

The University of Michigan

**Micro Capillary Tube Grinding**

**Team 14**

**Winter 2023**

**MECHENG 450 Design Project**

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Andrew Smith

Cohen Bryant

Sparsh Thapa Chhetri

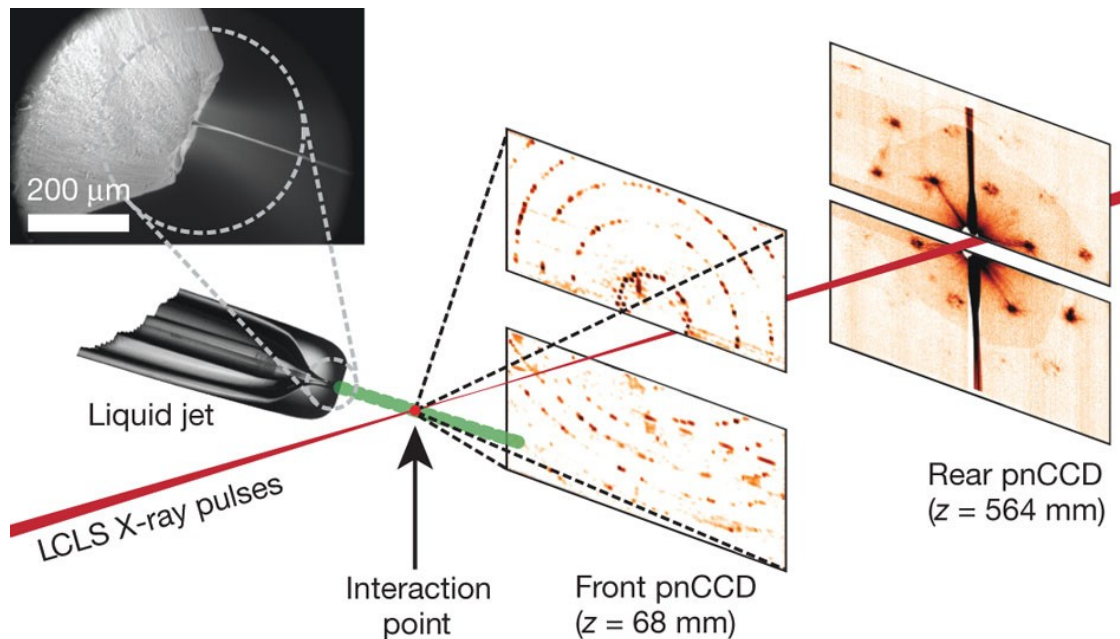
Devon Freeland

## ABSTRACT

SLAC (Stanford Linear Accelerator Center) performs experiments on nanocrystallography by exposing X-ray beams to fluids with nanocrystals. The fluid is delivered using glass capillaries which need to be ground and polished in-house in order to meet the requirements needed for the experiments. Currently, the process is labor intensive, specialized (being limited to 3-5 people equipped to perform the process), and slow. As a result, SLAC is seeking an improved and automated method for the preparation of these tubes which will reduce preparation time. Specifically to develop a robot/mechatronic system to be used in the capillary grinding process to interface with a Ted Pella XP-8 grinder and the SLAC designed capillary mount.

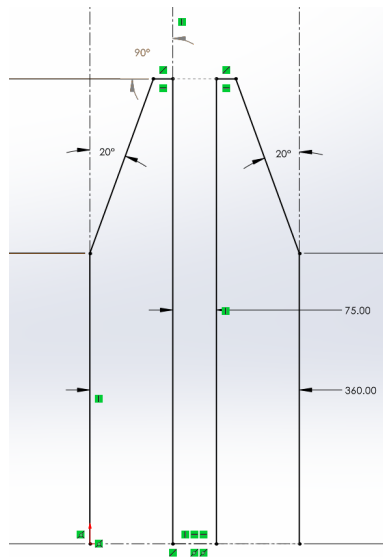
## PROJECT INTRODUCTION:

Dr. Mark Hunter and Dr. Moises Smart, the sponsors for this project, are lead scientist and staff engineer respectively and are active researchers in SLAC National Accelerator Laboratory. With their focus on Nanocrystallography, a crucial aspect of their research focuses on the structural analysis of nanocrystals. As shown below, The structure of nanocrystals is determined by propelling liquid filled with nanocrystals through a capillary tube and intercepting the fluid with X-ray beams in order to map the structure. The following figure shows the description of one such experiment with the involvement of one of our sponsors, Dr. Mark Hunter, where a liquid jet propels as a continuous stream through a capillary tube in order to determine the structure of protein with a femtosecond X-ray being used as the interacting beam.

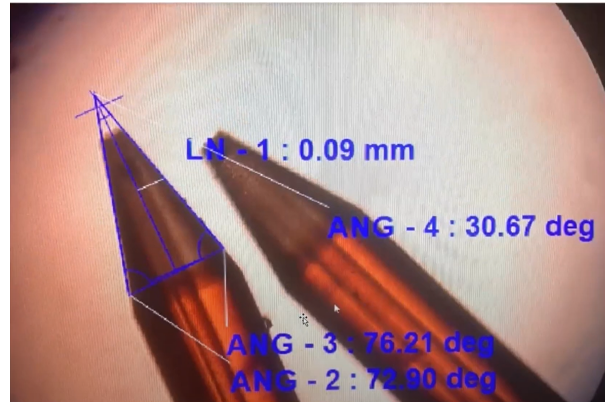


**Figure 1**, “Femtosecond X-ray protein nanocrystallography”[3] article by Dr. Mark Hunter that displays the use of the capillary tube in one of his experiments.

The experiment requires capillary tubes to be ground and polished symmetrically and with a flat tip. This is required as without a flattened tip, the meniscus that is formed during flow will cause the liquid jet to not flow parallel to the tube. The following figures show the expected dimensions of the capillary tube after grinding along with an example of a tip that has been ground properly.



**Figure 2a**, 22 degrees is one of the tolerable measurements for the capillary tube; the figure also shows the necessary symmetry along the center of the cylinder.

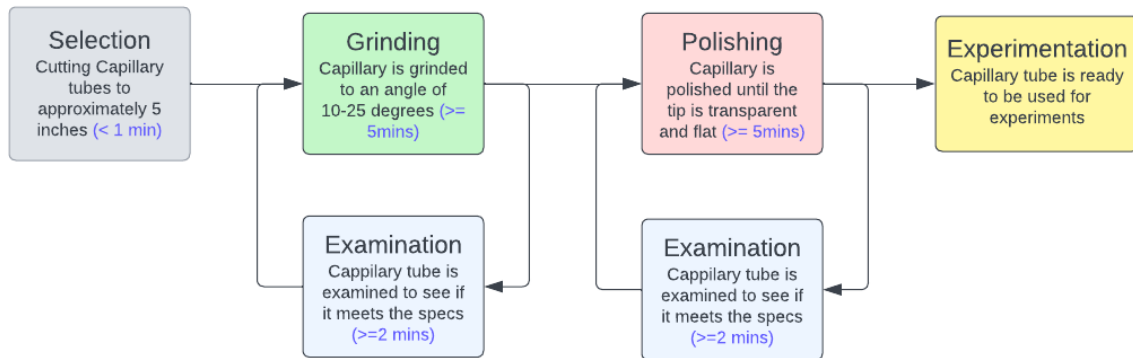


**Figure 2b**. This is an example of the measurement process as used by the engineers. A special note is that due to the resolution of the microscope the points chosen have to be arbitrary.<sup>5</sup>

The dimensional requirements for the tubes are achieved through a two step process of a grinding stage, followed by a polishing stage. Currently, only lab technicians Mason Landrum and Stella are able to perform the grinding and polishing to the standards needed for the experiment. Additionally, such ground capillary tubes are not mass manufactured because of their niche demand, and the precision inherent to the small length scales requires the manual production of the tubes. With the labs' current setup, the process takes 20 minutes per person with varying degrees of success. Note that the length scale of the capillary tubes is on the order of 100 $\mu$ m, with typical outer diameters of 360 $\mu$ m, and typical inner diameters of 75 $\mu$ m.

The process is split up into multiple steps of grinding, polishing, and examining and can be illustrated with the block diagram below. The process was obtained from Mason Landrum and Stella who are constantly working on the process. The current grinding process itself consists of a spinning diamond grit wheel rotating at a user specified RPM, to which the capillary tube is lowered into via a precision Z-Stage with a hand wheel. The angle of attack and sweep rate across this horizontal grinding disk is also user specifiable. Lastly, the capillary tube is allowed to spin in its holder, leading to a conical grind.

The following block diagram illustrates the various steps and times in the current grinding process.



**Figure 3.** Shows the process from the selection to the final point of being used in an experiment. Additionally, the rough estimate for the time spent on each process is also included. However, it is important to note that since this process is manual, there are variations during each iteration that lead to longer times and also the development of tubes that can not be used and need to be scrapped.

The grinding process has two feedback loops where the tubes need to be examined after or while being ground and polished in order to ensure standards needed for the tube. Both the grinding and polishing process have to be monitored manually, and is done with a Q-scope (a high magnification camera) attached to the grinder. In order to measure the final product, we will disconnect the q-scope from the grinding arm and place it into an inspection mount. Using the Q-scope software, we are able to measure the angles, as shown in Figure 5.



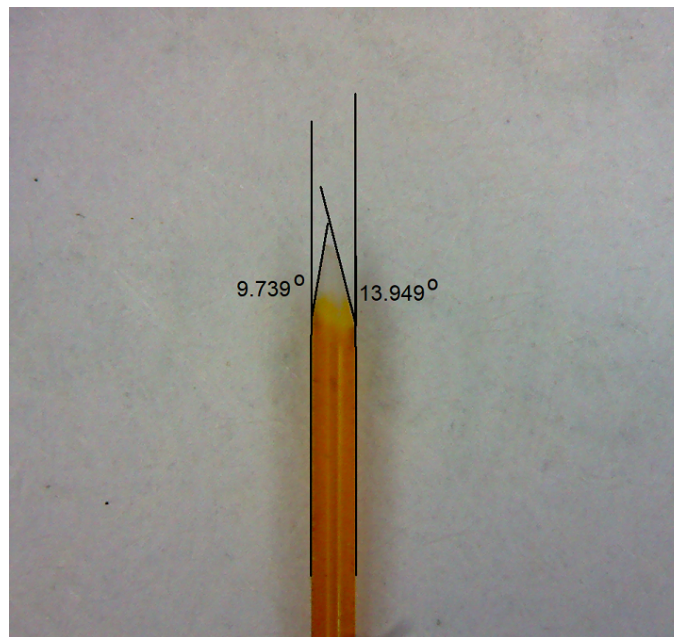
**Figure 4a:** Capillary Tube before grinding



**Figure 4b:** Capillary tube mid-grinding

It is important to note, that the tubes are supplied by the manufacturer (MOLEX) with an epoxy coating providing them structural rigidity, and as the grinding process commences the underlying glass tube becomes more visible.

As a result, the prime motivation for this project is the hope of optimizing efficiency and therefore allowing the researchers at SLAC and the LCLS (Linac Coherent Light Source) to prepare experiments at a higher rate, while also improving sample delivery quality.



**Figure 5:** This figure shows the measurement process for the angles that we will implement. The tube measured was ground by hand, leading to poor axis symmetry and angles that do not fall within the acceptable range.

The major objectives and goals of this project are to improve the efficiency of the micro-capillary tube grinding process, via the engineering specifications and goals laid out in a later section.

A successful project outcome would be characterized by measurable and trackable improvement in both the preparation time and final product quality to the sponsor, while also adhering to the necessary engineering standard and expectations for environmental conservation. This could be achieved by reducing waste during the process, as our team hopes to reduce the amount of discarded capillary tubes. Our main contact at SLAC, Mason Landrum, has spent significant time on this project to improve the grinding process, along with another technician, Stella. They have worked to design an improved capillary tube holder that rotates the capillary tube removing procession from the grinding setup which was the cause of non-symmetrical ends of the capillary.

Despite the improvements by Mason and Stella, the process still requires extensive manual labor and intensive focus on the process, which at the moment can only be completed by Mason and Stella themselves. If they desired to move this preparation to another member of their team, a steep learning curve would necessarily take precious time. Furthermore, while the solutions produced by Mason and Stella have improved the quality of the capillary tubes, they are still far off of their desired success rate, and significantly distant from their target time of preparing one tube. They currently achieve approximately 50% success, and it takes 20 minutes, and they want to reach approximately 70% success in 15 minutes, as we will discuss in our Requirements and Specifications.

With respect to the concern of whether or not that this project had already been solved, and whether our team had simply not found a pre-existing solution; having had discussions with our sponsors about the project, our team asked whether or not similar solutions to their problem existed in labs of their colleagues, and therefore had the possibility to already have been solved. Their response was that their specific use case was relatively far from typical, and therefore necessitated the use of in-house preparation of these capillary tubes. Furthermore, the most similar work to the project we are trying to accomplish comes from the ULTRAPOL Fiberlab System which is currently being used alongside the Ted Pella XP8 grinder. The following labeled figures show the currently used grinding setups employed by the lab.



**Figure 6a:** Ultrapol Fiberlab grinding system



**Figure 6b:** Ted Pella grinding system

The ULTRAPOL Fiberlab System is modular, with one of the modules, the chisel tip module [9], allowing for grinding of the desired angle. The chisel tip module is an attachment that attaches to the ULTRAPOL grinder and allows for a sharp angle in only one axis. However, with multiple investments towards that module from the Lab team, they found it to be inadequate for their purposes, along with it suffering multiple issues as it isn't designed explicitly for the application it is currently being used in. Some of the issues come from the deflection of the capillary tube, or the inability of the system to spin the tube properly as it is being ground. Additionally, the chisel tip module does not allow for the flat tip required on the forward most face of the capillary, which is paramount for their experiments.

With respect to our sources of information, most of the information was gathered during our meeting with the sponsors, where we were provided with the current methods being used along with the efforts they have expended in order to increase the efficiency of the process. We also have collected information from external literature sources such as the engineering standards for this field, and the current industry standard practices for micro-grinding, which is discussed in a later section. Lastly, during our initial meeting with our sponsors as well as the technical staff for the SLAC laboratory, Raymond Sierra was able to give precise detail of the current system function, key features, and desired outcomes.

Due to this being a project that interacts with a disc-grinder the standards addressing motor-operated tools will be used throughout the project in order to maintain production standards. The specific engineering standard our group has selected is:

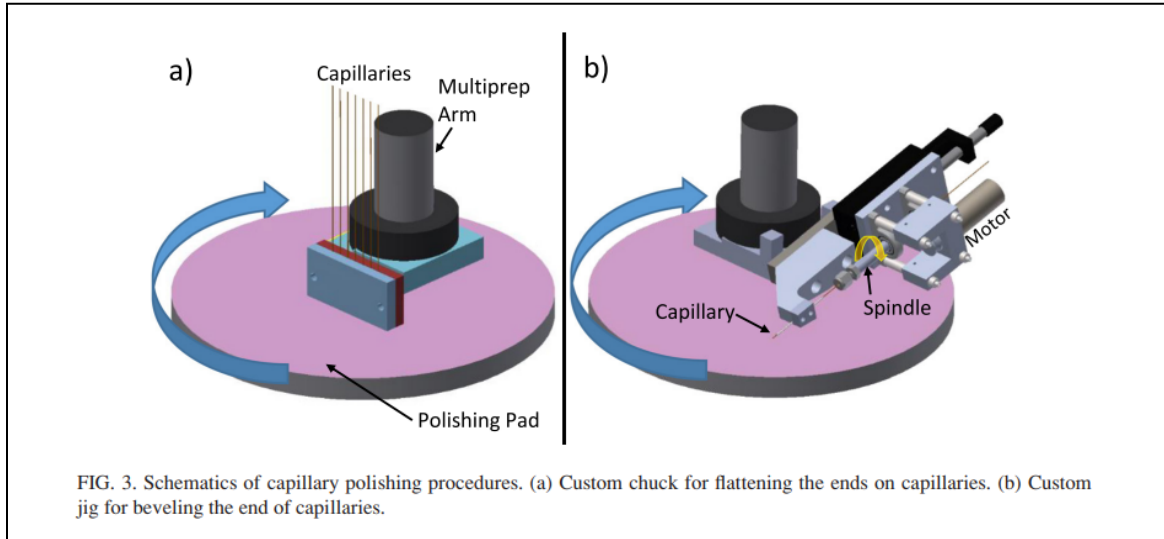
22/30450411 DC BS EN IEC 62841-2-3 AMD1.

Electric motor-operated hand-held tools, transportable tools and lawn and garden machinery. Safety. Part 2-3. Particular requirements for hand-held grinders, disc-type polishers and disc-type sanders.

This standard will be followed throughout the design process in order to ensure that the project conforms to a testable and verifiable methodology, specifically we will be using this standard to ensure safe operation by the technicians who will be using it, such as compliance with pinch hazards and electrical components and terminals. With this in mind, the following sections will detail how we approach our problem, including preliminary analysis.

## BENCHMARKING:

From what we have seen, other labs use a manual process for grinding/polishing, similar to SLAC. These processes generally require 2 people working on it at all times, and from what our sponsors have told us, the competitors' processes take a similar amount of time to their own (approximately 20 minutes).



**Figure 7:** Competitor Polishing Methods from Cornell University [4]

In the figure above, we can see a similar process to the one we are creating. One difference is that the process we are being asked to create will not involve the step shown in the figure where the ends are flattened. However, we may consider making our arm be able to accommodate multiple arms, similar to this, allowing for a design similar to this to be used in the future. Outside of that difference, this configuration is something that we will look at in our design process as a possible source of inspiration while ensuring that we are not legally violating any patent law when designing our engineering solution. One thing that this product is missing is a way to view the capillary as it is being polished. Due to the small size of these capillaries, it cannot be inspected without magnification, so not having that would make it very difficult to view progress.

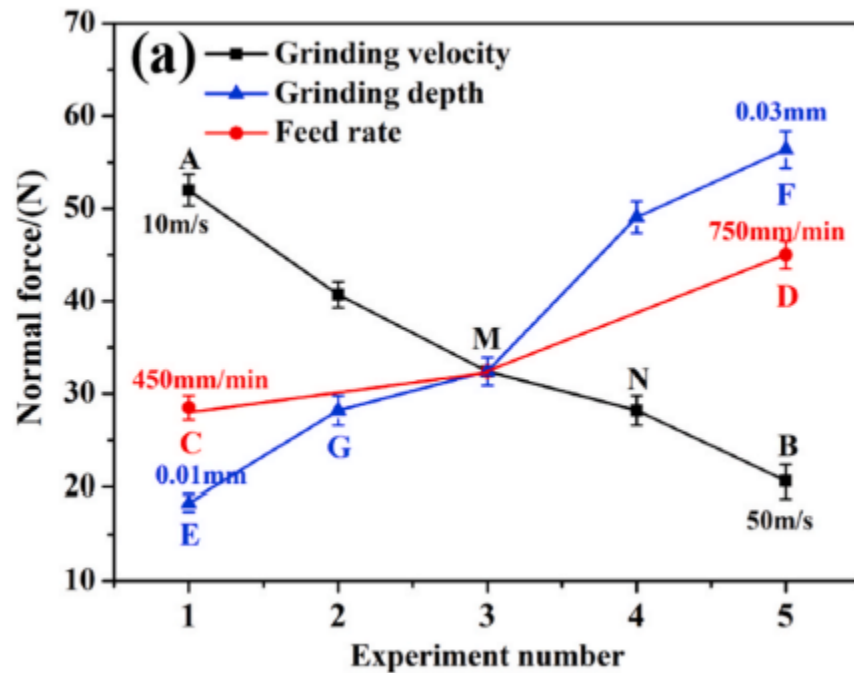
As we conducted our interview with the sponsors and technicians at SLAC, we attempted to determine what was most important to them. We learned that the most important aspects to them are that it must be faster than the current process, while only having one person supervising. This is important because it will open up a technician to work on something where they can have more of an impact on the research. Additionally, the requirements were cross checked with our sponsor Mason Landrum, alongside the project description sent to us in order to ensure that their requirements were met and that it was clear that between the parties involved.

