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A ROBOTIC DEVICE FOR THREE-DIMENSIONAL MANIPULATION OVER THE INTERNET

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ABSTRACT

The PumaPaint site has been allowing users to create paintings remotely over the Internet since 1998. Although this site allows for some artistic creativity, the task is inherently two-dimensional and lacks any real manipulation capability by the remote user. On a similar theme but with much higher complexity, we are creating a robotic device that will allow true, three-dimensional manipulation by the remote user with an added capacity for force control and kinesthetic feedback. The robotic device will be a roughly anthropomorphic pair of limited degree-of-freedom mechanical hands arranged in mutual opposition. We are designing these hands by building parametric models using AutoDesk Inventor® and then fabricating the components in our sparsely equipped machine shop. This paper will preset the design concept and details of the modeling process, plus how this process is informed by our fabrication capacity. The paper will also present the partially completed robotic device and discuss remaining obstacles to completion.

INTRODUCTION

The PumaPaint Project [1,2,3,4,5] is an online robot that allows World Wide Web users to remotely create original artwork. The original site at Wilkes University [6] operated from June of 1998 to March of 2000 with approximately 25,000 unique-addressed machines downloading the interface to produce about 500 canvases. The newer site at Roger Williams University has been operational since August 2002 and has had about 10,000 users to date. However, this site is not without its limitations. Though users can create paintings by commanding the PumaPaint robot, this manipulation is essentially symbolic. The highest level of direct manipulation a user can exert on the robot is commanding the location of brush strokes.

PumaPaint is an experiment in "telepresence," that is, a remote representation, via electronic means, of your actual self. It is the ability to create change and react to changes in an extant world environment through electronic signals transmitted to and from the user. PumaPaint allows users to manipulate paintbrushes across a canvas space, by reacting to what they see through two different cameras. This is a form of telepresence, but a limited form indeed. We intend to create a system that operates at a higher level of telepresence. A level where users not only see their environment, but feel it as well. By creating a pressure sensitive robotic manipulator open to web use, and allowing users to interact with a physical environment, we hope to achieve this higher level of telepresence.

PROJECT CONCEPT

Our goal is to give users the ability to both see and "touch" the remote environment. The ability to touch will take the form of digital touch sensor data. Therefore, our challenge was to conceive a pressure sensitive robotic manipulator that would interact with a pressure reactive media, and deliver pressure states to a user. The manipulator would also have to be something that would exhibit a familiar motion, i.e. it would not confuse a user outright. A desirable feature of PumaPaint is that just about everyone knows how a paintbrush works, and has seen one before. Our new robotic manipulator would need this same innate familiarity.

One of the most interesting aspects of PumaPaint is its artistic nature. The paintings users create are not only an experiment in telepresence, but also an experiment in painting. With this in mind, we decided that this new web robot should allow users to model clay. Clay is an ideal pressure reactive substance, it is an art medium, and it is familiar to most people.

It seemed evident that the manipulator should resemble a pair of human hands. Not only would mechanical hands be innately familiar to users, they would also serve as an effective means of gathering pressure data. Data will be collected through pressure-sensitive shells, placed on areas where the hands will come into contact with clay. This will allow users to "touch" the clay, viewing and reacting to the pressure data.

The potential result will be something novel in online robotics. A more complete form of telepresence, where users have active control over the robotic manipulator and can react to what they see and "feel."

THE MECHANICAL DESIGN PROCESS

Our design process consists of two phases, beginning with parametric computer modeling. These models are then tested and redesigned using computer animation. We used AutoDesk Inventor® to create schematic layouts, and these layouts serve as the blueprints for fabrication, our second phase.

AutoDesk Inventor® Model

The primary design consideration for the hands is anthropomorphic movement. Our design concept calls for a set of two "hands," symmetric to each other (Fig. 1). Each of these hands consists of a "palm" mounted with one major "index finger" with one degree of freedom, one minor "index finger" also with one degree of freedom, and one "thumb" with two degrees of freedom. We began our design process with the major index finger using the seven bar linkage system discussed in [7]. This paper describes a theoretical system of bars and joints that accurately mimics the measured movement of a human index finger. The challenge was to develop this into a full mechanical design. We utilized AutoDesk Inventor® to virtually assemble the bar linkage system by constructing and parametrically constraining generic bar elements. Using the animation capabilities of the program, we fine-tuned the movement of the system until a satisfactory motion had been achieved.

