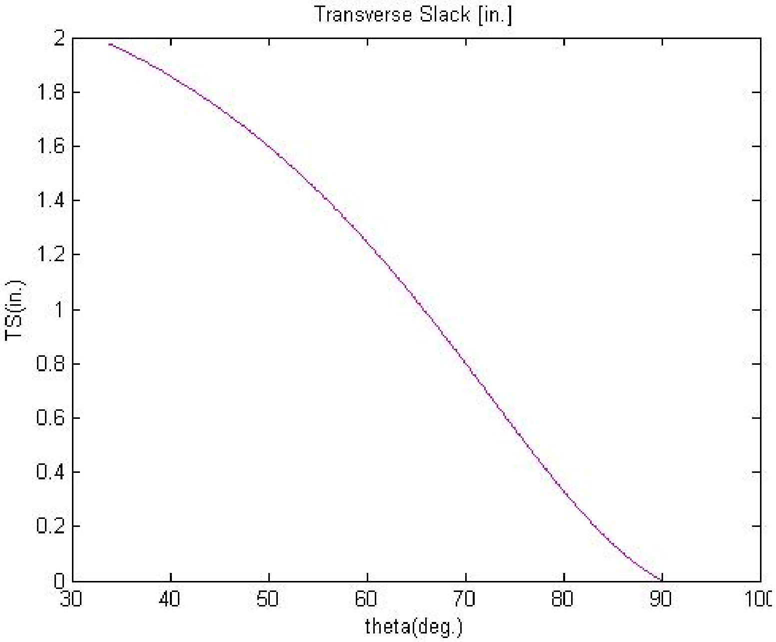


Figure J

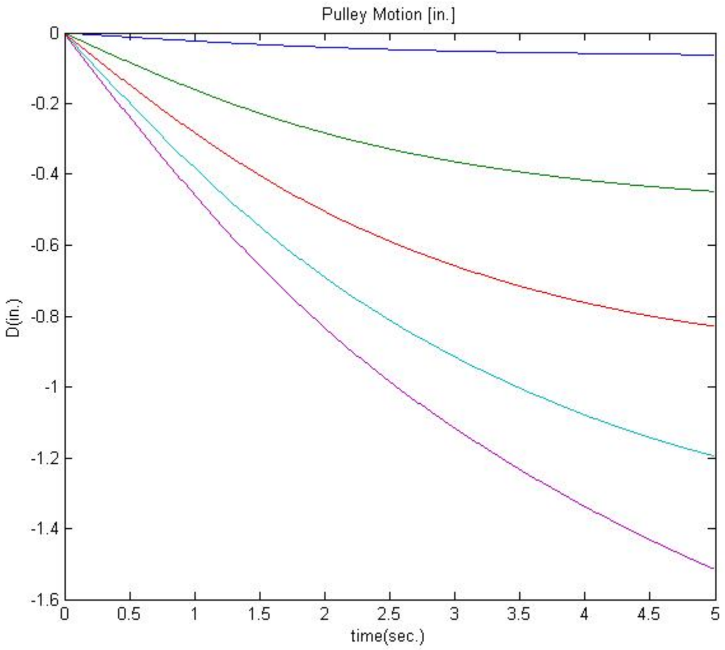


Figure K

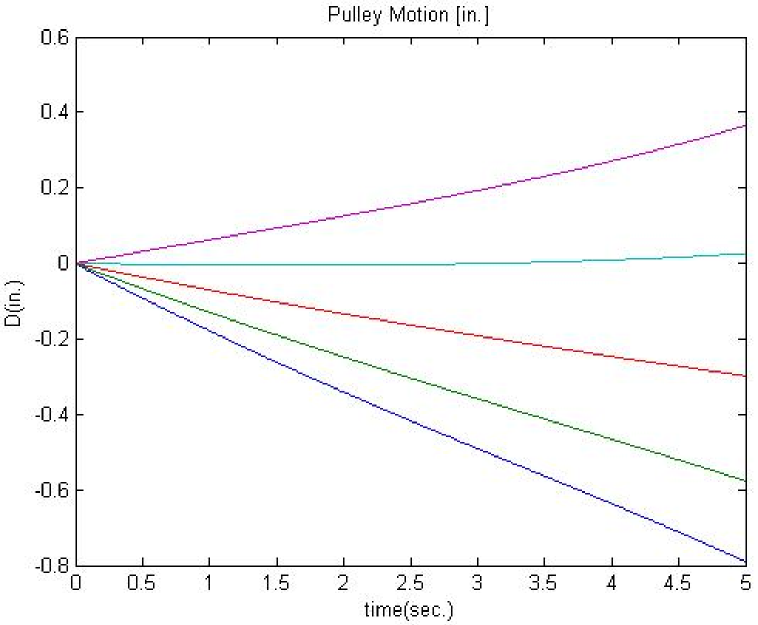
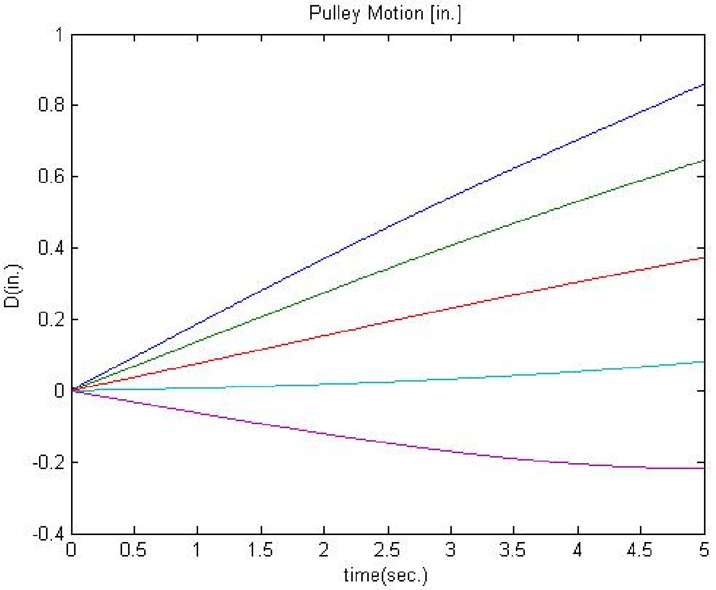


Figure L



Appendix I: FEA Analysis of output gripper

Figure A: This figure shows where the cable attachment point would apply force to the joint.