From the requirements we were able to generate from our interview and research, we created a list of engineering specifications in order to achieve those goals. In order to create this list, we discussed what would be needed with our sponsors in order to quantify the level of precision. As we continue research into different concepts for this project, we may find there are other specifications that we must achieve for our project to be successful. In order to verify that what we create is satisfactory, we made each of our specifications quantifiable and testable, as well as what we believe to be achievable.



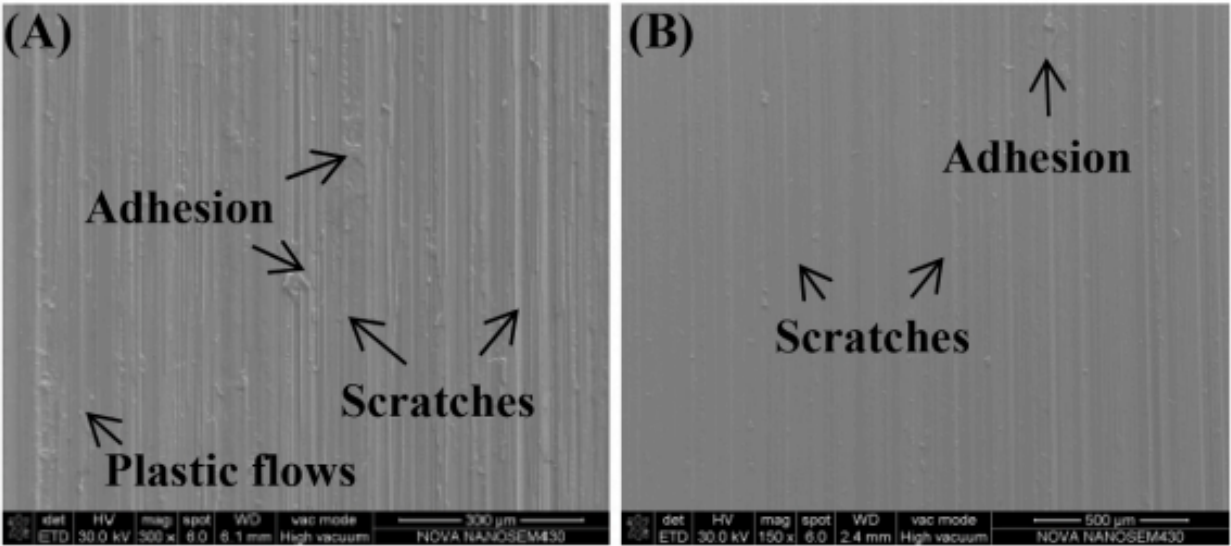
## FACTORS IMPORTANT TO CAPILLARY TUBE GRINDING

Research was conducted in order to determine the forces and factors that are important for grinding materials using a grinding wheel as a material removal method. A group of researchers already conducted the research relevant to our project. Their work was published in the October 2020 issue of Vacuum.<sup>9</sup> The research was peer reviewed and published with the help of laboratory research conducted in Beijing.



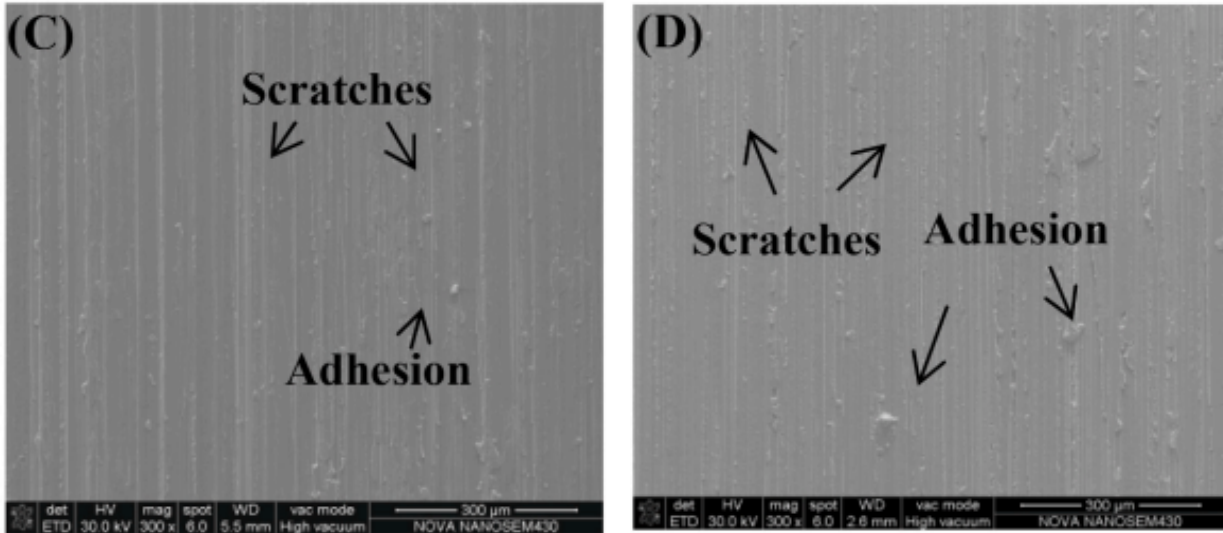
**Figure 8:** Factors affecting the Normal Force

The first relevant section of the study focused on normal force exerted on the material being worked. The research concluded that the normal force contributes significantly to the material removal rate – which we can intuitively understand. In Figure 8 above we can see that as the grinding velocity increases, that is to say the relative motion between the grinding disc and the worked material, the normal force will decrease. This is illustrated in the figure above by the black line. The blue line shows the relationship for the grinding depth, commonly referred to as the depth of cut and in this case the grit of the paper used. They found that as the grit of the paper is increased the normal force acting on the material being worked will also increase. The third line, which is colored red, shows the relationship between the feed rate and the normal force. In this case the feed rate is how quickly the material is being pressed down onto the grinding wheel. We can see that as the feed rate is increased the normal force also increases. In summary the material removal rate will increase with larger grit sized paper, a larger contact arc (which was mentioned in the research, but not shown in the figure above.), and an increased feed rate. The material removal rate will decrease as the grinding velocity goes up. Their research also investigated how grinding velocity, feed rate, and depth of cut will affect the surface quality of the worked material.



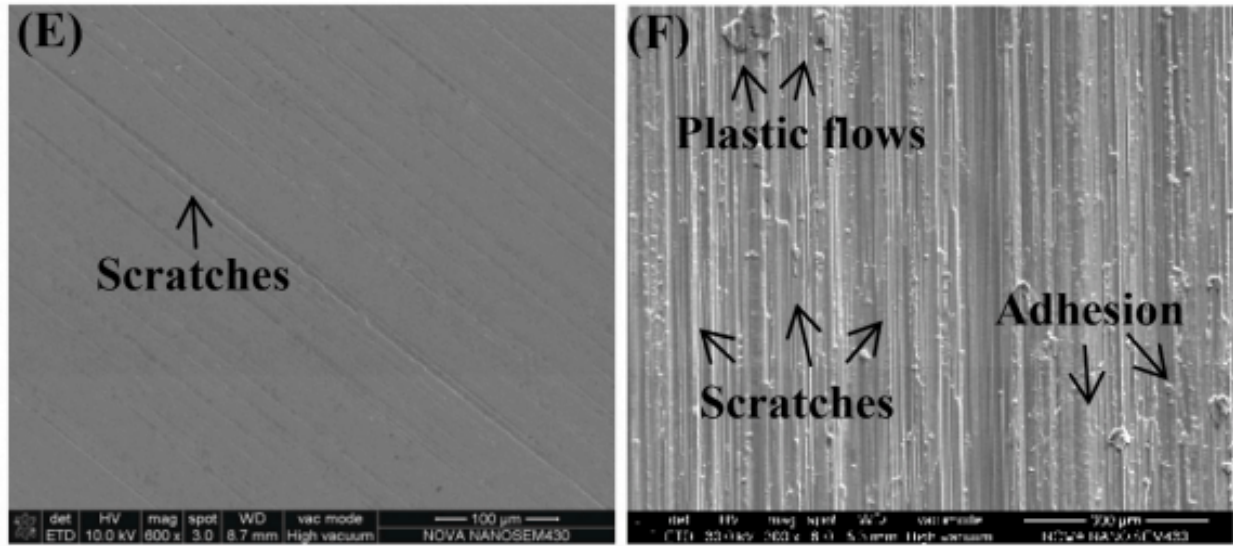
**Figure 9:** Grinding Velocity and Surface Finish (left: 10 m/s Right: 50 m/s )

In Figure 9 above we can see that a change in the grinding velocity from 10 m/s, seen in A, to 50 m/s, seen in B, shows significant improvement to the surface quality. This makes sense, as the grinding velocity increases the normal force exerted on the worked material decreases which decreases the material removal rate thereby increasing the surface quality.



**Figure 10:** Grinding Velocity and Surface Finish (left: 450 mm/min right: 750 mm/min )

In Figure 10 above we can see that a change in the feed rate from 450 mm/min, seen in C, to 750 mm/min, seen in D, shows a minor decrease in the surface quality of the worked material – specifically we can see greater adhesion marks on the worked material. This supports the conclusion drawn in the graph above. We can see here that the surface quality becomes worse as the feed rate is increased.



**Figure 11:** Depth of Cut (grit) and Surface Finish (left: unspecified Right: 0.3m )

Figure 11 above shows us two separate depths of cut that was performed by the research team, but it is important to note that E, on the left, is zoomed into 100 micrometers while F, on the right, is zoomed into 700 micrometers. Furthermore the research paper failed to specify the depth of cut used on the image on the left. However, based on their conclusions and the data that was graphed above the researcher concluded that as the depth of cut, or the grit of the paper, is increased the surface quality decreases.

## USER REQUIREMENTS AND ENGINEERING SPECIFICATIONS:

After talking to our sponsors, and understanding what their needs were, our group carefully weighed the importance of each of the requirements, in conjunction with the scope and ability of this class. Many different facets of the problem were explored and deliverables were determined. The scope of the project demanded a mechatronic system and the parameters for running the system effectively. However, with the scope of our class and time frame, the primary focus from both the sponsors and us was placed on the mechatronic system with which we determined our primary set of user requirements and translated them to testable engineering specifications.

**Table 1:** The following table displays our requirements and engineering specifications.

User Requirements	Engineering Specifications
Precise Arm Height Control	Height motion with $<10\mu\text{m}$ resolution
Able to achieve wide range of arm angle	Make 20 discrete steps between $15^\circ - 35^\circ$ angle with $1^\circ$ angle adjustment
Desirable End Product	Final Capillary Angel Falls within tolerance of $18^\circ \pm 7^\circ$ End Perpendicularity relative to axis of flow tolerance with $5^\circ$ Angles of Cone axisymmetric $\pm 1^\circ$
Low Production Time	Total Process takes $< 15$ minutes
High Success Rate	Desirable product generated $> 70\%$ of the time
User Friendly	Less than 5 input parameters to control
Minimal user interaction	Only one person needed to supervise process
Arm will be able to rotate/move along the grinding surface	Arm will be able to move the capillary across the pad with a resolution of $10\text{-}20 \mu\text{m}$

We have determined our engineering targets based upon interviews with various members of SLAC, as well as documents they have provided us. We conducted an interview with the lab leaders, Dr. Mark Hunter and Dr. Moises Smart, as well as the technicians who actually manufacture the capillaries. In this interview, we were able to generate a list of desires that each of these groups have for this project.<sup>5</sup> Along with their desires, we were able to tap into their experiences with this type of process in order to find out what was feasible. All the engineering specifications can be tested, all in different fashions, and deal with the specifications for the mechatronic system.

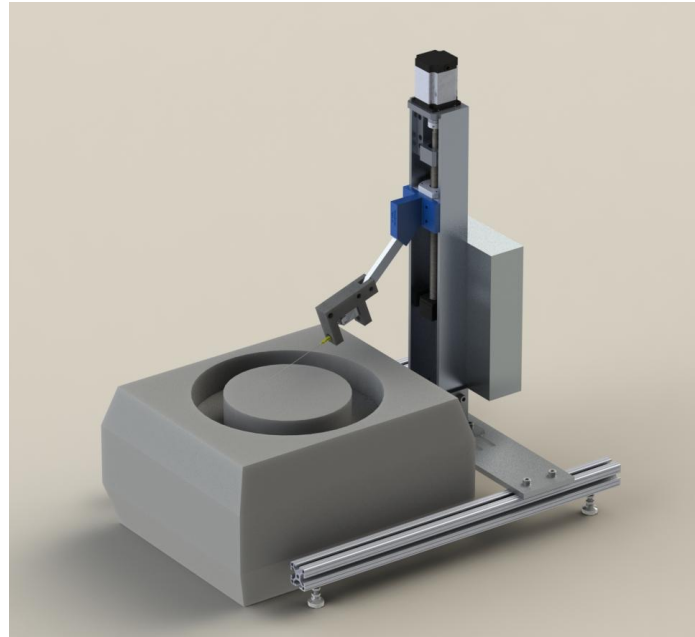
All of the requirements above must be met with the exception of the time requirement. The system we designed must be capable of meeting the time engineering specifications above after proper implementation of controls software and optimization. A cursory review of available platforms and their

associated  $\mu\text{m}$  resolutions are reasonable. Further details on this process are explained in detail in the appendices.

## **FINAL DESIGN**

In this section, we will describe the key subsystems of our final design in detail, as well as the reasoning behind their creation and the design decisions therein.

The 3-D model for our final design can be seen below in Figure 12:

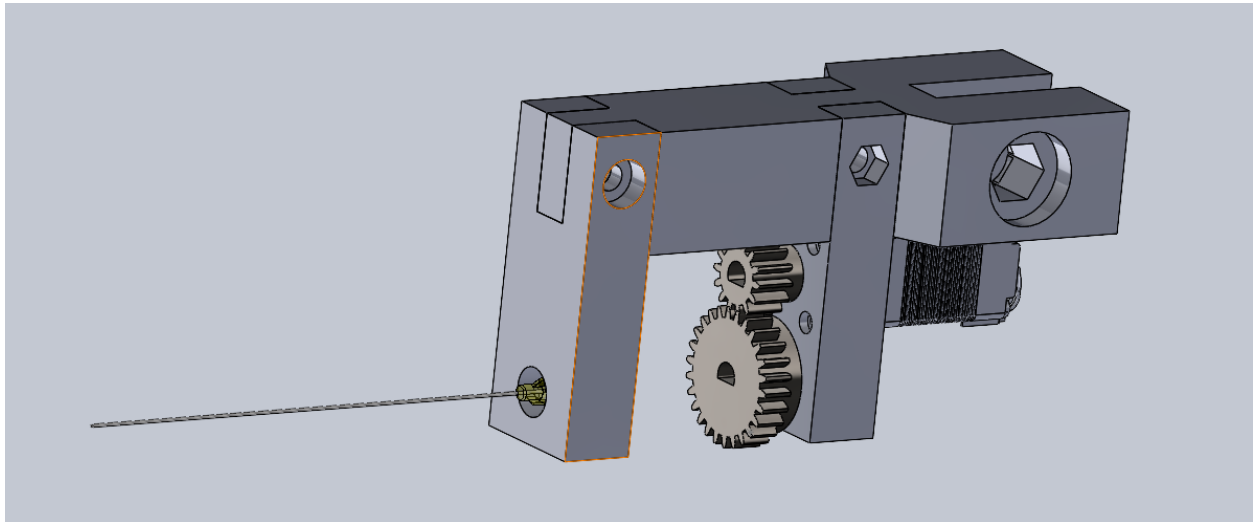


This section of the report will be split into the various subsystems of our mechatronic device, as follows:

- 1: Capillary Holder Design**
- 2: Column / Z-Stage Design**
- 3: Base / Legs Design**
- 4: Support Arm / Attachment Design**
- 5: Inspection Stage Design**
- 6: Controller Design / Programming**
- 7: Complete Assembly**

There have been many changes made from the alpha design, all of which are addressed in the sections mentioned above and the appendix. While designing and completing the manufacturing process we faced many problems which allowed us to learn more about the design process while developing solutions.

## DESIGN SECTION 1: CAPILLARY HOLDER



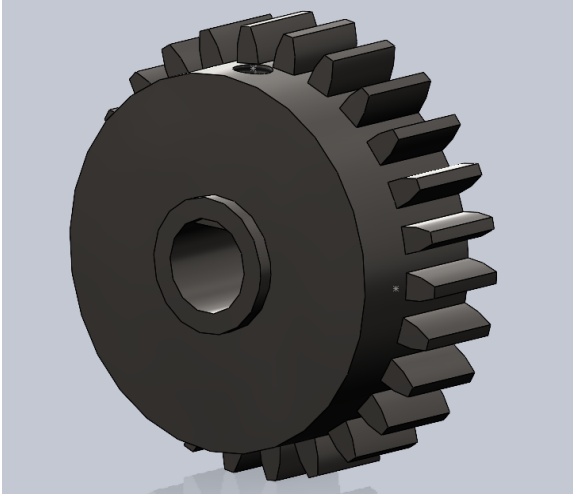
**Figure 13:** Capillary Holder Final Design

The capillary holder was 3D printed. Three interlocking subassemblies fit together and are fastened with bolts and nuts. The motor shaft has an extension fitted onto its end and is secured with two set screws. The hollow opening above the motor houses the bearing which supports the capillary tube holder. Angle modulation is achieved by using a clap affixed to the hole below the motor as seen in figure 13 above.

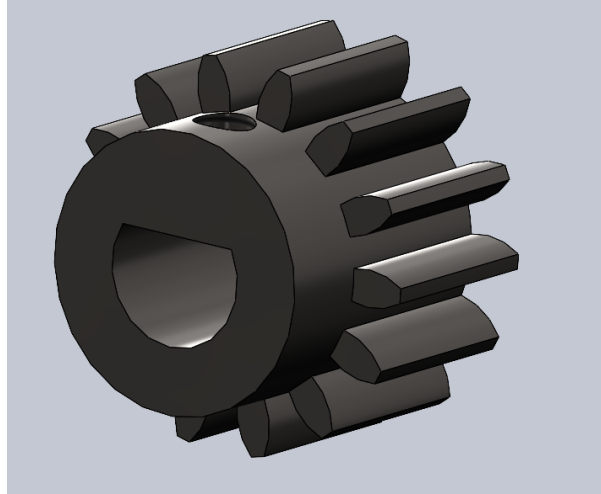


**Figure 14:** Capillary Tube Holder

We finally settled on a smaller chuck that would be lighter and easier to open and close around the capillary tube – seen above in Figure 14. This chuck was placed into a lathe and its diameter was reduced to fit into the bearings we selected and a through hole was drilled into the center to allow the capillary tubes to pass fully through the chuck.