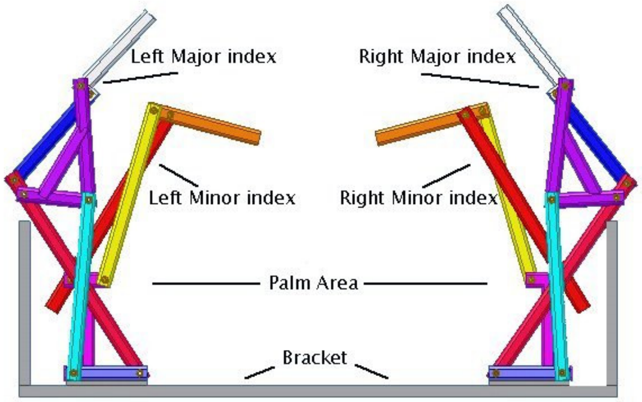


Figure 1. Robotic hand substructure

The linkage of the major index finger drove the design of the minor index finger. We wanted the minor index finger to mimic the motion of the major index finger in the middle of its path. Also the minor index finger had to break out of synchronization with the major index finger when it was at the beginning and end of its motion path. This would better mimic the motion of the human hand. We parametrically modeled a four bar linkage system, once again using the animation capabilities of Inventor® to refine the dimensions of this system until the desired motion was achieved. This involved mounting both linkage systems on a virtual "bracket" and animating them simultaneously.

After the desired movement was achieved, the next task was to "flesh out" the two designs with correctly sized materials and mechanical components. During this process we experimented with many different bar shapes and joint types. All components were parametrically modeled in Inventor®, and assembled as dictated by our generic bar linkage systems. Parametric modeling enabled us to easily alter component size and shape. We then "tested" these designs using animation.

Our materials selection process was dictated by our limited budget, and fabrication capabilities. All materials chosen for the fabrication of the robot had to be readily available, or easily fabricated. Therefore, we looked at online catalogs, salvaged parts from other devices, and visited the local hardware store before implementing our components in our computer model.

Our major design constraint was component interference in the motion. To lessen the risk for unintentional mechanical "hard" limits, we refined our designs to give sufficient clearance to all components. Concurrently, this dictated the size of the overall design. Once again, we "mounted" the designs on a virtual bracket to find the clearance they would need relative to each other. A mirror image duplicate model of each finger was mounted in opposition to its counterpart, and the assemblies were animated simultaneously. We used these observations on the design of the fingers, and also to design their final mounting position.

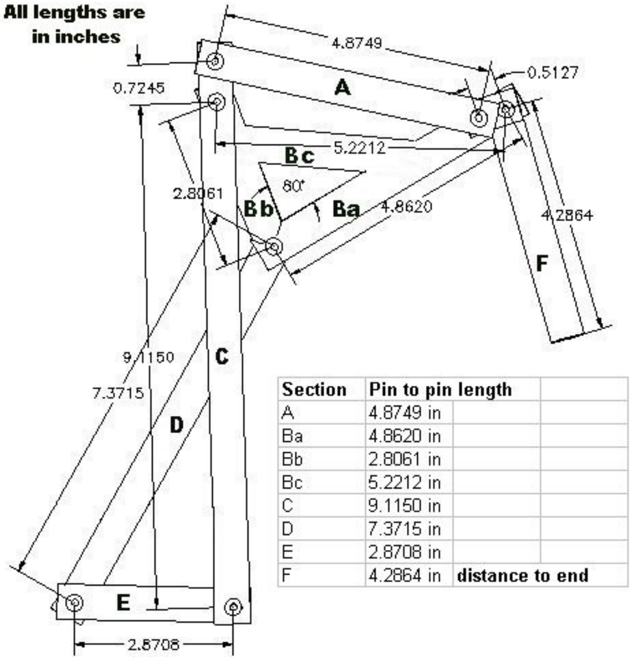
The most challenging aspect of the design was the joints. We needed to create a joint that exhibited smooth planar rotational motion, and was also strong enough to manipulate the clay. We knew that fabricating a component such as this would not yield satisfactory results; therefore we based the design on components bought from online catalogs. We experimented with these components in order to create an effective joint design.