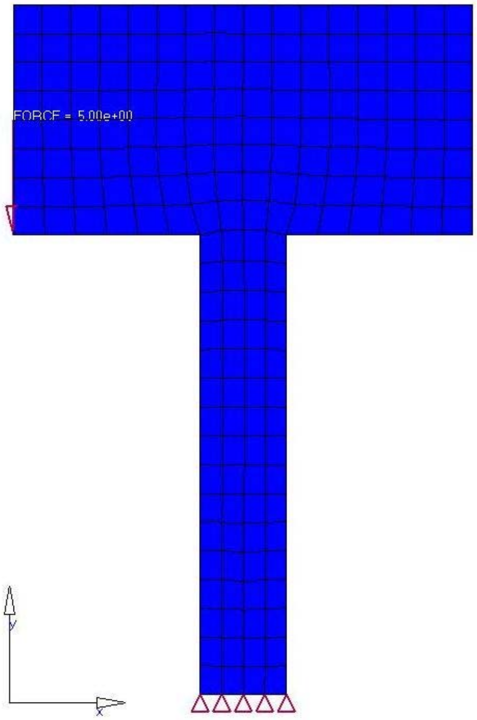


Figure B: This figure shows favorable angular displacement of the joint under 5N force.

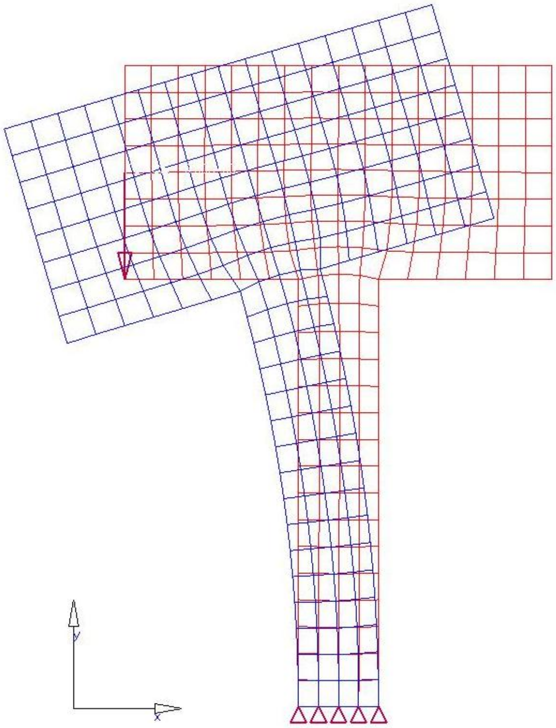


Figure C: This figure shows that the maximum stress concentrations of the compliant joint. The maximum stress on the joint is well below the yield strength of the material to be used.