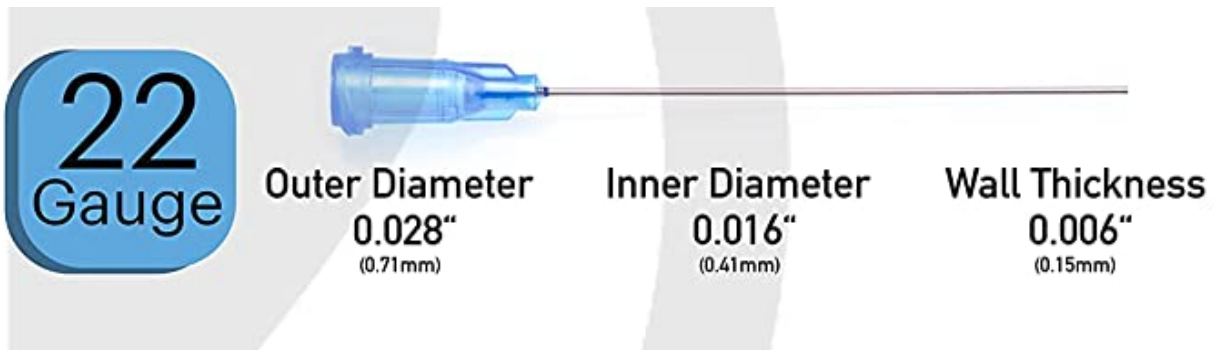


**Figure 15:** Capillary Holder Gear



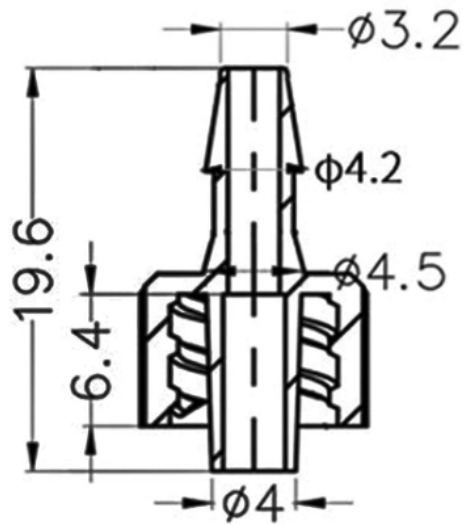
**Figure 16:** Nema 8 Motor Gear

Custom gears were also created and 3D printed which drive the rotation of our chuck. They can be seen above in Figure 15. The gears are slotted to allow for easy assembly and disassembly. The Capillary gear is larger – a 1M, 26T, 14.5PA, 12FW, gear with a 0.75mm D shaft slot depth. The motor gear is smaller – a 1M, 14T, 14.5PA, 12FW, gear with a 1.5mm D shaft slot depth. Both gears have a set screw hole built into their design. Both are sized for M3x0.5, though the thread pitch is not fixed as these gears are made of plastic.



**Figure 17:** Luer lock needle

The capillary tube is supported by a standard 22 gauge Luer lock needle. We purchased 4” needles and cut them to approximately 1-2 inches using a dremel on a low speed setting. The needle luer lock was picked so that they can be exchanged with other needles if other sized materials need to be machined on the design in the future.



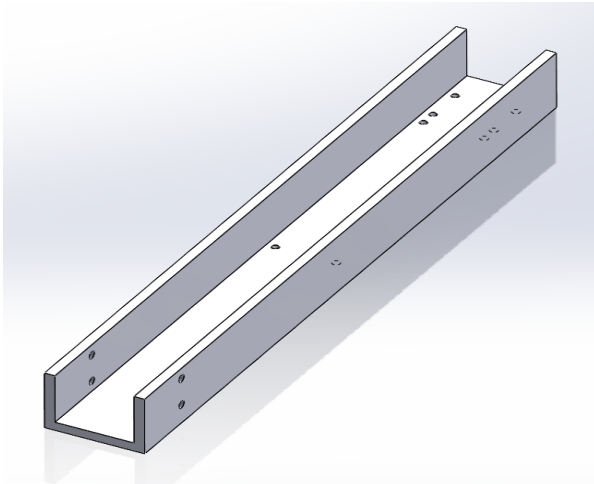
**Figure 18: Male Luer-to-Barb Adapter**

The luer lock system has a male and female attachment method. The male Luer adapter fitting is placed inside the circular through hole at the end of the capillary holder. The fitting measurements can be seen above in figure 18.

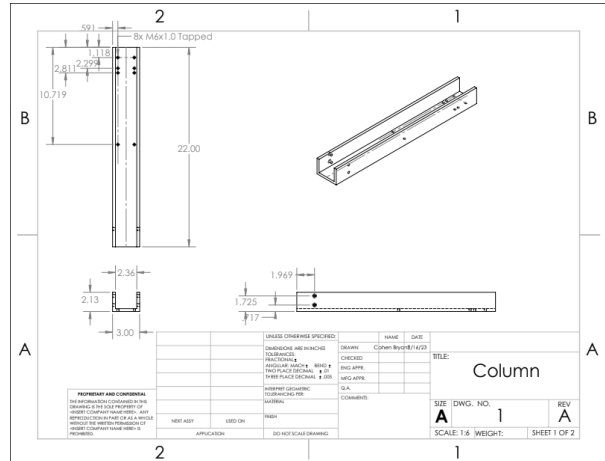
## **DESIGN SECTION 2: COLUMN / Z-STAGE**

This section summarizes the design process for creating the Z-Stage of our project, which controls the engagement of the capillary tube into the grinding surface, and provides the attachment method for the other subsystems of the design, such as the capillary holder and its respective mounting arms. To begin, a suitable column was needed, which our ball-screw assembly could attach and fit into. This means that the column needs to be rigid and strong enough to support the forces our team expects our machine to experience during the grinding process, while also being able to be easily machined. Thus an aluminum “W” channel section was chosen for our project. This material was available to us through our University of Michigan machine shop, as were other materials to be discussed in other Design Sections. This material was milled to open the inside dimension to provide a slight interference fit into the bearing blocks of the ball screw assembly, and also milled flat to provide a smooth running surface for the capillary arm attachment, which is made of PLA plastic. An isometric view and the engineering drawing for the column are shown in Figures 19 and 20 below:





**Figure 19:** Column Isometric View



**Figure 20:** Column Engineering Drawing

The ball screw assembly, as was selected in our down-selection process discussed earlier in this report, was purchased through Amazon.com, as they offered the best pricing and availability for the parts that we required. Our team, through discussions of cost and performance, settled on two mating systems of a Nema-23 stepper motor with high-accuracy encoder and driver, as well as a precision 16mm x 4mm pitch ballscrew. This specific ballscrew was chosen due to its low cost and fast arrival time, as well as its “Plug and Play” nature with the stepper motor system we selected. Furthermore, it specified a “zero backlash” system where the follower of the ballscrew is preloaded, which contributes greatly to our high precision motion requirements and specifications. The stepper motor itself was selected with the mindset that “bigger is always better”, in that a larger motor did not have significant drawbacks compared with a stepper motor of a smaller size, which would have sufficed given our calculated loads. This provides flexibility in the future for our sponsor, if they wish to add additional attachments to the column or arm assemblies, as the larger motor will be able to accommodate them without additional changes. Figures 21 and 22 below show the stepper motor our team selected, as well as the ball-screw kit. The specific part numbers and prices are discussed in the Bill of Materials (BOM) section later in this report.



**Figure 21:** Nema 23 Stepper Motor w/ Driver



**Figure 22:** 16mm Ball Screw Assembly

Finally, the combination of these two subsystems demonstrated to our group the feasibility of our design for meeting the requirements and specifications we set out in the beginning of this project in collaboration with our sponsor SLAC labs, in that the motion and resolution requirements were easily met in our initial testing, more information of which will be discussed in the Verification and Validation section. CAD and build images of our final column / Z-Stage assembly are shown in Figures 23 and 24 below:



**Figure 23:** CAD of Column with Stepper / Ball Screw Assembly



**Figure 24:** Build of Column with Stepper / Ball Screw Assembly

### DESIGN SECTION 3: BASE / LEGS DESIGN

Our process for the design of the base and legs of the device was far more simplistic as that of the other systems of our project. The only requirements that these parts had were to be stable and rigid enough such that excess flex and vibrations would not be transferred into the capillary tube while grinding, and that a slot mechanism was present such that the team at SLAC were able to shift the entire column assembly relative to the surface of the grinding plate. We used materials that were on hand to construct these parts, such as a large plate of  $\frac{3}{8}$ " aluminum, which was cut using a bandsaw to the rough shape, then milled flat on a Bridgeport milling machine, before finally having the position adjustment / mounting slots and mounting holes milled and drilled. We plan for this part to be sandblasted and painted for aesthetics. The legs of the device were selected in a similar fashion, being aluminum 1530 series extrusions, as they were readily available and allow for fast adjustment of the position of our device relative to the grinder, and are extremely rigid. Our group was able to positively determine that our design was more than capable of meeting the requirements it needed to fulfill, being extremely rigid and providing a sound and structural base to our grinding machine. Furthermore, the slot design satisfied the angle modulation requirements discussed in earlier sections of this report, as after a mid-project meeting with our sponsor it was determined that the angle modulation requirement was not as important as our team had initially believed, and could therefore be simplified to remove the automation initially planned. This simplification allowed our team to focus our efforts into the optimization of the grinding process toward the end of the project. Drawings of the base and the build therein are shown in Figures 25 and 26 below.

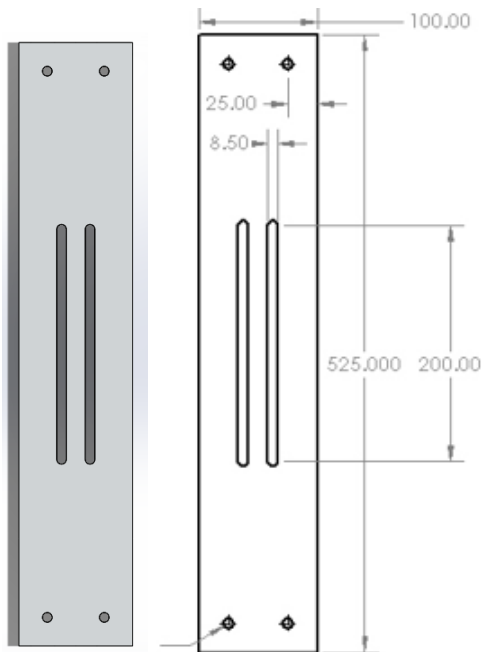


Figure 25: Grinder Base CAD

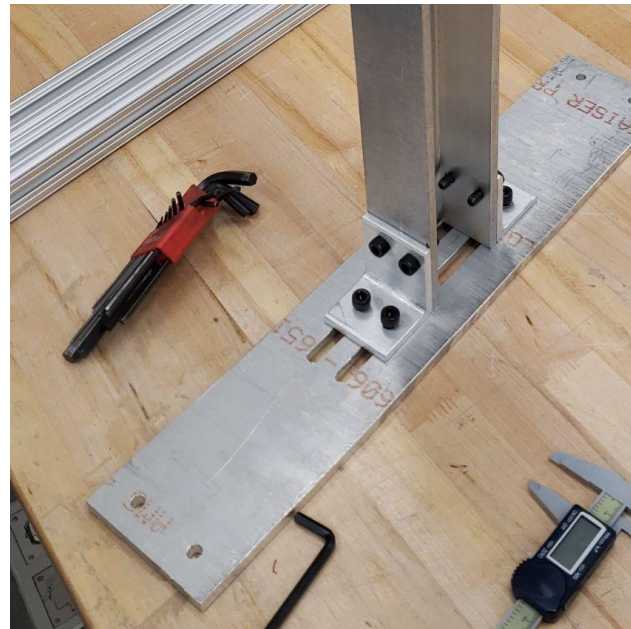
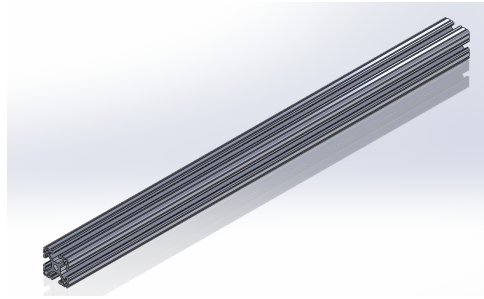


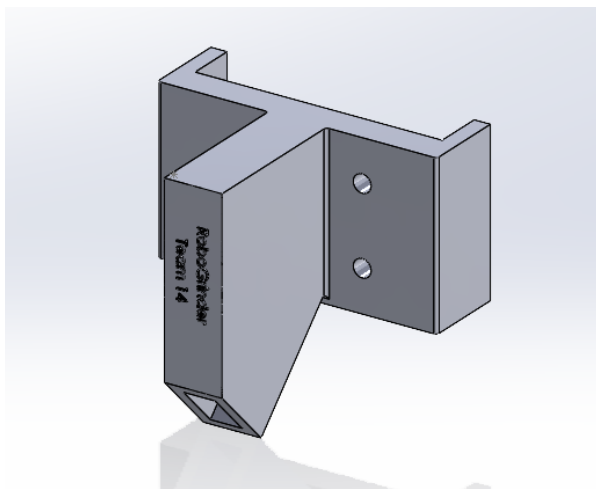
Figure 26: Grinder Base Build



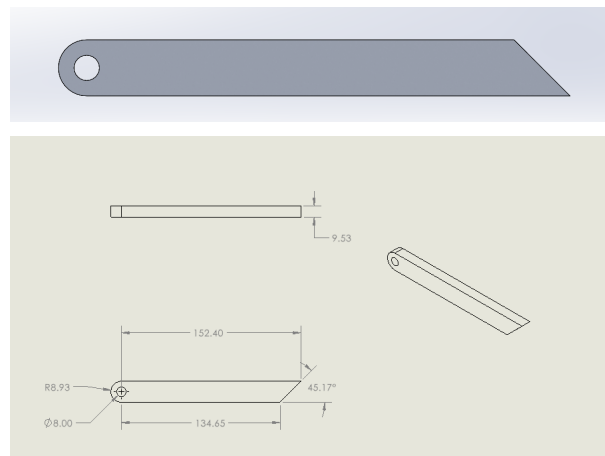
**Figure 27:** 24” Aluminum 1530 Series Extrusion (8020)

#### **DESIGN SECTION 4: SUPPORT ARM / ATTACHMENT DESIGN**

Initially, as we had discussed in the concept generation, the team had decided to use a lead screw in order to deal with the angle modulation. However, as we got the parts and began manufacturing, due to a lack of proper materials, or manufacturing abilities, a 3-bar linkage was chosen which can be seen in the section below. After performing some preliminary analysis in Solidworks, and encountering issues with an efficient method of achieving the angles we needed, we decided to go with a fixed arm which was one of the preliminary ideas we had. We decided to have the angle modulation occur with the capillary holder itself in order to more efficiently change the angles, and to simplify and therefore increase the reliability of the system.



**Figure 28.** Attachment bracket for arm to Column

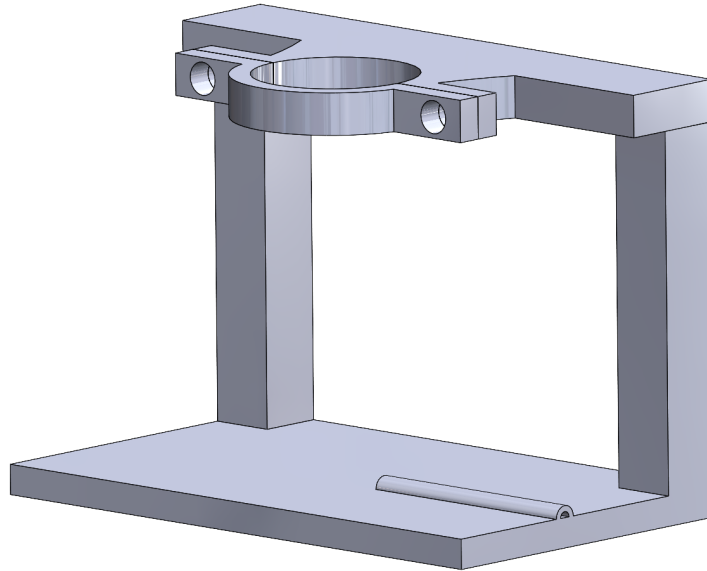


**Figure 29.** Capillary holder Arm

One of the considerations for the mount was the extruded edges in order to minimize any rotary motion that would be caused from the lead screw. The part was 3-D printed for rapid prototyping, but showed excellent durability and compatibility with our system. The arm itself was made with a  $\frac{3}{8}$ ” thick aluminum sheet that was cut using a water jet. Further dimensions for the arm can be seen in the figure above.

## DESIGN SECTION 5: INSPECTION STAGE DESIGN

As discussed before, one of the problems we had foreseen was the inspection of the capillary tube with the provided Q-scope, and keeping it consistent if it was to be done manually. The Q-scope needs to be extremely close to the tube in order to get accurate measurements from it. The problem was addressed by creating an inspection station as can be seen in the figure below.



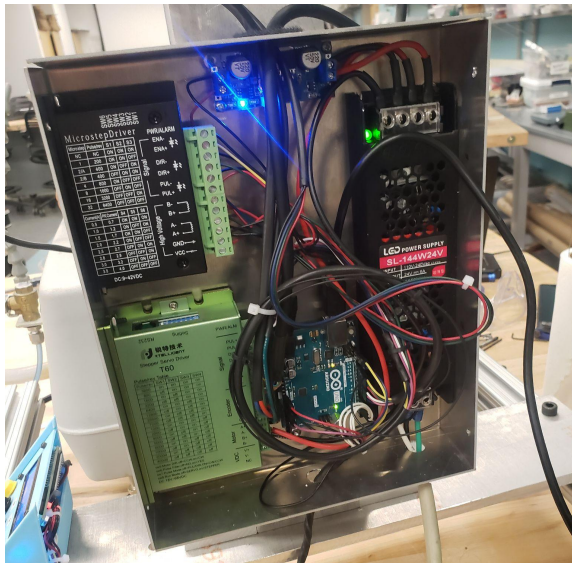
**Figure 30.** The Inspection station used to verify the quality of the grind for the capillary tubes.

The station allows the Q-scope to be mounted consistently, on top of one section without varying the distance from the capillary tube. This allows for easier verification of the capillary tube, and the results have been used throughout the report to show the capillary tubes that have been tested. The station was also 3-D printed in order to get it set up quickly, to allow us to inspect the capillary tubes we will be processing in the optimization of our system.

## DESIGN SECTION 6: CONTROLLER / PROGRAMMING

The design of our controller utilized off the shelf components for the motor drivers, power supply, and an off the shelf Arduino. Also needed was a DC-DC step down converter to drive the smaller capillary motor at a lower nominal voltage other than the 24VDC rail from the power supply. These were all hard mounted to the custom laser cut and bent control box which is affixed to the column of the grinder for packaging. Figure 31 shows the final layout and construction of the control box.

The design of the user interface panel was defined by the need for four buttons, a dial and a screen to monitor settings. These buttons were selected to be a Zeroing function, a menu scrolling button that advances through the menus on the screen, the start button for the grinding program, and an emergency stop. The dial allows adjustment of parameters that are selected in the user interface panel.