After a period of testing and redesign, we achieved a satisfactorily "fleshed out" assembly of virtually modeled mechanical components for each of the index fingers. We used Inventor® to create detailed schematic layouts of each assembly part. The creation of these layouts began the primary fabrication process.

Fabrication Issues

The challenge of fabricating our designs lay in our fabrication capability, as well as the availability of materials. We have the most basic of machine tools at our disposal, so to accurately machine the parts for our assemblies we must follow a careful process for each tool. The tools we possess are: a miter saw with a metal cutting blade, a drill press, drill taps, various clamps and vices, and grinding and sanding equipment.

The first step in accurately machining our assemblies was to start with a simple design. When fabricating, the construction of each part had to then be broken down into steps simple enough to complete using our equipment. Indeed, our fabrication limitations would drive our design processes. We modeled each part using 5/8" square steel tubing. Steel tubing seemed an optimal choice because of its affordability, availability, and strength. Also, its hollow cross sectional shape makes it easy to cut accurately and to run wires.



Section	Pin to pin length		
A	4.8749 in		
Ba	4.8620 in		
Bb	2.8061 in		
Bc	5.2212 in		
C	9.1150 in		
D	7.3715 in		
E	2.8708 in		
F	4.2864 in	**distance to end**	

Figure 2. Major index finger schematic

We began the fabrication process with the major index finger (Fig. 3). There were two main sections to its completion; the first was the physical construction of each of the bar linkage components (Fig. 2). This entailed cutting and drilling steel tubing as specified by our design schematics. We cut the steel using the miter saw, setting up each cut as accurately as possible. Measurements were made and marked on the tubing; the material was then positioned and clamped securely in place. The cuts were then made slowly to avoid welding the metal and grinding and sanding cleaned any excess material. The same process was followed on angled cuts, with the modification of changing the angle of the saw blade. After cuts were made, we drilled holes. Again in this process, each piece had to be accurately marked, positioned, and securely clamped to the drill press. Each marked hole was punched, and, for larger sizes, some holes were predrilled with smaller bits. Each hole was drilled using machining oil to prevent wear on the bit, and to make the cut smoother.

After this preliminary fabrication was complete, some of these raw bar linkage components had to be assembled. This entailed joining some of the pieces with fixed connections. We chose welding for creating accurate and durable fixed connections with steel. However, we lacked confidence in our ability to weld with the needed accuracy. Our first attempts at creating a fixed connection involved securing the pieces together with steel bands screwed into holes tapped on each piece. Though the connections were strong, the method did not produce accurate parts. It also introduced a problem with interference between parts. We decided to seek outside assistance, and had the parts welded by CAM, a precision fabrication company in Bristol, RI. We made special fixtures to hold the pieces precisely in place, so the welder was only required to run a nice "bead" down the weld joint. The parts they produced were very accurate. However, after this difficulty with fixed connections, we incorporated them less in future part designs.

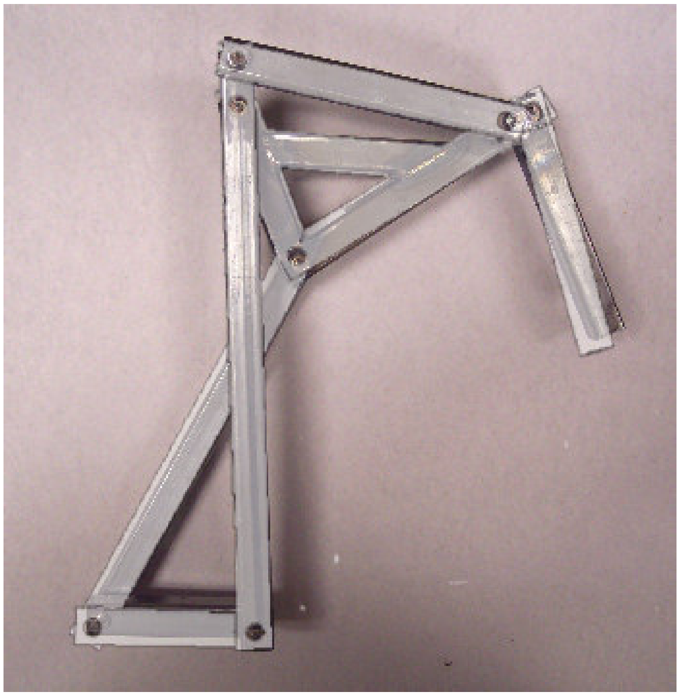
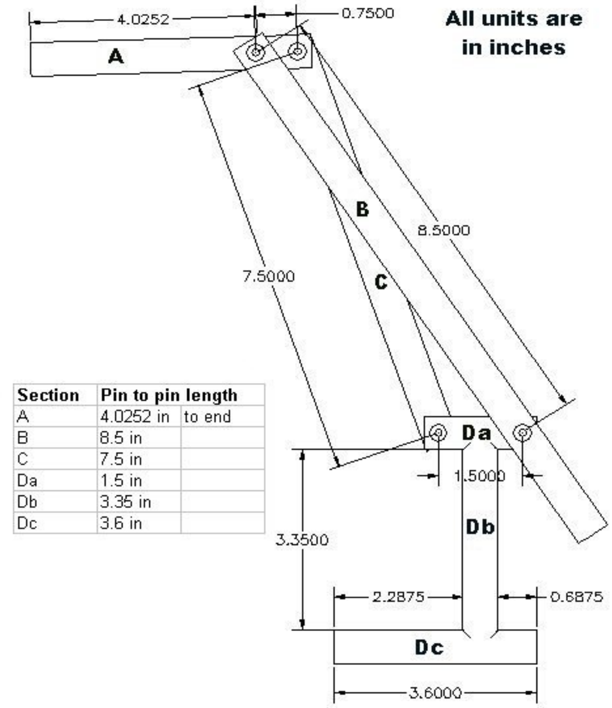


Figure 3. Fabricated major index finger

With the fundamental bar linkage pieces complete, the next phase was to assemble these parts with mechanical components. Given our inability to create precise mechanical components from scratch, we opted to design our joints using standard mechanical components found in catalogs. Our final joint design incorporates both our strengths and weaknesses. We used our ability to drill accurate holes as the foundation of our design. Each joint must only be allowed the freedom to rotate about an axis perpendicular to itself, with no other movement, in order to ensure maximum strength and stability. To control motion in the x and y (see Fig. 6) directions we inserted bronze flanged bearings into each hole. The bearings had a 1/8" inner diameter in which we inserted a cylindrical steel rod. To control movement in the z direction, each end of the rod was notched at the edge of the flanged bearing, and fitted with a retaining clip. Inserting the sections of rod into the drill press, and lathing them with a vised cutting bit created the notches. After all parts were assembled using the rod-based joint, the major index finger was tested. It exhibited the same motion seen in our computer animations.

Our fabrication of the first two (major) index fingers has already inspired changes in the design of other components, in order to expedite their fabrication processes. In the design of the minor index finger, we opted for a four bar linkage system instead of seven. We also designed it with less fixed connections, and no angled cuts. We hope that these changes will allow for an easier fabrication process. Currently, the minor index finger has been fully "fleshed out" and tested using animation. The next step will be to fabricate a pair of minor index fingers, and test their accuracy against both the computer model, and the already fabricated major index fingers.



Section	Pin to pin length	
A	4.0252 in	to end
B	8.5 in	
C	7.5 in	
Da	1.5 in	
Db	3.35 in	
Dc	3.6 in	

Figure 4. Minor index finger schematic

Sensors

A sensory system is essential to the task that this robot will perform. However, we have to balance the amount of control we give the user with the amount of space we have and our limited fabrication ability. The sensory system has the primary purpose of telling the user if the robot is in contact with the clay, and if so how much pressure is it contacting with. A relatively easy to implement sensor system that can accomplish this has three states: one for the "off" state (not touching clay), one for low pressure touching, and one for high pressure touching.

It could be argued that a higher number of sensory states could give a user an even greater control. However, this adds complexity to the design, and it is uncertain that this complexity is warranted. We are ultimately limited in our ability to communicate pressure information by the capacity of the communication channel and the ability to display haptic information in the presence of communication time delay. Even with haptic display, (e.g. a phantom device at the user station) the time delay in communication limits the haptic communication to symbolic presentation. It makes little sense to design more pressure sensing instrumentation into the hands than can be effectively communicated to the remote user. Therefore, three pressure states seemed to be a balance between enabling control and transmission of contact data. We recognize that this is an open research issue and we may find more pressure states are necessary for useful haptic remote control.