**Figure 31:** Finalized Control Cabinet



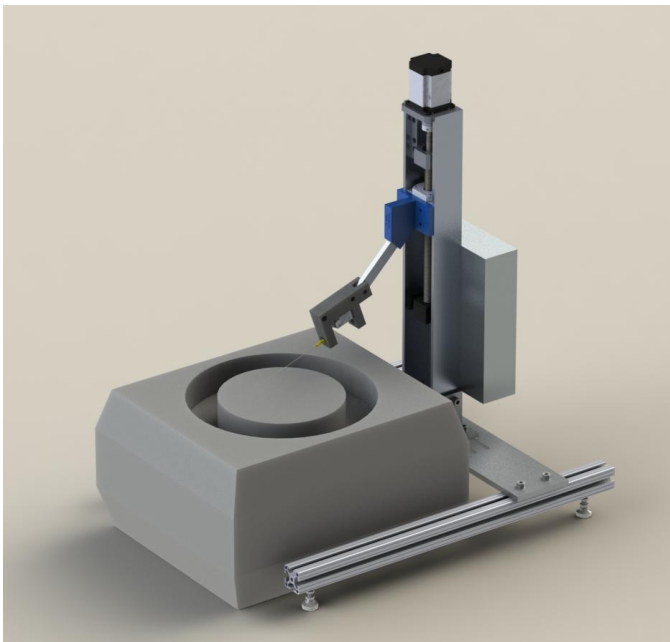
**Figure 32:** Finalized User Interface Panel

The code used is included in a separate file, and is annotated for clarity.

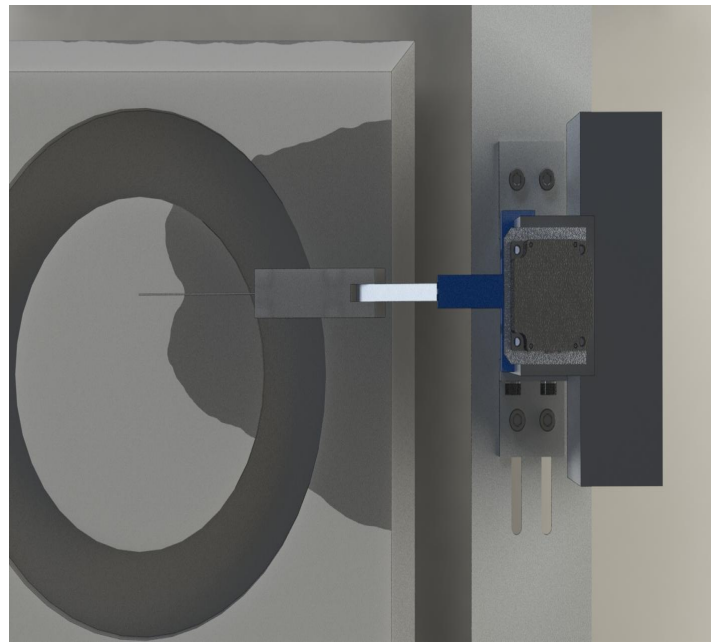
## DESIGN SECTION 7: COMPLETE ASSEMBLY

Our final assembly of our grinding device combines all of the elements shown in the previous design sections of this report. Note on our design decisions for the overall structure and placement of parts: Our group decided against rigidly coupling the grinding machine to the Ted-Pella XP-8 grinder for three main reasons; firstly, we aimed to provide flexibility to our sponsors if they wished to change the grinder used in the future, or to integrate our system with existing solutions. Secondly, our team sought to reduce vibrational effects transferred into our system through the Ted-Pella grinder which would ultimately adversely affect the quality of the capillary tubes after processing. Lastly, we determined that attachment methods of our system to the Ted-Pella grinder would have been insufficiently rigid if implemented due to the plastic construction of the grinder itself. Additionally, the height of our grinder is noticeably high, a decision also related to future flexibility in the hands of our sponsor. Lastly, it can be noted that the overall construction of our device is with machined holes and screws, lacking welds, press-fits, or glued joints. This construction method was chosen due to the simplicity of manufacture and assembly, and the ability for parts to be easily replaced in the case of failures during the lifecycle of our device.

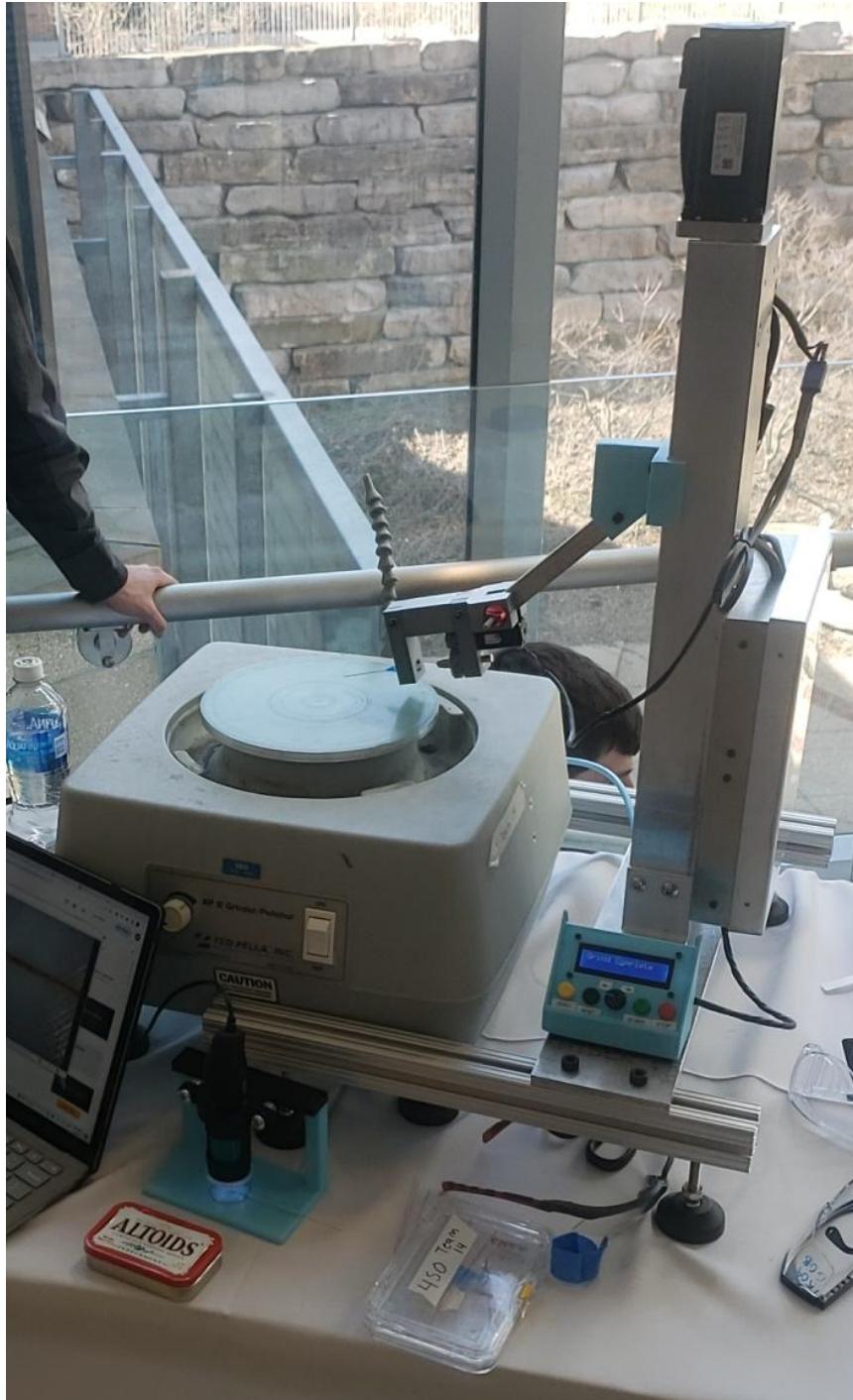
The completed assembly of our device is shown in the following 3D renderings.



**Figure 33:** Isometric View of Final Design



**Figure 34:** Top View of Final Design



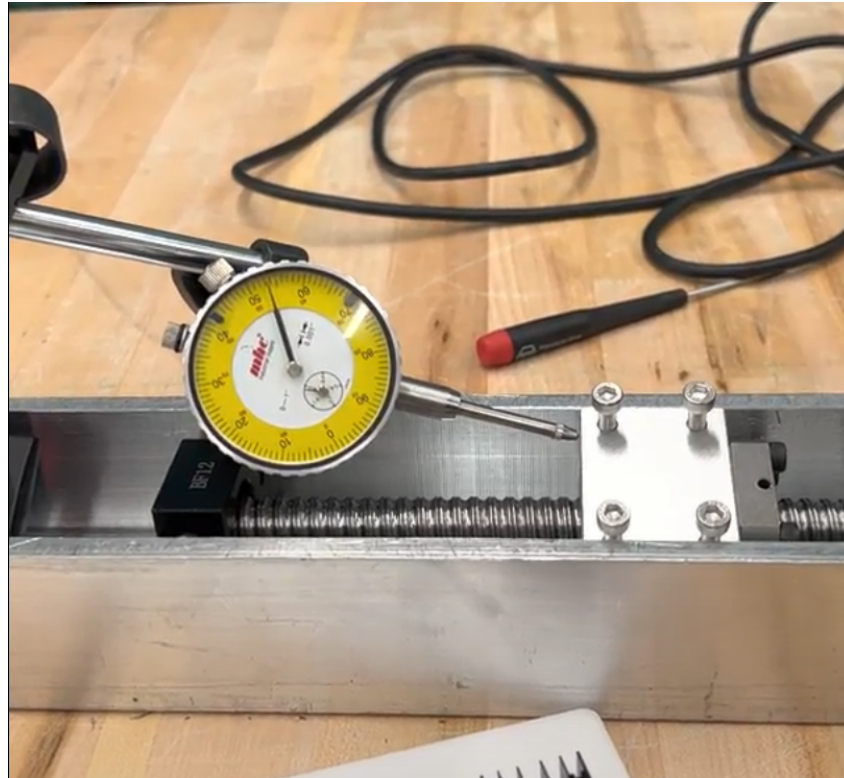
**Figure 35:** Final Design at Design Expo

## **VERIFICATION**

**Z-Axis Stage:**



The key specification that we wanted to verify is that we can control the Z-axis with <10 micron precision. To do this, we connected our motor to an Arduino that told the motor to move 50 steps in one direction, then back 50 steps in the opposite direction. While this was performed, we used a dial indicator to observe the movement. Doing this, we were able to find that we were reaching the precision that we expected, and we found that there was no perceivable backlash in the system upon manually loading the ball screw.



**Figure 36:** Experimental setup

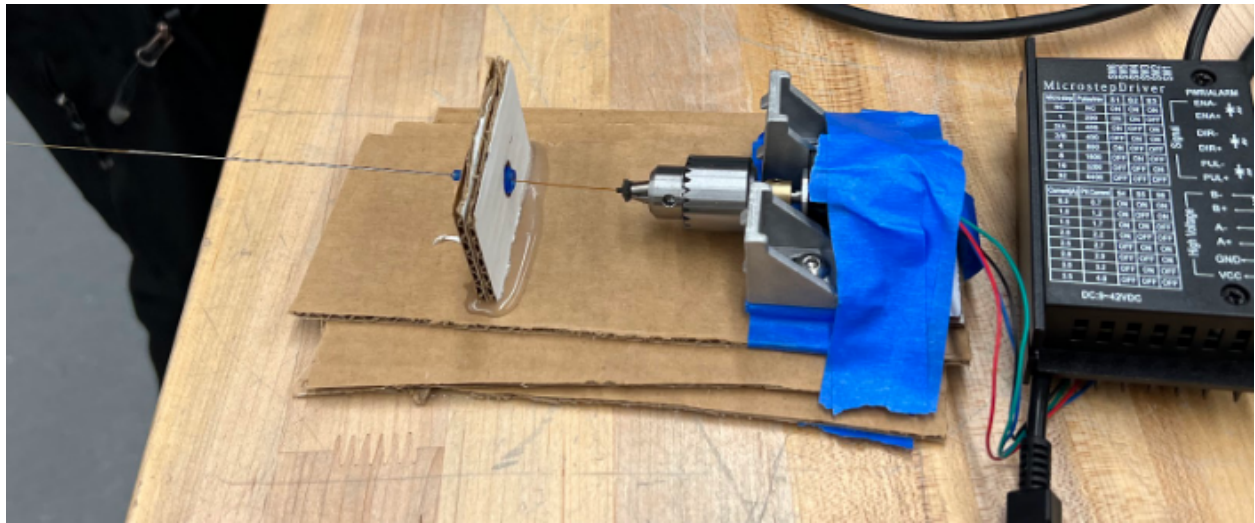
### **Angle Modulation:**

The key specification for this is the ability to control the angle of the capillary tube from  $15^\circ$  to  $35^\circ$  in 20 discrete steps. Since we are able to get within  $\pm 1^\circ$  of the desired angle, we consider this test a success. The capillary holder is able to rotate around the arm, the angle can be measured using a protractor, and it is then clamped down so that it does not move.

### **Capillary Tube Rotation:**

As we have progressed with this project, one of the biggest challenges we have experienced was being able to grip the capillary tube. It is very small, and along with this, it is quite delicate. This means that when we put it into our chuck, there is the fear that if we grip too tightly, we will damage the tube, leaving it useless for experimentation. However, if we don't grip it tightly enough, the system will rotate, but the capillary tube will not rotate with it. To fix this problem, we created a small rubber gripper to place inside of our chuck, which both increases the friction between the chuck and the tube and will absorb the force, allowing us to worry less about damaging the tube.

To make sure our solution worked, we created a very rudimentary motor mount with a capillary holder shown below.



**Figure 37:** Capillary Rotation Testing

This setup allowed us to see if the capillary tube rotated with the motor. We were able to verify that this method of holding the capillary tube was effective in rotating the capillary tube without damaging it.

**Inspection:**

In order to verify the inspection process, we took a single capillary tube and measured it 5 separate times. We would expect that we should get the same measurements every time, and if we do, we can assume the process is consistent.

When we completed this testing, we found the following results which compare the angle we wanted to achieve against the angle we measured. For a detailed look at the axis-symmetry see figures 39-41 below.

Measurement #	Top Angle (deg)	Bottom Angle (deg)
1	13.436	14.379
2	13.335	14.346
3	13.261	14.159
4	13.277	13.951
5	13.157	14.617
<b>Avg</b>	13.29	14.29
<b>Std. Dev</b>	0.10	0.25
<b>Min</b>	13.16	13.95
<b>Max</b>	13.44	14.62
<b>Range</b>	0.28	0.67

**Figure 38:** Inspection Validation

As we can see, the standard deviation among our measurements is a max of .25°. This is well within the range of being able to measure within 1°, so we feel this proves our methodology is sufficient, however, there is certainly room for improvement.

**Low Production Time:**

In our testing, we have found that we are able to complete the process in approximately 9 minutes. It takes approximately 2 minutes to set up the system with inserting the capillary and zeroing the system. Once it is zeroed, our process calculates the distance it needs to grind based on the angle, OD, and ID. With our current capillary sizes, at 15 degrees, it will need to travel 128 microns.

Our grinding process involves moving down 10 microns at a time, at a rate of 500 microns per second, and then waiting at that spot for 20 seconds. It does this until the final step, where it will then wait for 30 seconds. Based on that timing, it takes around 5 minutes to grind.

Once it is ground, we can take out the capillary tube and inspect using the inspection station. This takes around 2 minutes to take the image and measure the angles. With these elements, we find it takes a total of 9 minutes to grind each capillary tube. With a goal of less than 15 minutes, we have been very successful.

**User Friendliness/Minimal User Interaction:**

The final specification to achieve is less than 5 input parameters, and having only one person needed to supervise the process. Our system does achieve this with one supervisor needed and only 3 input parameters. Our system works as intended so we do not need any interaction with the machine after zeroing, there is no need for a second person to be supervising the process.

**Summary:**

Overall, we feel very satisfied with the performance of our system. Each element that we have created is able to perform successfully and passes our design requirements and specifications. We feel that as we are able to achieve the resolution and angle modulation necessary along with all the other requirements that we were given. We ultimately believe that our design is a success.

## VALIDATION

After the design was assembled, we verified against the user requirements. One of the things we tested for was the symmetry for the capillary tubes. This was done by laying the capillary flat, and measuring the angle of the slope in respect to the tube for the top and the bottom. We conducted tests for 3 different angles, 15, 20 and 35 degrees. With 8 tests for 15 degrees, 6 tests for 20 degrees, and 6 tests for 35 degrees. The distributions of top and bottom angles around the design can be seen below in Figure 39 for 15 degrees, Figure 40 for 20 degrees, and Figure 41 for 35 degrees. Detailed images of all test samples can be seen in the Appendix.

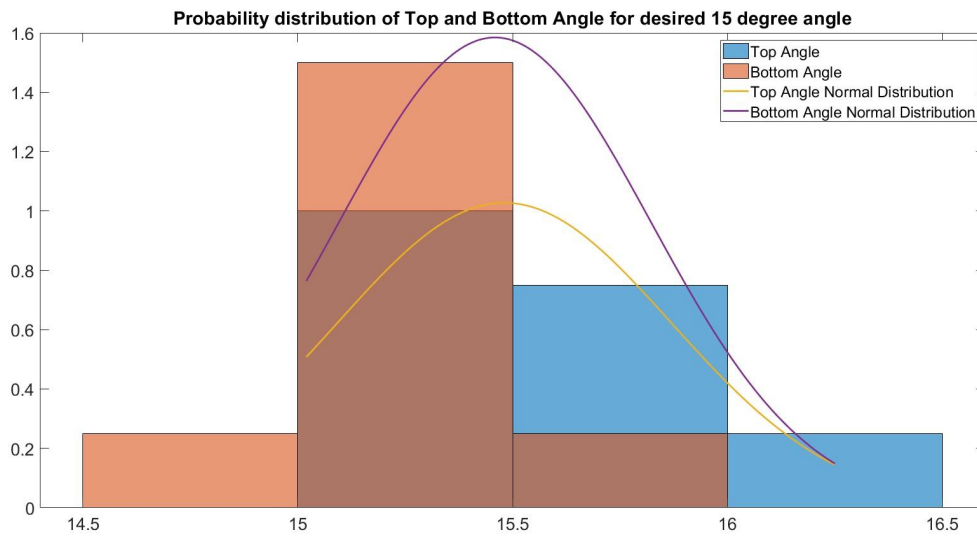
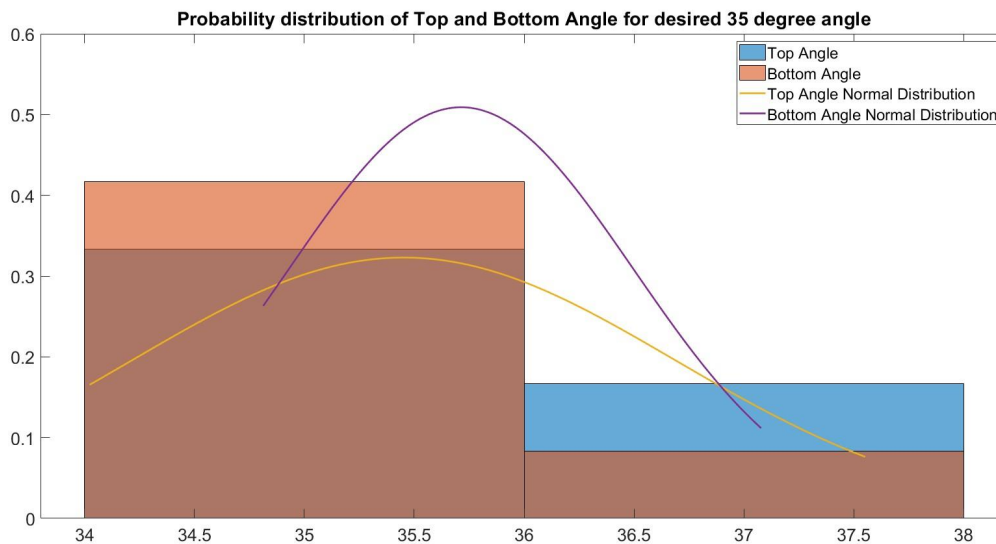
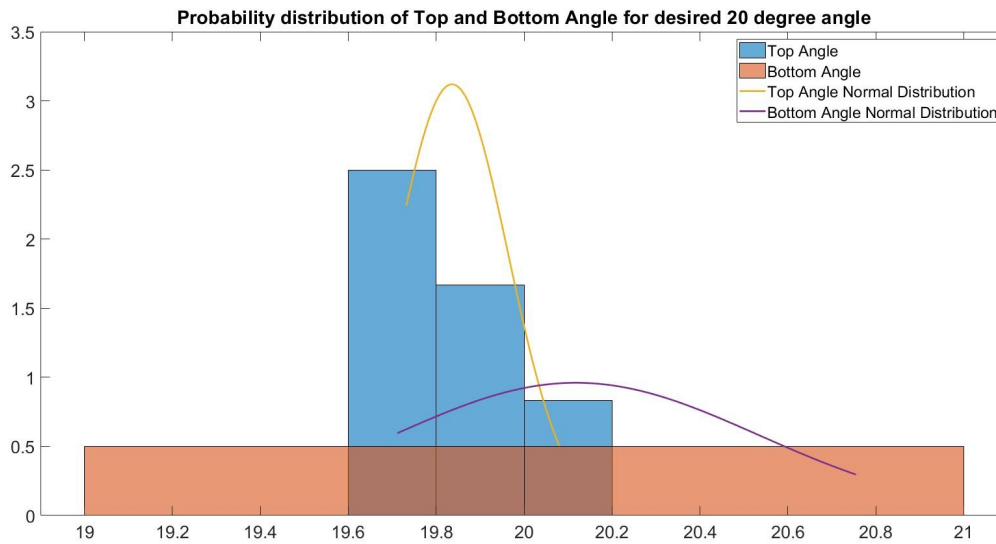


Figure 39



**Figure 40 (Top) and Figure 41 (Bottom)**

The distributions show that the design tends to work best for 15 degrees with a maximum deviation of 1.5 degrees with a relatively low probability. Furthermore, the 20 degrees only deviates 1 degree from the desired angle with a high probability of it being at 20 degrees. Finally, the design seemed to give variations around higher angles such as 35, here the angles deviate at a maximum of 38 degrees, with the distribution showing more towards 36. The desired angle is off by a bit, but in the case of axis symmetry, the relative angles are close, but it tends more towards one side of the tube shaving off.

## **OUR PROJECT IMPACT:**

Our project has a very small scale and is being developed for SLAC labs and will directly impact two lab technicians employed there. Some visiting researchers who use their facilities may be indirectly impacted, but only because they will perhaps use some of the capillary tubes that our device will create. As a result we do not foresee our project directly impacting many individuals and we expect that only a few of our devices will be made in the future.

However the automated system will create capillary tubes, which are used for research purposes in many fields. The capillaries used could be indirectly linked to developments in medicine and other fields, but to attribute that directly to our mechanism is not realistic. However our device could have a tertiary or quaternary impact on these developments by making the associated experiments easier to perform and to increase the allowable volume of experiments performed.

As our project is currently understood we cannot foresee any ethical issues related to our project in any way – regardless of how far you analyze the reach of its impact. Moreover, public health, safety and welfare are not impacted by our project beyond that which has already been discussed in the paragraphs above.

## **FUTURE IMPROVEMENTS**

As we have completed the project and now look towards the future with our design, our team has developed a small list of future improvements that we believe would improve the quality of our device, as well as make its use simpler and more efficient.

Firstly, we envision an automatic cutting and feeding system as an attachment to our grinder, which would feed the capillary tubes into our holder, requiring less user intervention in the loading and preparing of the capillary tubes, such that a spool would mount to the side of the grinder.

Secondly, we envision a system where the zeroing of the Z-Axis is automatic, with a sensing method of some kind able to detect when the capillary has touched the grinding plate. Some of our ideas for this included a load cell attached to the capillary arm that would detect an increased force exerted on the Z-Axis, as well as electronic sensing by placing a charge on the grinding disk, then detecting any current through the capillary holder once it touches.

Thirdly, our team struggled to find a simple and effective solution to reliably grip the capillary such that it could be spun with our motor. Our current solution is a miniature chuck designed for micro-drill bits, which was functional in the testing of our device, however not optimal.

Fourth, our team believes that the tolerance in the angle can be reduced. We also believe that the total time it takes to grind a capillary to an axis-symmetric point can be reduced as well. We envision a future development team taking out design and performing tests to determine the maximum feed rate and best suited support mechanism to achieve these ends.

Lastly, one of the initial parameters of our project was for automatic angle adjustment for the capillary. Our team decided against this due to the timeline constraints we faced, however powering or automating this process with a suitable stepper motor would be ideal.

## TEAM MEMBER BIOS:

Name : **Sparsh Thapa Chhetri**

Hometown : Chicago, IL

Why mechanical engineering?

Growing up I always had a fascination towards physics, mostly being inspired by Richard Feynman and his book “Surely you’re joking Mr, Feynman”, and the countless fascinating videos he had talking about physics. That love for physics only blossomed into a love for mechanical engineering as I began discovering my aptitude and love for problem solving. With the ability to impact and create tangible things while exploring my curiosities in math, physics, and problem solving, I pursued Mechanical engineering.

Interesting Facts :

I was born and lived in Nepal for 11 years

I have a fascination and interest for philosophy and art, and draw at my free time





Name: **Cohen Bryant**

Hometown: Derby, VT

Why Mechanical Engineering?

Ever since I was a little kid, I have loved taking things apart and figuring out how they work. As I have grown up, this curiosity has stuck with me. Becoming a mechanical engineer has allowed me to understand on a much deeper level, and begin to not just understand how things work, but how they are made and how to use what I see in others' designs in my own projects.

Future Plans: I plan to enter the workforce, hopefully in the robotics industry. However, I do not have any specific plans at the moment as I am still in the job search process.

Interesting Facts:

- Growing up I wanted to become a circus clown, so I learned to ride unicycles, juggle, etc.
- I play soccer, basketball, and hockey
- I have been to Canada



Name: **Devon Freeland**

Hometown: Milford, Michigan

Why Mechanical Engineering?

I have always had an interest in the way that the world works and how the products that we interact with were designed and produced, as well as a fascination with machinery and transportation. I have a deep interest in cars and racing which I developed from a young age watching the golden age of modern Formula 1. This fascination naturally led me to studying Mechanical Engineering here at U of M, as it allows me to achieve my goals and provides me with the information I need to be successful in the fields of my interest. I currently work in racing at a performance shop and have been there for the past three years designing products for racing applications, developing tuning libraries for customers using dynamometers, and working on customer installations for performance modifications. I love my job and would like to advance in this field further, hopefully working within a racing series such as Indycar or even Formula 1 itself. One interesting fact about me is that I studied abroad in Germany for a year at the end of highschool, an experience which drastically changed my mindset and understanding of the wider world and the engineering thought process.



Name: **Andrew Smith**

Hometown: Zanesfield, OH

Why Mechanical Engineering?

I spent my childhood growing up in a small town with little money and had few electronics and toys so they needed to last. My parents did not have the time to fix things that were not working properly. I was the one who needed to figure out how to fix the things I owned. So at a young age I was troubleshooting and fixing broken electronic components.

This troubleshooting mindset followed me through life and fortunately led me into a challenging job position as an electronics technician and nuclear reactor operator in the

United States Navy. After serving the time I promised I set my eyes on an engineering degree. I attended Jackson College for 2 years earning an associates degree. I was originally a biomedical engineering (BME) student when I arrived at UoM, but later I opted to switch to mechanical engineering to ensure I could easily find employment after graduation.



Interesting Facts:

- I was in the USN, where I was a nuclear reactor operator.
- Two summers ago I spent 34 days in the Absaroka Mountains backpacking, 12 days camping/rock climbing, and 16 days camping/rock climbing in Utah on a wilderness expedition with a team.
- I've been to remote villages in Peru one summer and Honduras another summer on medical missions to provide care to remote villages in neglected and hard to reach jungles.
- I am a licensed EMT and Wilderness EMT and work on an ambulance part time.

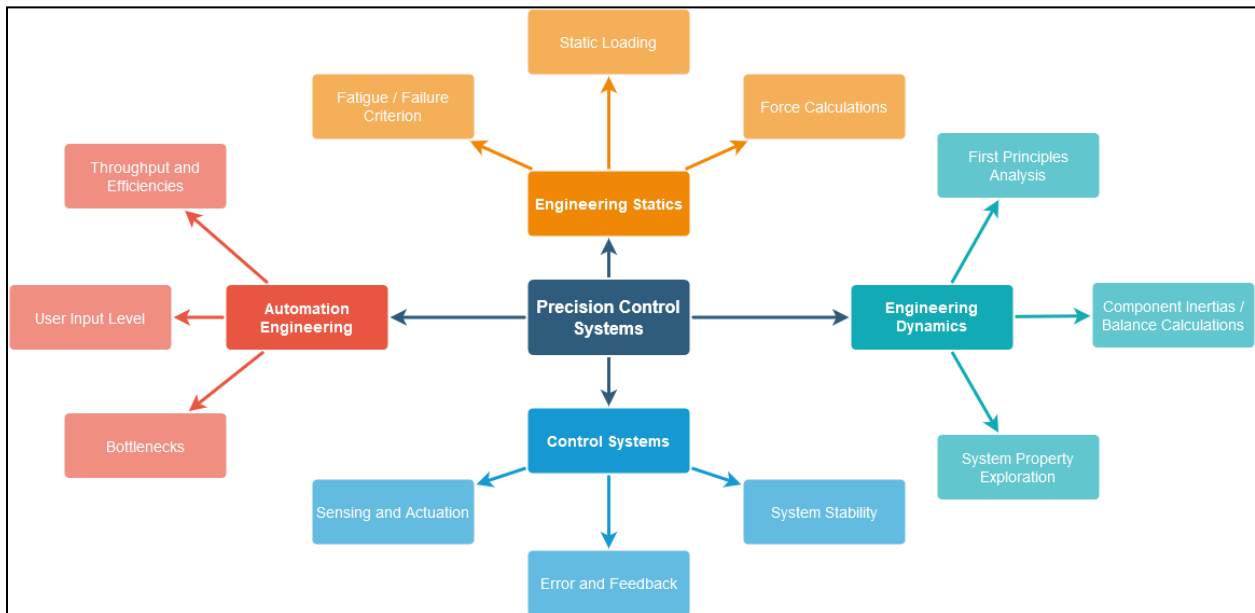
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- [9] <https://www.ultratecusa.com/product/ultrapol-fiberlab-module-system/>

## Appendix:

### A. Problem analysis

In our project, there are well defined engineering specifications and requirements that give us a fantastic engineering framework to work within. These specifications incorporate multiple engineering fundamentals which will need to be assessed to evaluate the performance of our design. We have determined four engineering domains that we will be working with, primarily that of engineering statics, engineering dynamics, automation engineering, and control systems. The following figure outlines the engineering domains that our project falls under, as well as the important constituent parts.



**Figure A1:** Engineering Domain Analysis

In analyzing and assessing the engineering specifications given our project, some difficulties may arise. Firstly, one of the core requirements of our project is the tight control of multiple physical parameters of the end-product ground capillary tube; mainly the restrictions on the ground angle of the tube, and the end face width, which directly correlates to the rigidity and resistance to fracture of the capillary tube under use. These tolerances correlate to an even tighter tolerance in the feed rate of the Z-Axis of our design, which will control the feed of the capillary tube into the grinding wheel which was provided to us. Our preliminary analysis suggests that this measurement will need to be in the single micron level, which is incredibly tight considering normal engineering tolerances. Therefore testing and validation of this system will require more advanced measurement techniques, such as high precision micrometers. Furthermore, the device that our group will design relies on high precision movement in the X Plane, with very little to no tolerance for loose fits. This means that our design necessarily cannot utilize certain technologies and techniques that would be far simpler to implement, and must resort to more creative methods of achieving our design goals and specifications. This restriction of the design space is extremely important to understand and work within, and will be acknowledged in the design space exploration stage of our project.

Lastly, we have identified our project problem as a mechatronic system, which will therefore require a control system of our choosing. As our group has considerable knowledge of these systems and their function, as well as how to best implement them, we anticipate that the majority of the issues regarding the control system will be budgetary constraints, given the relatively high cost of the components we will be requiring. Furthermore, the development of a control system for this project will be time intensive, and therefore may not be feasible considering the time constraints of this project. Update for DR3: having made the majority of the purchases and further evaluation of the project we have updated our challenges and expectations, as discussed later in this report.

With regards to difficulties concerning concept generation given our specifications, we anticipate that some our specifications will require materials and manufacturing methods that may push our project outside of the budgetary constraints given to us, however we aim to solve this problem by utilizing existing designs and pre-built hardware wherever possible, as these solutions are extremely time and cost effective, which we anticipate will be the ultimate crux of our project going forward.

In analyzing the gaps of knowledge of our project, currently the largest gaps in our knowledge stem from the lack of understanding governing the specifics of the grinding process, such as that of optimized feed rates and speeds, as well as the various grits we may need to employ to maximize our results. We will either obtain this information from sources inside of U of M, through our sponsors and their prior knowledge of the subject, through external literature sources, or by defining this problem and allowing a further team later on to optimize the system that we create and define.

The problem has been determined to be the design and creation of a mechatronics system that will allow for the automation of the grinding process. The mechatronic system as seen in the previous section shows a very alpha design. In order to develop the process further, the following analysis must be performed.

1. Determine moment, weight exerted on the lead screw.
  - This is a solid mechanics problem and will be solved using computational methods in order to determine the moment and the weight. This step is planned to be completed towards the end of the project in the process of the reliability and lifecycle analysis.
  - This was done by combining all the masses and comparing it to the stepper specifications, and realizing we were magnitudes lower than what the motor can handle.
2. Determine the optimum speed to grind the capillary to ensure the speed is as fast as possible, while keeping the grinding wheel wear as low as possible.
  - This is a manufacturing problem and we plan to tackle this problem by having one of our group members Andrew talk to his ME 481, Manufacturing Processes, professor in order to determine how to approach and quantify the problem,
  - Initial steps have been taken, and can be seen in the section describing the grinding process.
3. Analyze the total power required to operate the leadscrew, direct drive, Arduino controller, and any sensors at maximum rated load/speed.
  - This will be a specification problem, where after determining the materials we are planning on using, we determine the maximal power needed in order for the

system to operate. The materials that will need to be specced are the motors, the Arduino controller, and the power it draws. The mechatronics system will be external to the grinder and won't share any power consumption with the grinder.

4. Determine if the stepper motor/ leadscrew have any hysteresis losses or backlash and quantify them as a tolerance for grinding capillaries.
  - Refer to Figure 47 on page 38 for details on this testing.
5. Determine where sensors need to be placed for future implementation of automation:
  - a. Top of capillary support force feedback.
  - b. Live position reporting of the lead screw (IE the y direction movement)
    - i. Current position
    - ii. Total distance traveled
  - c. We need a sensor to “zero” the capillary and grinding plate distances prior to grinding beginning.
  - d. Report rotational speed of platter and rotary capillary wheel.
  - e. Sensor or fixed guide to ensure that the capillary extension out of its rotary mechanism is always the same.
6. Develop basic Arduino code in text form that contains all the algorithms necessary to automate the process through controls.

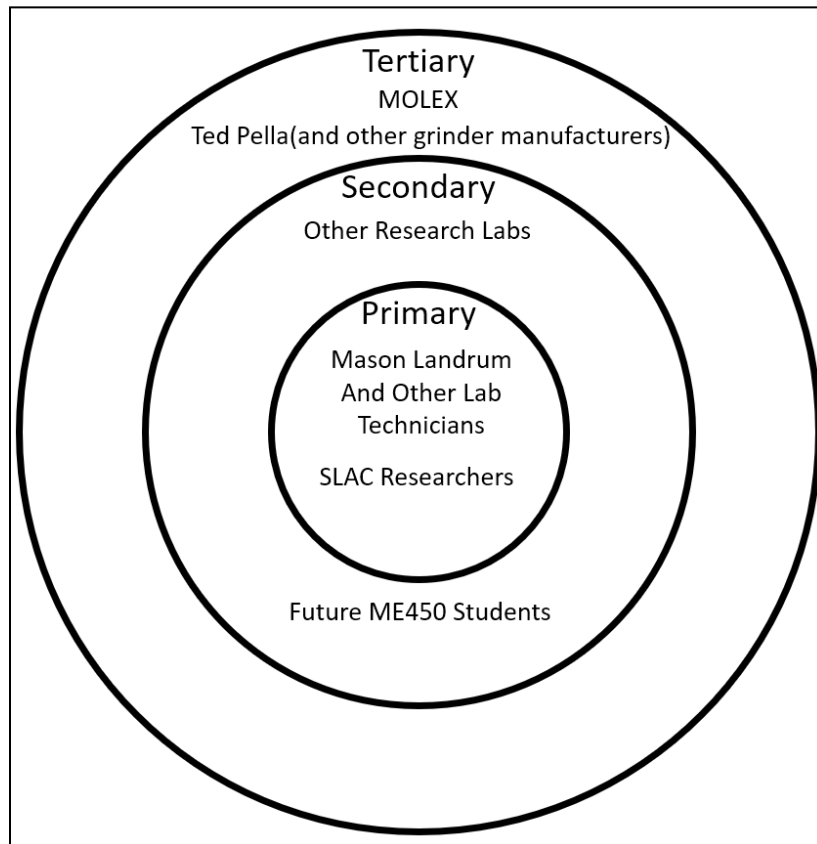
## **B. Stakeholder involvement**

With regards to the stakeholders involved in this project and their impact on the initial designs, the laboratory technicians Mason and Stella, as well as Raymond are our primary stakeholders. They have been pivotal in our understanding of the problem our group has been faced with, as well as helping guide the design. After our initial alpha design was created, our team met with these SLAC members and the design was discussed. They provided fantastic information with regards to what systems were most critical, as well as showing us features of our alpha design that would not be critical for success. Overall these three have provided general feedback and guidelines for what they would like the outcomes of this project to be, and have not restricted our design in any way. In fact they have encouraged us to push the boundaries and explore a wide range of the design space.



## C. Design Context

Although our project solves a very niche problem dealing with the SLAC laboratory. The project itself has potential to affect not only the researchers at SLAC but entities outside of the laboratory. The project being an engineering project will always have an impact outside of just the initial recipients and users. This is better illustrated with a stakeholder map listing the influences that the project will have in different levels, primary, secondary, and tertiary.