THE ROBOTIC MANIPULATOR

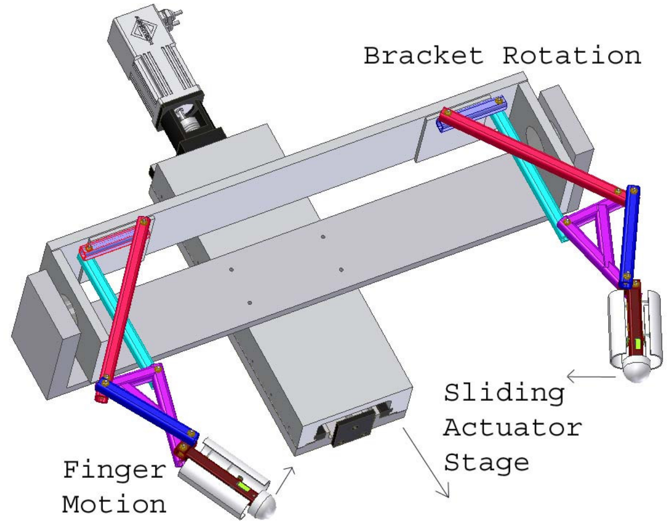


Figure 5. Mounted Assembly

Each of the two "hands" will consist of three "fingers" each with one degree of freedom: a major index finger, a minor index finger, and a thumb (yet to be designed). These fingers will be driven by a motor system currently in design. We have dissected a Rhino robot for its motors and gearing and will be using these components for actuation. The entire hand assembly will be attached to a linear positioning stage to supply forward and backward movement. Fig. 1 shows the complete parametric Inventor® model, with the four designed fingers on a bracket in opposition. Fig. 3 shows the fabricated portion of this design, the two major index fingers, mounted in opposition on a bracket. Fig. 5 shows an Inventor® simulation of the currently fabricated major index fingers in their mounted positions on a linear actuator stage. Note that the device displayed has a total of ten degrees of freedom, as are indicated in the figure. Below is a breakdown of the mechanical design for each of the two designed fingers, and for our conceived sensory system.

Major Index Finger

The major index finger will be positioned at the top end of the "palm" area. There are six bar sections connected by fourteen joints, the length of each section is noted in Fig. 2. Each bar has been modeled using 5/8" square steel tubing. This tubing has a filleted hollow square cross section with an inner wall length of ½". Two of the sections are made up of welded bar sections (sections F and B) the angles at which they are welded are noted in Fig. 2. Each joint (Fig. 6) is assembled by drilling a ¼"diameter hole in the bar section. A flanged bearing is inserted into each hole at both sides of the bar section. Each bearing has a 1/8" inner diameter, an outer diameter of ¼", and a flange width of 1/16". A 1/8" steel rod is then inserted through all bearings making up the joint, and the joint rotates smoothly around the rod.

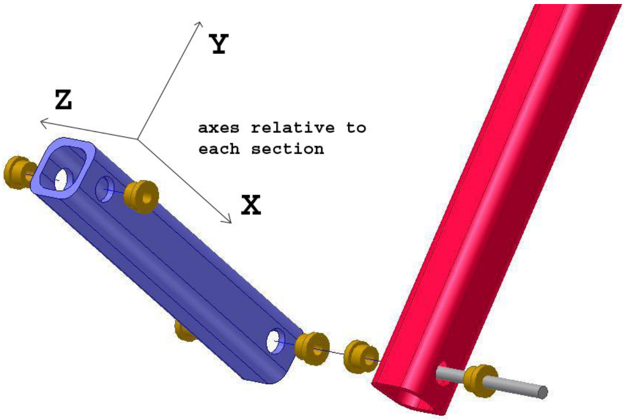


Figure 6. Exploded joint view

The overall motion this mechanical assembly exhibits is similar to that of a human index finger as you can see in Fig. 7. The opaque image represents the initial position of the assembly. The images get less opaque towards the end of the motion direction ending with another opaque image. This motion is exhibited when the base bar section (section E) is fixed. A pair of these fingers has been fabricated, shown mounted on the bracket in Fig. 5. The motion of the fabricated mechanical assembly and the motion exhibited by the Inventor® model match very well.