**Figure A2: Stakeholder Map**

As we can see from this map, the primary stakeholders are those involved in SLAC, specifically Mason Landrum. Mason Landrum is our main contact at SLAC and is the primary manufacturer of the ground capillaries. Automating this grinding/polishing process would greatly benefit him, as it would allow him to spend time doing other, less tedious work. Along with Mason and the other lab technicians, the researchers can be greatly impacted by our project. These capillaries are a key part of their research, so having high quality capillaries ready more quickly will prevent this process from being a bottleneck in their research.

The secondary stakeholders include other research labs and future ME450 students. SLAC is not the only lab that uses capillary tubes in their experiments, so it is likely that these other labs would have a use for our automated system, either through purchasing a similar system to manufacture capillaries themselves, or to purchase produced capillaries from SLAC. It may also allow for other research labs to begin using these capillaries if they are not already. Due to the multifaceted nature of the project, the project might

extend up to further semesters. Future ME450 students could also be impacted in the event that this project becomes a multi-semester project.

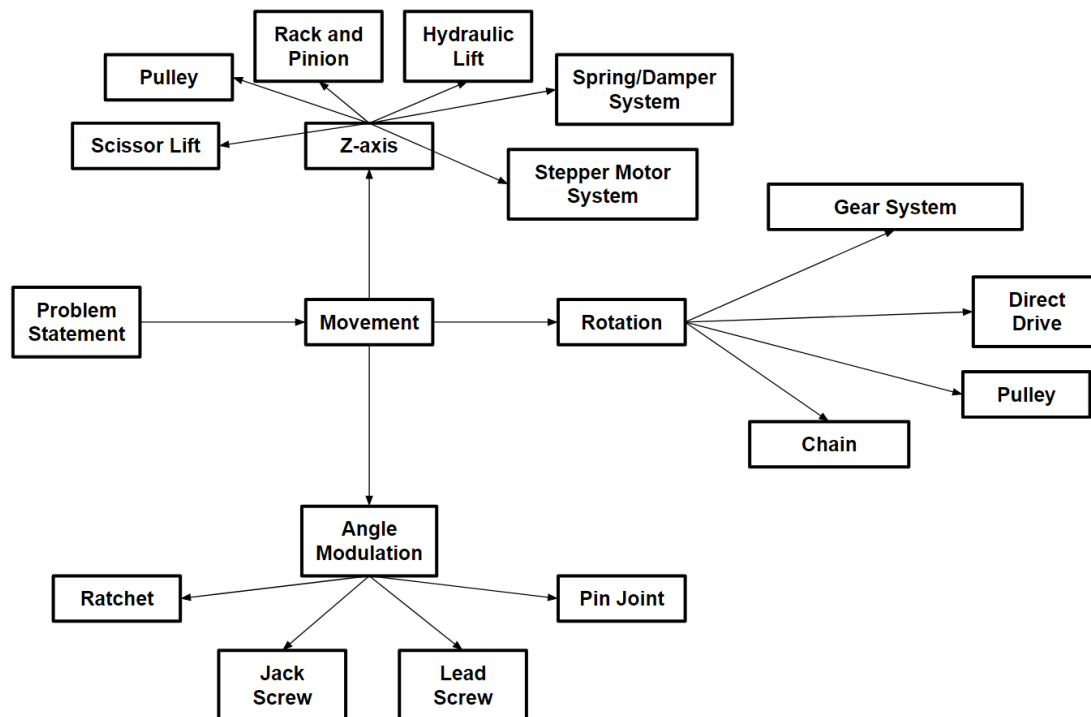
The tertiary stakeholders we have identified are MOLEX and Ted Pella, as well as other grinder manufacturers such as ULTRAPOL. MOLEX produces the base capillary tubes, which labs like SLAC purchase. If we are able to increase the rate at which we can grind/polish the tubes, it may lead to more capillaries being purchased. This would benefit MOLEX. For the same reason, Ted Pella and other manufacturers may find more grinders being purchased if this process becomes more common/used more frequently. As we are designing for the Ted Pella, this means other grinder manufacturers may be opposed to our project, as us being successful could lead to other labs opting to get a Ted Pella grinder rather than their own. However, ULTRAPOL would most likely experience some negative returns, because currently they also sell modules for their ULTRAPOL Fiberlab Module System that are intended to solve a similar problem. Their modules do not fit the requirements required from the lab team, and thus the project would produce an almost similar counterpart to their chisel tip module. Specifically the modules cannot accommodate material on the small scale of the capillary tubes and the precision to make symmetric ends is not present. A cursory search of the internet did not show any manufactures that make grinding products for capillaries on this scale.

Along with being beneficial for those working with these tubes, our project should make their grinding/polishing process less wasteful. Currently, they achieve their desired results ~50% of the time, meaning around half of their tubes have to be disposed of without ever being used. We have a goal of >70% success, meaning we would decrease the amount of wasted tubes by more than 40%. These tubes are not typically recycled, meaning they would be going to a landfill, which is something we want to avoid. This wouldn't be a very large amount of waste due to the small size of the tubes, and the relatively low volume of tubes manufactured, however, every step towards avoiding waste is a positive.

Lastly, intellectual property has not played a significant role in our project so far, excluding the design improvements done by the team at SLAC on the existing machine used for grinding. Otherwise our team anticipates that intellectual property will be much more important at the end stage of our project, when we hope to have a finished prototype able to be utilized by the lab for years to come. As a part of this project, we have signed over the intellectual property of anything that we generate as a solution. This will mean that SLAC will have full ownership over what we create this semester. This could play a role in what happens with other labs, as they may want to create similar automated processes to what we are attempting to design.

## D. Concept generation

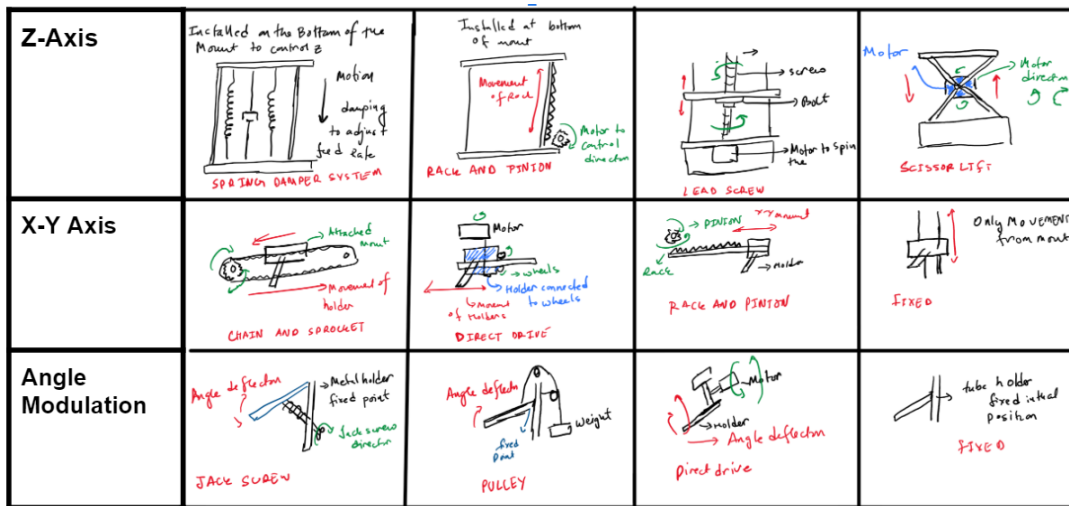
Initially, we began the design process by independently coming up with our designs based on the learning blocks and the objectives provided by the learning blocks. After doing so when we began sharing our ideas with each other, we realized that the ideas we came up with had similarities and dealt specifically with movement. This allowed us to use an ideation chart in order to map the different solutions we might have to the different subsystems. The team was set on developing a mechatronic system that would allow us to automate the grinding process, as that was part of the scope of the project. However, the team also did attempt to solve the primary problem of increasing the time needed to speed up the grinding process with solutions such as micro crabs, or using lasers and furnaces to melt the capillary tube into shape. This led to a lot of daring ideas, but based on the scope of the project and the desired deliverables the team decided to decompose the problem statement as movement, and then separated it into the movement in the Z-axis, capillary rotation, and the angle. Having decomposed the system we could then come up with different solutions from the different subsystems. As a result, and as seen in **Figure A3**, for the Z-axis, we came up with solutions of using a scissor lift, pulley system, rack and pinion, hydraulic lift, spring/damper system and a stepper motor system. Furthermore, for the capillary rotation, we came up with solutions of using a meshed gear system, directly driving the capillary, using a pulley system (similar to the one SLAC currently uses), or a small chain system. Finally, for the angle modulation we came with solutions of using a ratchet, jack screw, lead screw and a pin joint.



**Figure A3.** Initial Ideation chart decomposing the system

The ideation chart allowed us to decompose the design into subsystems that allow for different functionalities. Similar to a morphological chart. A lot of the subsystems were part of fully thought out

design involving movement in all the different degrees. However, in order to better determine and understand the effectiveness of each of the subsystems we came up with we decided to create a morphological chart in order to better visualize the different subsystems.



**Figure A4**, Morphological chart of the different subsystems

The morphological chart as shown in **Figure A4** is filled in the rows with Z-axis concepts, capillary rotation concepts, and angle modulation concepts in a top to down row method.

The first concept seen in the Z-axis is the spring damper system, the idea generated from the way feed is controlled in industrial saws, the spring will be providing the clamping force and having an adjustable damper would allow for adjustable and consistent feed rate. The second concept was using a rack and pinion, the concept would have the capillary tube holding system in a stand that has a part of it be the rack with a motor controlling the pinion for controllable feed rate. The third concept had the platform on the stop of a lead screw which would be actuated with a motor. The screw would go in the middle and the stop would hold the capillary system. Finally, for the Z-axis we also considered a scissor lift which is something we had seen being used in larger applications like lifting a car.

The first concept in the X-Y axis would be the geared system, where the tube would be inserted into a holder, which is connected to a gear. This gear would be meshed with another gear, which is connected to a motor. The second concept was using a direct drive where the capillary tube is in a holder that is directly mounted to the motor. The third concept was using a pulley where the tube holder would be attached to the belt and the pulley was actuated with a motor. Finally, the last concept for the capillary rotation would be the chain and sprocket with a chain and sprocket instead of a belt.

Finally, the first concept in the angle modulation was using a jackscrew, where the capillary tube angle would be fixed and a jack screw would be turned in order to increase or decrease the angle. The second concept in the angle modulation was using a pulley in which the weight would be attached to a fixed tube feed and changing the weights would change the angle. The third concept was using a direct motor and connecting the tube feed directly to the motor and moving it as much or little as we want by varying the voltage we provide. Finally, an option we also had was keeping it fixed, however this relied on an extra degree of freedom on the radial plane of the grinder where we would try to achieve the angle by keeping it flat and varying the speeds at which we push it towards and away from the center of the grinder.

## DOWN SELECTION

Following the guidelines set out in the UofM ME450 design process modules, our team elected to use Pugh charts for our initial down selection of designs, with each member contributing over forty designs. These forty designs were initially discussed qualitatively with one another, with each member providing feedback and a gut-check analysis to rule out any erroneous solutions which would not satisfy the requirements set out to us by our sponsors. From this any of our similar design concepts were combined into distinct categories and split into three subsystems. These subsystems were identified such that our modeling and analysis phase could be more easily split between the team members, as well as so the systems could be created and tested individually. These include the Z-Axis which controls the feed of the capillary into the grinder, the X-Y axis, which controls where the capillary is located radially relative to the surface of the grinder, and the angular axis, which controls the angle of attack of the capillary relative to the surface of the grinder. The Pugh charts of these systems are shown in Figures A5, A6, and A7.

		<i>Z-Axis</i>							
	Weight	Spring / Damper System	Stepper Motor with Lead Screw	Pulley	Scissor Lift	Hydraulic Lift	Pneumatic Lift	Linear Actuator	Rack and Pinion
Precision	5	0	1	-1	0	-1	-1	-1	-1
Cycle Time	4	0	1	-1	1	0	0	1	1
Ease of Use	4	0	1	1	1	0	0	0	1
Cost	1	0	-1	1	-1	1	1	-1	1
Manufacturability	2	0	-1	1	0	0	0	0	1
Ease of Installation	1	0	0	1	0	-1	-1	1	-1
Compatibility	3	0	0	-1	0	-1	-1	1	-1
<b>TOTALS</b>		0	<b>10</b>	-4	7	-8	-8	2	2

**Figure A5:** Z-Axis Pugh chart, note that a stepper motor driving a lead screw was our top choice.

		<i>X-Y Axis</i>								
	Values	Actuator	Direct Drive	Rack and Pinion	Hydraulic	Lead Screw	Pneumatic	Chain and Sprocket	Gears	Pulley
Precision	1	0	0	-1	-1	1	0	0	0	-1
Cycle Time	3	0	0	0	1	0	0	0	0	1
Accuracy	2	0	0	0	0	1	-1	0	0	-1
Ease of Use	4	0	1	-1	-1	0	0	0	0	1
Cost	2	0	0	-1	1	1	-1	1	1	1
Manufacturability	2	0	0	-1	-1	1	-1	1	-1	1
Ease of Installation	3	0	1	-1	-1	0	0	-1	-1	-1
Compatibility	5	0	1	-1	-1	0	-1	0	-1	-1
Debris	5	0	1	-1	1	0	-1	0	1	0
<b>TOTALS</b>		0	<b>17</b>	-22	-5	7	-16	1	-3	0

**Figure A6:** XY-Axis Pugh chart, direct drive stepper motor configuration was chosen.

		<i>Angular Modulation</i>							
	Weight	Pin Joint	Pulley	Actuator	Direct Drive	Rack and Pinion	Jack Screw	Lead Screw	Ratchet
Precision	5	0	-1	-1	-1	-1	1	1	-1
Cycle Time	1	0	-1	1	-1	1	-1	0	1
Accuracy	4	0	-1	-1	-1	-1	1	0	0
Ease of Use	2	0	-1	0	-1	0	1	1	1
Cost	3	0	-1	-1	-1	1	1	-1	0
Manufacturability	3	0	-1	-1	-1	-1	-1	0	-1
Ease of Installation	3	0	-1	-1	-1	-1	-1	0	0
compatibility	4	0	-1	1	-1	0	1	1	1
<b>TOTALS</b>		0	-25	-13	-25	-11	11	8	-1

**Figure A7:** Angular Modulation Pugh chart, note that a Jackscrew was our top choice.

Finally, the top two choices from these three Pugh charts were combined into eight different systems, each having a different component. These were then weighted against a reference of a stepper motor Z axis, a direct drive XY axis, and a Jackscrew for the angular modulation.

		Favorite Concepts							
Weight		Z Stepper XY Direct Drive	Z Scissor XY Direct Drive	Z Stepper XY Leadscrew	Z Scissor XY Leadscrew	Z Stepper XY Direct Drive	Z Scissor XY Direct Drive	Z Stepper XY Lead Screw	Z Scissor XY Lead Screw
		A Jackscrew	A Jackscrew	A Leadscrew	A Leadscrew	A Leadscrew	A Leadscrew	A Jackscrew	A Jackscrew
Precision	4	0	-1	0	-1	0	-1	0	-1
Cycle Time	5	0	-1	-1	-1	0	0	-1	-1
Ease of Use	3	0	-1	1	1	1	0	0	0
Cost	1	0	1	0	0	-1	0	-1	0
Manufacturability	2	0	1	1	1	0	1	1	1
Ease of Installation	3	0	1	0	1	0	1	0	1
Lifecycle	4	0	0	1	1	1	1	1	1
<b>TOTALS</b>		0	-6	4	3	6	5	0	0

**Figure A8:** Concept Pugh chart, note that the winning selection was a Z-Axis stepper drive with a lead-screw, a direct drive X-Y Axis, and a Leadscrew for the angular modulation

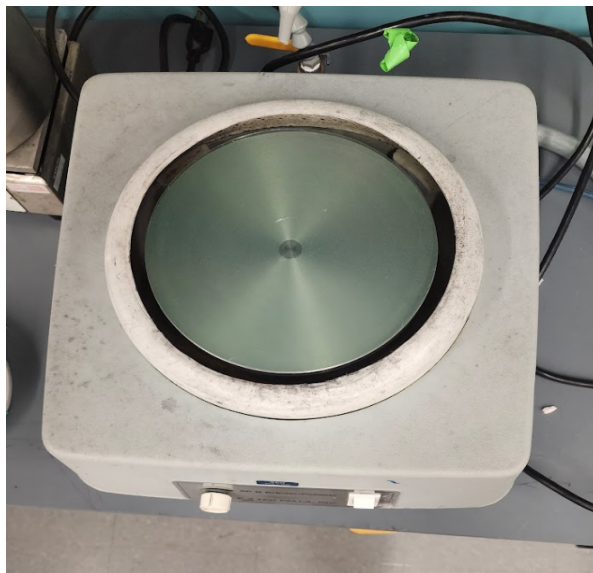
Assigning the scores in the pugh chart as seen above (Figure 16) was done with the following considerations. When compared to column 1 precision, ease of installation, manufacturability and cycle time scored the same as the reference getting a score of (0). Our final design selection based on the pugh chart has a higher cost. Cost was not assigned a high weight because: SLAC didn't assign considerations in our design requirements and we decided that the overall mechanism will cost a reasonable amount regardless of which controls we adopt. Therefore, even though cost scored lower than the reference design it did not have a significant impact on the final score. Our selection has better ease of use because direct drive (XY) will be easier to work with than the lead screw and a jackscrew in (A) would add complications to ease of use. Our selection also has a longer life cycle primarily because the Lead screw will last longer than the jackscrew since the jackscrew operates through elastic deformation of a metal bar which will fatigue over time.

## **E. Initial testing**

After our initial design analysis, our team received a shipment from SLAC labs which included the Ted Pella XP-8 grinder, which would be the basis for our design and what the team at SLAC would be using to polish their capillary tubes. Two images depicting the grinder are shown below in Figures A9 and A10.



**Figure A9:** Ted Pella XP-8 grinder (Front)



**Figure A10:** Ted Pella XP-8 grinder (Top)

Additionally, our team received samples of completed ground capillary tubes, as well as a not-yet prepared sample from the manufacturer Molex. Two images from our initial testing are shown below, beginning with a roughly cut capillary tube in Figure A11 and a hand-ground tube on the right in Figure A12.



**Figure A11:** Roughly hand-cut capillary tube



**Figure A12:** Hand-ground capillary

The goal of our initial testing was to get hands on with the grinder itself and the capillaries, and to understand the scale and precision of the task our team was assigned. As we quickly noticed, the size of the capillary tubes was significantly smaller than we had imagined, as well as more rigid than anticipated.

Furthermore, noticing the limitations of the geometry of the Ted-Pella grinder as well as the lack of any speed control informed our group very well of additional restrictions on our design that were unknown until our initial testing and hands on experience.

Another big step was understanding the inspection process and the requirement for live-video feedback while grinding, as a Q-Scope camera was also supplied to us by SLAC laboratories, which is what allowed us to capture the above images. A rough camera stand was constructed out of aluminum extrusion to attach the Q-Scope to the grinder, allowing us for live-feedback during the hand-grinding test.



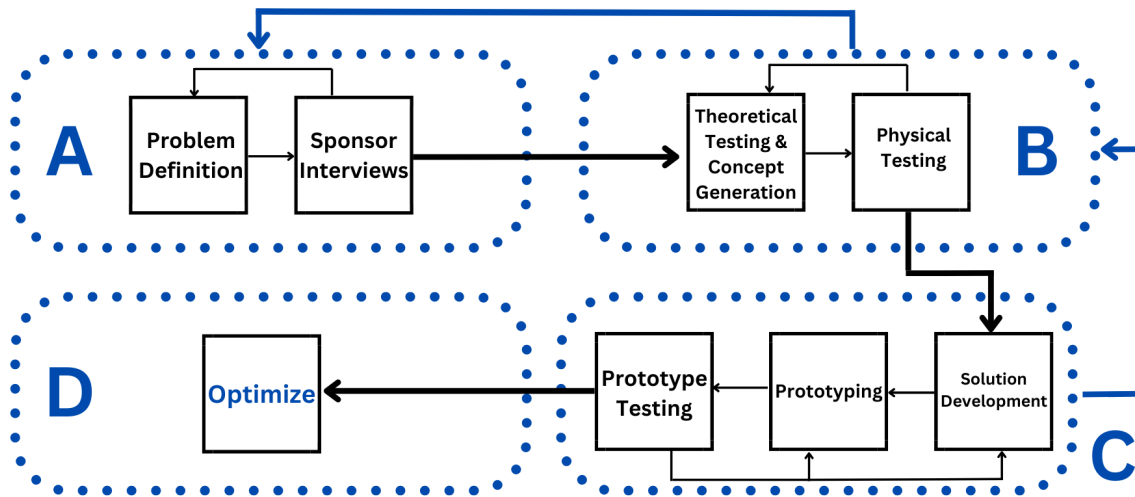
## **F. Design process**

Our project team considered following a solution-oriented approach, however it became evident that the problem definition needed to be extensively refined into engineering specifications and deliverables.<sup>1</sup> In this initial stage of our design process we realized that aspects of the problem were not clearly defined and prior attempts to solve the problem were not yet known. Therefore, the first stage of our design process has been activity based.<sup>1</sup> We developed an initial problem definition, then took those ideas back to our sponsor for feedback, then modified our initial problem definition. We used several cyclic iterations in this first stage focusing heavily on an accurate problem definition. Therefore, we are using a problem-oriented approach.<sup>1</sup> Furthermore, we have avoided any work towards design solutions in our first design stage as to not reduce the scope of our solution early on in the design process.

Our team will use, in the second design stage, a very different method than that of the initial problem definition stage. We see the activity based problem-oriented approach being replaced by a solution oriented approach. A solution oriented approach is necessary due to the short project timeline coupled with the fact that our first project deliverable is an automated mechatronic system to grind and/or polish the capillaries.

Due to the micron level precision needed for the automated mechatronic system extensive hands-on testing is necessary. Delivery of initial project equipment has been fulfilled by our project sponsor and we have begun theoretical and hands-on testing. We have modified our design scope based on this testing as stated above in our problem definition.

Our initial problem analysis is outlined in Figure.xx below. Block A, was focused on defining the problem through research and sponsor interviews. We took an iterative approach and modified our specification several times while receiving feedback from our sponsors to ensure that we were working towards an acceptable end product. Moving on to block B we began our design process by going through concept generation techniques discussed in detail below in problem domain analysis and reflection (pp ). We then took our design concepts and performed theoretical testing to determine the best designs that should move forward. Next we performed physical testing as discussed below in the initial testing section (pp ). We allowed the physical testing performed to inform our concept generation as far as it was able to. In block C we took our initial solutions and began prototyping our concepts. These prototypes were integral to our testing. Block C was also iterative and we allowed results of our testing to better inform our solution development to create prototypes that performed better than their predecessors. The last block in, block D, is a future block that we will not have sufficient time to fully explore. This last block focuses on optimization of our design through software development and generating documents for best practices while using the device in order to produce a consistent and acceptable capillary tube. A design process block diagram can be seen below in Figure **A13**.



**Figure A13:** Team 14 Design Process Block Diagram

Our project closely follows the ME 450 capstone design process framework, but is becoming more linear as we proceed further through the process.<sup>2</sup> Moreover, we have split the last design block, Solution Development and Verification, into smaller blocks. We expect to soon reach a stage of prototyping and testing. Also after the final design is created our team, given sufficient time, will focus on optimization of our design's controls system.

This figure represents the total design process our team has selected for use in our project. It features four main blocks, that being the problem definition and sponsor interview block which has been completed at the time of the writing of this report, as well as the next steps for our project. Note both the feedback aspects of our design process, which we hope to allow for extremely refined and tight design, as well as the last block in the chain, being that of optimization. This block is important, as we have narrowed our scope to suppress this step, and have elected to allow the optimization to be developed by teams further down the design process ladder, being either the team at SLAC, or a future ME450 design project. More information about this decision is given in a future section.

## **G. Engineering Analysis**

### **Z-Axis Stage:**

The key requirement linked to the Z-axis stage was the ability to travel with a resolution of less than 10 microns. When purchasing our part, we performed initial engineering analysis to verify that the stage we purchased would be sufficient.

Distance travelled per step:

$4\text{mm Pitch} / 40,000 \text{ Steps / Revolution} =$

0.0001mm per step, or  
0.1 micron per step

Our Z-Axis target resolution: 10 micron

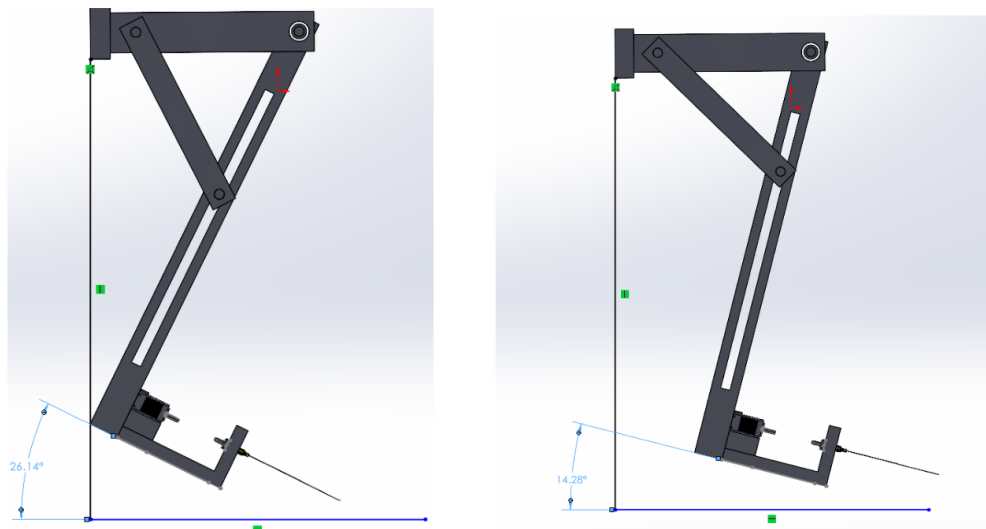
Our ballscrew has 100x the resolution we targeted!

### **Figure A14: Analysis of Z-stage**

We feel that this level of analysis was sufficient to be confident in our system. Our only concern was with backlash, as we were unsure if any would occur when force is applied to the system or a change of direction occurs. However, because what is attached to the Z-axis stage is quite lightweight, and there are very small forces being applied through grinding, we felt this concern did not merit more engineering analysis. We planned to verify the lack of backlash experimentally, the results of which will be discussed in further detail later in the report.

### **Angle Modulation:**

The key requirement linked with the angle modulation is the ability to adjust the angle of the capillary tube from 15° to 35° in 20 discrete steps. Since we have not yet built this part, the only verification we have performed is through SolidWorks.



**Figure A15: SolidWorks Verification of Angle Modulation**

In the above figure, we can see the previous design for the arm, along with a measurement of the angle of the capillary tube with respect to the grinding wheel. This system shows we would be able to achieve angles from  $14.28^\circ$  to  $26.14^\circ$ . This did not reach the standard set by our sponsor, which led to our redesign.

Because we are manufacturing with tight tolerances, we feel that simply using the geometry in SolidWorks is sufficient to ensure we will be able to achieve the full range of angles. We are quite confident that upon the manufacturing of these parts, they will perform nearly identically to what we see in our CAD.

We have updated our design near the writing of this report to accommodate angle modulation from  $15^\circ$  to  $35^\circ$ . As a result we do not yet have the final CAD model to display in this report. However a solution has been reached and verified to function as needed.

### **Capillary Rotation:**

For this section, our main concern was that we needed to be able to rotate the capillary tube as it was being ground in order to have it be axisymmetric. Due to the lightweight nature of the tubes, we determined that in order to spin the capillary tubes a very small motor would be capable of providing enough torque to rotate it. This was ideal for us, as based on what we know about statics, the greater the weight at the end of the arm, the greater the moment that will be applied to the supports. Since our initial prototype is using PLA for the arm holder, we wanted to prioritize minimizing the weight. This is why we chose the NEMA 8 motor, as it provides 2.3 oz. in. of torque while only weighing .35 ounces. While we did not perform detailed calculations for the amount of torque needed to rotate the tube, our engineering intuition told us that this would be enough to do so, which we were able to verify upon receiving the motor.

### **Summary:**

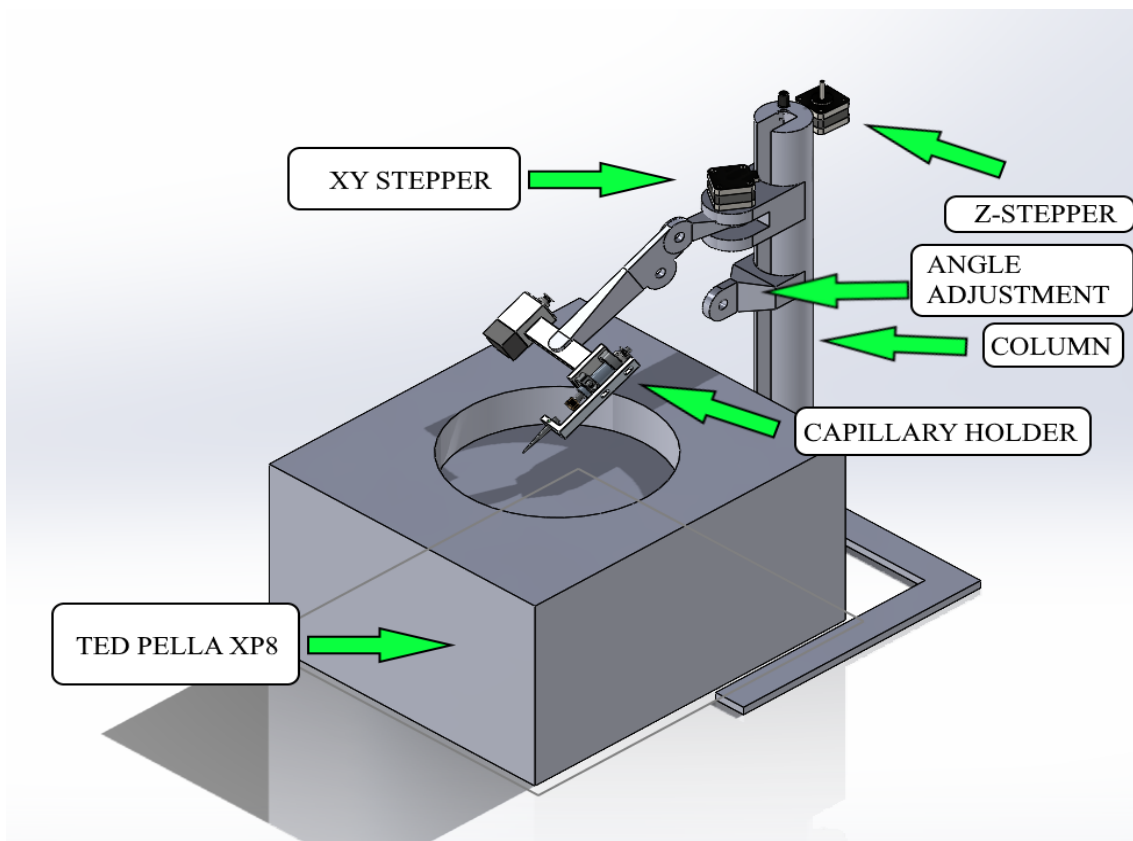
The remainder of our specifications are far too complex for us to accurately determine by engineering analysis. For example, we do not have the knowledge to determine if our system will be able to create a desirable product > 70% of the time. For this reason, we chose to focus on the Z-axis control, angle adjustment, and capillary rotation for our engineering analysis. We believe that if our system is capable of reaching those requirements, the other requirements will follow. Our plan is to verify the remainder of the specifications experimentally, as that will give us and our sponsors a much more realistic expectation of the performance of our system.

## H. Alpha design

### Overall Design

In this section we analyze our initial design prototype and show the relationship between it and our down selection process. Also discuss the next steps for the alpha design, like our thoughts on removing the angle adjustment leadscrew for simplicity and better accuracy.

Following our down-selection process, our team began to design an alpha prototype utilizing the design elements of the Pugh charts, meaning a Z-Axis stepper drive with a lead-screw, a direct drive X-Y Axis, and a Leadscrew for the angular modulation. These elements were then designed in our 3D modeling software of choice, Solidworks. This design is shown in Figure A16 below:

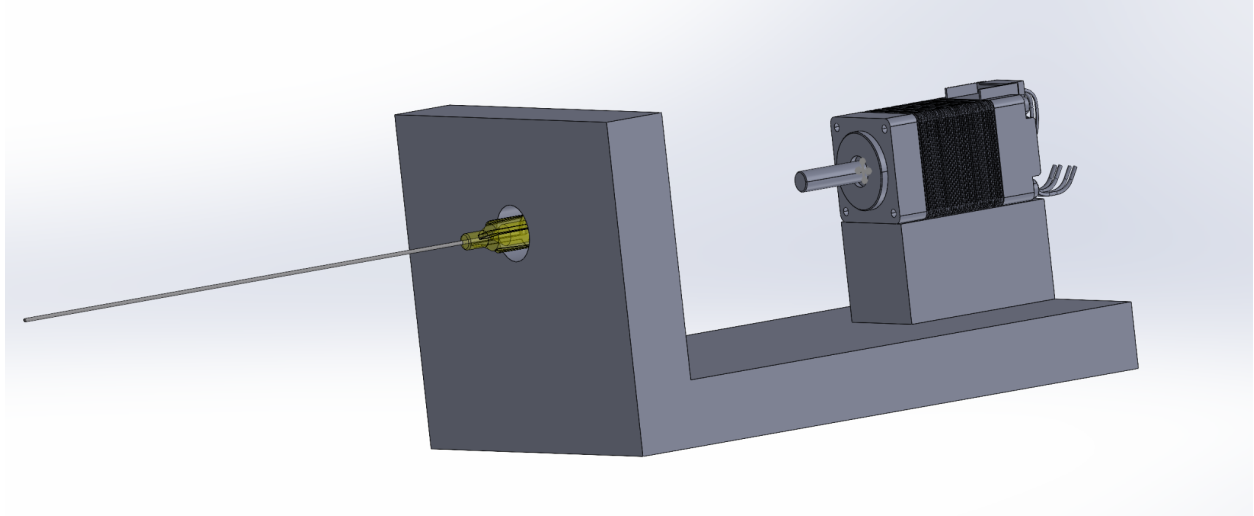


**Figure A16:** Alpha CAD design incorporating the elements from our down-selection process.

### Capillary Holder

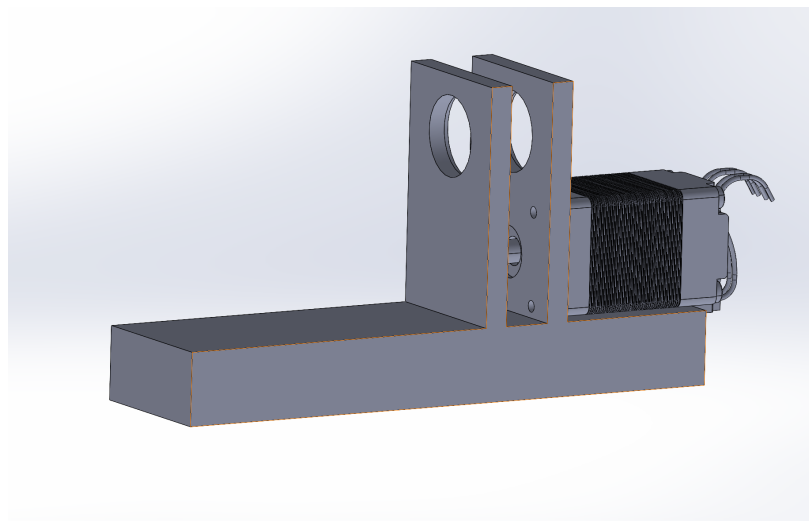
The first capillary holder was designed with a Nema-8 stepper motor positioned in-line with a guide tube, this was done with the idea of simplicity, to avoid any belts or gears that might complicate the design and add weight to this module. Below in figure.xx is the CAD model of this design. The only cylindrical metal tubes we were able to find within our budget were 22 gauge medical dispensing needles. The needle

size needed to be 22 gauge, because it offers an inner diameter of 413 micrometers, whereas a 23 gauge is too small with an inner diameter of 337 micrometers.<sup>8</sup> This measurement is critical, as the capillary tubes our sponsor works with have an outer diameter of 360 micrometers, thus giving the 22 gauge needles 53 micrometers of clearance, which is sufficiently tight for our requirements. We opted to purchase four inch needles so they could be cut to any needed length.



**Figure A17:** Capillary Holder Design 1

Design 1 did not make it past the CAD phase and a physical prototype was not created. After the team met and reviewed the design it was determined that the sponsor would be better served if the capillary length was not constrained by the placement of the motor in the design. Therefore the design was updated so that the motor sat below the capillary holder, thus allowing a through hole to accommodate a capillary of any reasonable length. Design 2 was also updated to include mounting holes for the motor, 2 support bearings, and made lighter weight. It was important to physically prototype this second model to verify the components fit properly and as a result the capillary support was not included in this early stage. This second design can be seen below in Figure A18.