Minor Index finger

The minor index finger will be mounted just below the major index finger in the “palm” area. This finger is designed using the same 5/8” steel stock as the major index finger, and the joints were implemented in the same fashion (Fig. 6). This assembly is also a one-degree of freedom linkage system, consisting of four bar sections connected by eight joints. The lengths of each bar section and welding angles are displayed in Fig. 4. This finger was designed to move in the exact pattern as the major index finger, when they are both in the middle section of their motion. Fig. 8 shows the motion of the minor index finger alone. It too exhibits a similar motion to a human finger. When this motion is compared to the motion of the major index finger (Fig. 7), you can see that the two assemblies experience alignment in the middle section of their motion paths, breaking away from each other at the start and end of these paths. One of the goals of our design process was to make the hands as anthropomorphic as possible. By allowing the fingers to align and create a surface, we hoped to create a similarity to the motion of an actual human hand. The fabrication of this finger is part of the next step in our fabrication process.

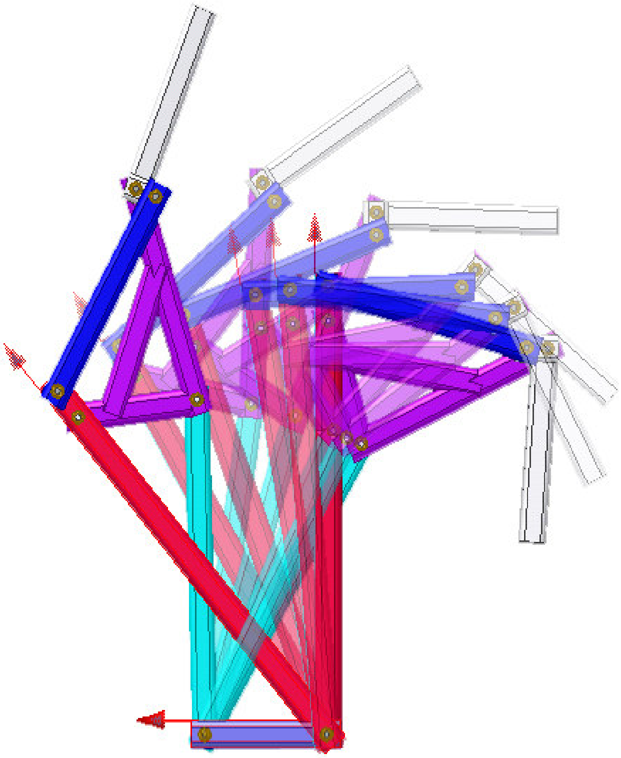


Figure 7. Range of motion of major index finger

Sensory System

The preliminary design of the tip sensor is based on the human Distal Interphalangeal joint. It consists of a hemispherical PVC tip, with a protruding cylinder. This cylinder is pinned into the sides of the 5/8” square steel tubing to provide a point of rotation. Protruding from the cylinder is a long trigger. This trigger activates sensors that are strategically positioned within the tip (Fig. 9). Optical sensors harvested from a copying machine were used in the design of the tip sensor. The tip pivots 10° in either direction, and resistance against motion will be provided by a rubber medium embedded within the walls of the steel tubing.

The finger side sensor strategy is based on sensor shells. We will implement this system with optical sensors. Each part in the assembly will be encased in a semi-circular section of PVC piping cut longitudinally. These semicircular cylinders of PVC will be secured to a piece aluminum channel affixed around the steel tubing section of each part. A spring-like foam pad will be inserted under each piece of channel. This will allow each PVC section to move up and down the y-axis relative to each part, but, because of the foam pad, return to a zero position when no pressure is applied. Two optical sensors will be installed within the steel tubing, and a tab attached to the square channel will trigger each as the PVC is pushed down. This means as pressure is applied the first optical sensor is triggered, when more pressure is applied the second is triggered. This sensory system will yield the desired three sensory states, and will be implemented on all areas of the fingers that will potentially come into contact with clay.

SUMMARY AND CONCLUSIONS

Our goal is to create an interface through which a human being can experience a heightened form of telepresence where they can see and also react to what they feel. By creating a pair of clay molding mechanical hands with pressure sensitivity we hope to achieve this goal.

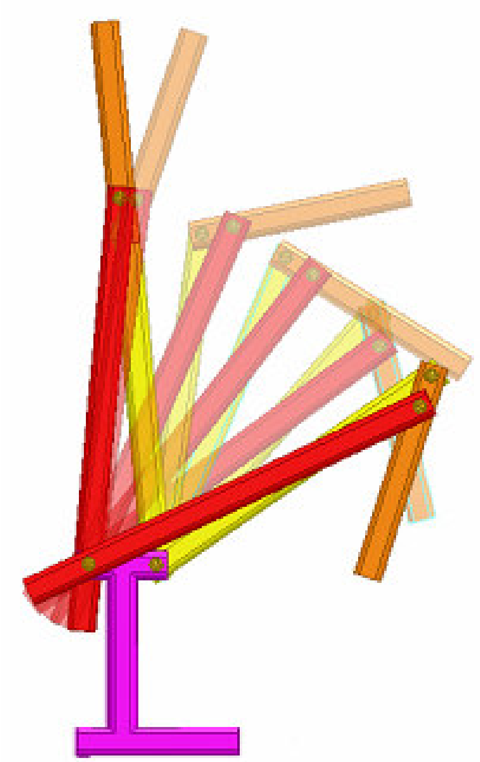


Figure 8. Range of motion of minor index finger

Status and Future Work

At this point we have completed preliminary design and fabrication of the robotic manipulator. This includes fabrication of the two major index fingers and mounting them on a bracket. Designs for the two lesser index fingers, and for the basic sensory structure have also been completed. The actuator table and brackets have also been modeled and tested in Inventor®.

We now have to continue the design and fabrication process. The next step in our fabrication will be to construct the two lesser index fingers. This will be followed by continued design of the sensory system, design of the "thumb", and design of the drive and motor control systems. All of which will then need to be fabricated and assembled.

Lessons Learned

We were able to make smoothly rotating joints easily, however we had difficultly giving them lateral strength. Our designs and fabrications were turning up with slop in the motion. This must be overcome in order to create an effective manipulator, so our solution to this was implementing retaining clips.

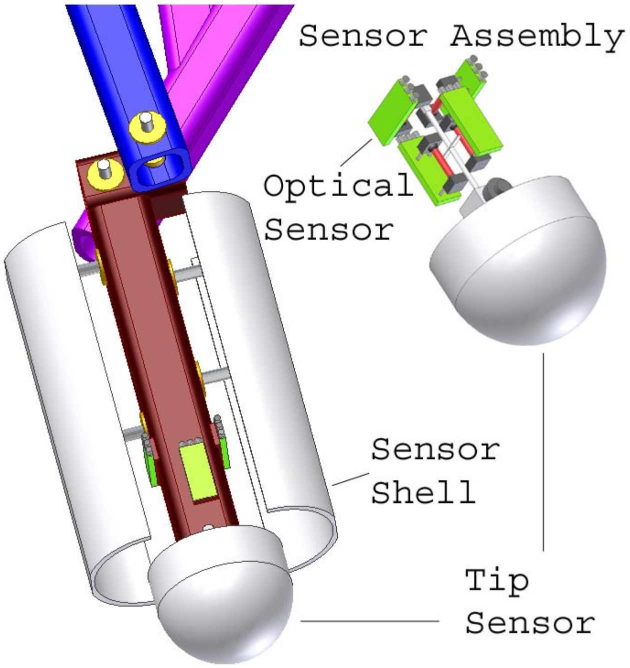


Figure 9. Pressure sensing instrumentation

We also learned about the usefulness of Mechanical AutoDesk Inventor®. Using it allowed us to thoroughly test our designs before they were constructed, and it saved us considerable time and effort. The program also has animation tools that will prove useful when creating presentations.

Finally, during our design and fabrication we realized the importance of incorporating fabrication and assembly into the design. Not only did our deigns have to be something relatively easy to fabricate; they also had to be easy to assemble. It important to take into account that assembly is a complex process, and it will take less time to assemble if we take the appropriate steps in our design.

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