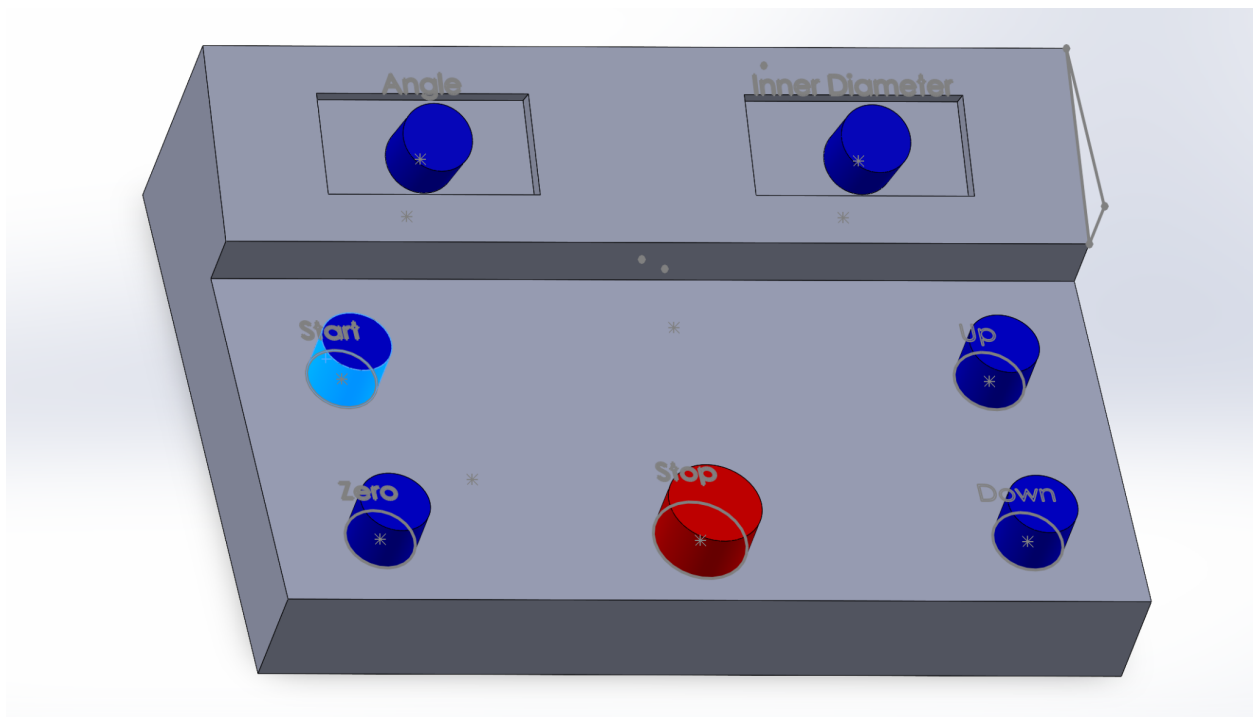
**Figure A18:** Capillary Holder Design 2

Design 2 was 3D printed and hands-on testing revealed that assembly was difficult and fitting gears into the small space between the two supports was not ideal. We found that the vertical supports were not strong enough when 3D printed which meant we would need to thicken the first support and remove the second. Therefore Design 3 created 3 subassemblies for easier manufacturing and assembly. Design 3 also has one support instead of 2 in order to allow easy access to the custom gears that will be created at a later stage. Design 3 can be seen below in Figure A19.

## Controller

After this alpha design was created, our team analyzed it and received feedback from our section instructor on plausibility. Our team then came to the realization that the design could be simplified and the rigidity and accuracy significantly improved by the removal of an automated angular modulation system. Therefore our team has settled to use a solution similar to that which SLAC is using at the moment, being a simple pin joint which is clamped together with a screw to lock it, with an electronic angle gauge being used to precisely measure the approach angle of the capillary relative to the grinder surface.

To allow for ease of use, we have determined that a small controller with two simple seven segment displays will be ideal. In **Figure A19** below you can see a simple alpha design for our controller.



**Figure A19:** Alpha Controller Design

The capillary tubes have a standard outer diameter of 360 micrometers, however the inner diameter can vary depending on the experiment. Therefore a control allows the user to input the inner diameter, which is critical to the grinding process as the outer diameter cannot be ground all the way through to the inner diameter. The capillary tubes will be set to specific angles based on the experiment. Therefore a control allows the user to input the approach angle of the capillary to the grinding plate, which will be determined with a digital angle meter. The program needs to know where the grinding plate is located so that it can





## **I. Project Challenges**

After going through the manufacturing process we realize that one of our biggest challenges will be figuring out an efficient way to zero the system in order to determine the distance we want the arm to move, and when to stop. There are also issues concerning the deflection of the tube, however there are some ideas to deal with that, for example having a stopper to stop the capillary tube at the same distance every time very close to the needle, but this is something that we will continue to verify through the process.

Optimizing the system after our system has been designed and built will be a challenge and time consuming process. We do not expect that we will have time for extensive optimization which makes optimization a challenge as well. If we do not do so then we will need to have a thorough documentation to pass off to the next design team or to SLAC labs to complete the optimization of our system.

### **DR3 Challenges**

As we are nearing the end of the semester and the design expo, we have a few challenges that we are hoping to overcome. The first that we envision is with assembly of the “final” prototype. The majority of our parts have been manufactured at this stage, but we have not connected them all. There is the concern that when we do complete this assembly, all parts will not mesh and work the way we initially thought. In the event that this happens, we are prepared to quickly redesign and manufacture parts that alleviate any problems that occur. Because we completed detailed CAD work, we are confident that any changes that will need to be made will be minor. As well as this, many of the remaining parts will be 3D-printed. This allows for us to easily make the changes and have the new parts in hand with a fast turnaround time.

The next set of issues we foresee is with programming the system. While you have seen our preliminary plans for a control system above, we have not begun to implement this, as we don't have our final assembly together. We feel it would be unrealistic to expect the system to work optimally upon connecting it to our controller, so we anticipate spending time troubleshooting the system in order to gain the level of control that our sponsors would like over the system. This time will be reflected in the upcoming Project Plan and Schedule.

Another issue that we anticipate will likely fall under the reach of the next team to work on this project is with “zeroing” the system. Due to the incredibly small size of the capillary, it is incredibly difficult to tell when the capillary first touches down on the grinding pad visually. Because we would like the grinding process to be autonomous, it is very important that a solution to this issue is found.

### **Lessons Learned :**

As the manufacturing process commenced, there were many unforeseen obstacles that occurred to be dealt with. One of the first problems we had was the rotary motion from the lead screw that was used in the column. There was tolerance between the column and the follower which is traversed by the rotation of the lead screw, which led to the existence of unwanted play along with the linear motion we were trying to achieve. As a result, the capillary holder mount we designed to connect with the lead screw had extrusions on both sides, in order to negate and minimize the side to side motion. This allowed us to realize that even if you have a 3-D model that works theoretically, it does not always address the manufacturing problems that arise such as unwanted clearance, however, verifying that the components

work as intended before assembling everything allowed us to recognize those problems and come to solutions.

Another problem that we faced was trying to get the angle modulation correct. The design initially had the arm rotate in order to get the desired angle. This proved to be more challenging than expected because we had very little tolerance for the variety of angles needed without having the arm interfere with the column. This was recognized with a virtual rendering, and checking for the angles we wanted. As a result the problem was addressed by keeping the arm fixed, and rotating the capillary mount instead, which allowed us to get the angles we wanted without it interfering with the column. This allowed us to learn that the use of virtual tools, even if not super extensive, can prove to be very useful especially when dealing with geometries, and it can be varied much easier than a physical model. It also prevented us from going down with the design that we had intended earlier, which would have led to less flexibility in the manufacturing process.

## J. Project Schedule/Plan

Our project plan will closely follow the ME 450 milestones – items that are required to be submitted at specific dates. The big picture for the project is outlined in the gantt chart below in **Figures A21- A25**, which focuses on design presentations, design reports, and items for the design expo at the end of this project. The most important items to complete are in red, medium priority items are in orange and low priority items are in yellow. Each vertical gray area denotes each weekend, the vertical green bar represents today, and each vertical blue bar represents the passing of each month.

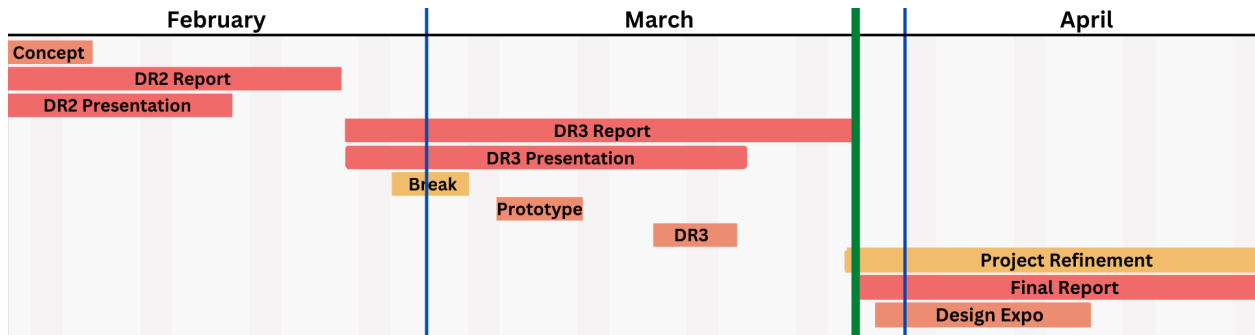


Figure A21: Project Overview

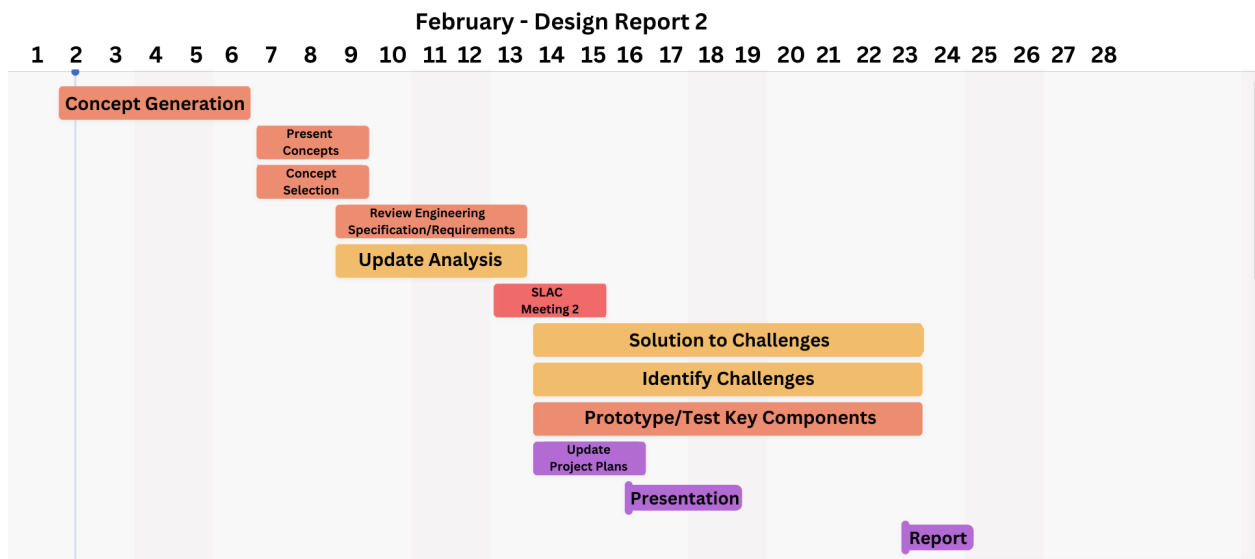


Figure A22: February Overview; Design Report 2

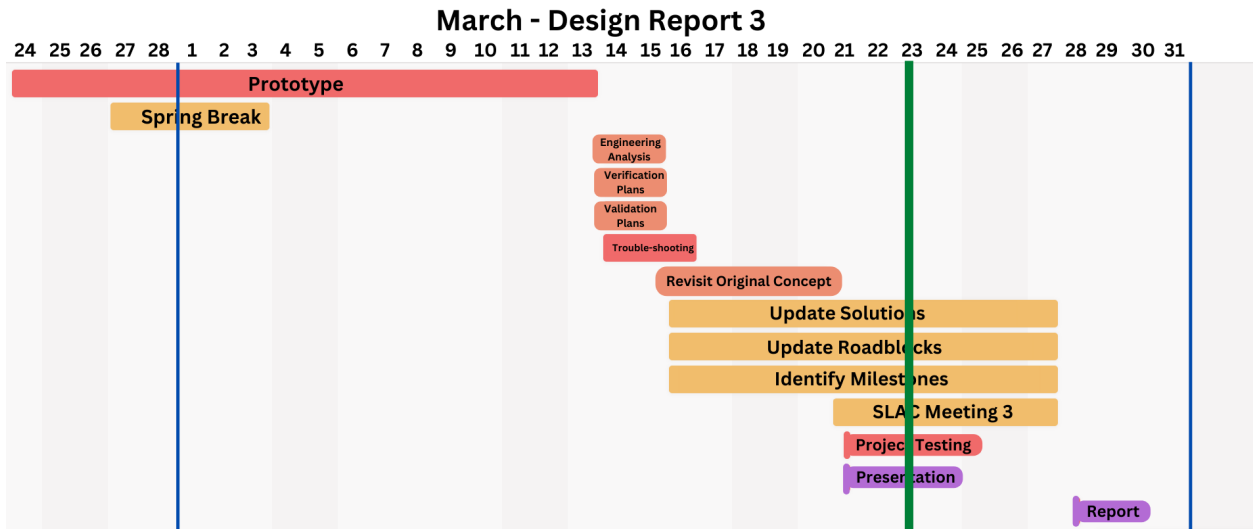


Figure A23: March Overview; Design Report 3

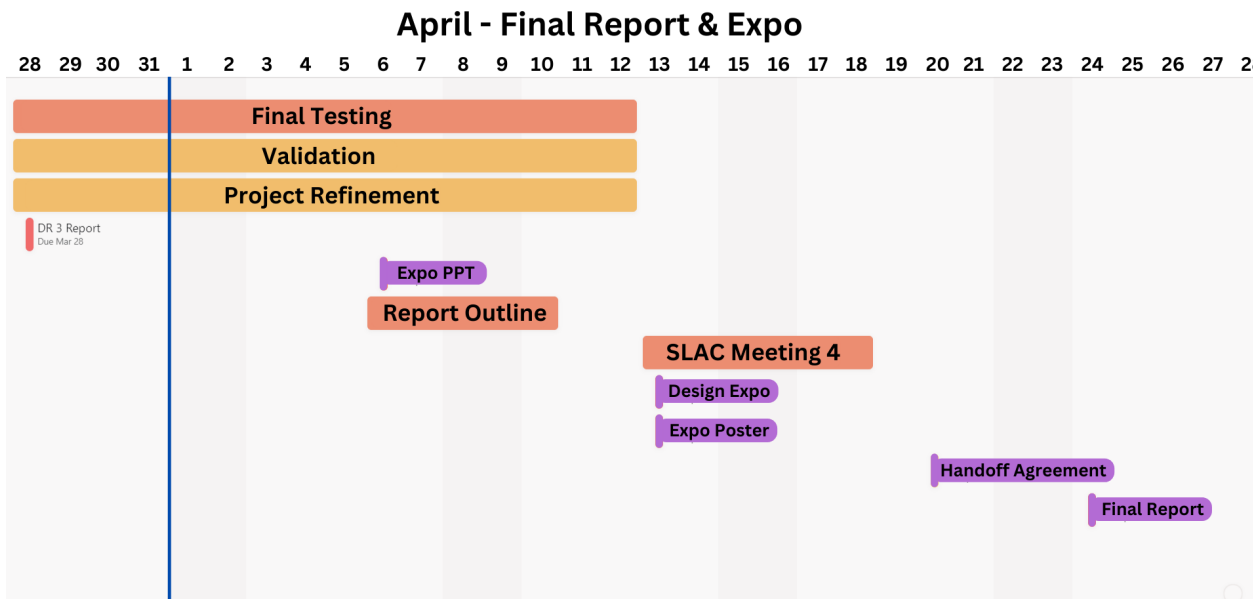


Figure A24: April Overview; Final Report and Exposition

Our team, upon careful consideration of the project scope and requirements set out to us by our sponsors, as well as through discussions with the sponsors themselves, have concluded that the scope of this project in its initial state was not achievable in the tight time constraints of a semester. Therefore we have elected to further refine the project scope to a much more manageable set of requirements that we aim to achieve before the end of this project. We hope to fully define the design problem, set up a framework for development given the key parameters for success, and develop a working prototype with hardware to be handed off to a future ME450 project group for optimization.

Furthermore, we believe that given the requirements and time constraints for the project considering our restricted project scope, we have developed a schedule that is attainable and manageable. Some upcoming tasks and milestones are the DR3 presentation and report.

With respect to the allocation of assignments, our team has agreed to not separate any specific tasks to one individual member, hopefully reducing bias and tunneling of tasks. We employed this strategy to provide an equal opportunity environment for learning for all of the team members involved, such that every member will receive the same exposure to the topics and creations this project will entail.

With regards to the most important steps to consider for our project, the most pressing for our team at the moment is the prototyping, alpha design, and testing – and the decisions made therein. Those decisions will ultimately dictate the future of our project and the end product for our team. We have already reduced conflict by utilizing design tools such as Pugh charts to analyze designs in a fair and objective way, such that no team member feels excluded in the design process. Furthermore, we have extensively discussed the financial constraints associated with our project, and anticipate that our project will reach those bounds. We still do not anticipate the need of an extended budget for our project, however, as we are confident in our abilities to design a solution that meets our requirements and specifications while maintaining under the project budget. Lastly, given the altered scope and our allocations of time within our team, we anticipate that our group will be successful in our goals of solving the design project given to us, and will not require additional support through additional team members.

## **K. DR1/DR2/DR3 conclusions**

### **DESIGN REVIEW 1 CONCLUSIONS:**

To summarize our initial design problem definition and exploration, we have narrowed our scope to reflect the project timeline and budget, as well as defined the key parameters for success both in our case and for that of the sponsor. Furthermore, to reiterate the problem statement given to us: SLAC Laboratories, a Stanford Lab in California, uses ground micro-capillary tubes in the sample delivery stage of their experiments, and is seeking an improved and automated method for the preparation of these tubes which will reduce preparation time. Specifically to make a machine/robot that interfaces with their capillary holder and positions the capillary for grinding on a Ted Pella XP-8. Given this problem statement, we have analyzed thus far the design process, problem context including stakeholder analysis, design considerations including user specifications and requirements, design domain identifying the key four engineering domains our project will operate in, and have developed a project plan with specific milestone dates to adhere to. We have also, through close contact and collaboration with our project sponsors, developed a technical understanding of the current process our team seeks to optimize, as well as conducted research into the standard industry practices and possible design spaces.

### **DESIGN REVIEW 2 CONCLUSIONS:**

After the completion of the DR2 presentation, we had a meeting with our stakeholders Raymond, Mason, and Stella. The presentation was informative, and some of the few takeaways were as following: The angle modulation would not need to be controlled by a direct drive, instead it would make more sense to have a pin joint system, something similar to what they are currently using. As we looked at our alpha design we realized that connecting x-y components with the angle modulation would be bulky and could cause issues with connecting the joints. One of the current issues that the current design has is the capillary tube holder coming in contact with the grinding surface as the angles got shallower and getting grinded away as well. In order to combat that we would also have to modify the capillary tube holder, or decrease the difference between the capillary tube holder and the stepper motor. The grinding paper gets eaten away as the capillary tube is grinded over time. As a result, one of the things that we need to test and consider is, if we want to move towards the center as the grinding process continues or if we want to keep it at the same radial position. This will have to be determined after testing, as the importance is on the speed and not the grit paper, and either of those solutions is viable as long as it is faster than before.

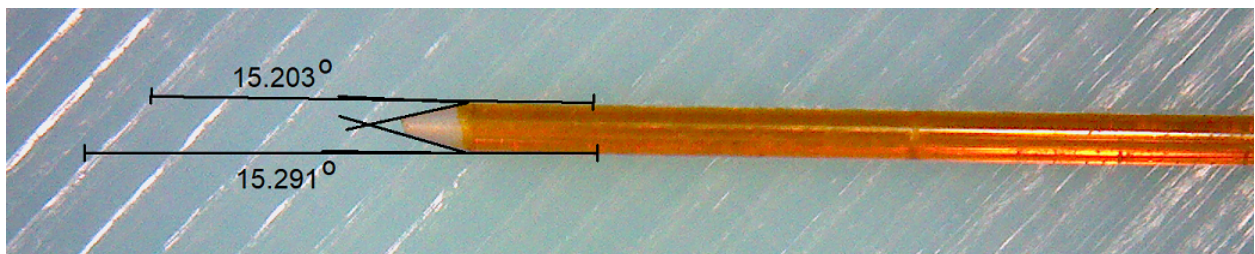
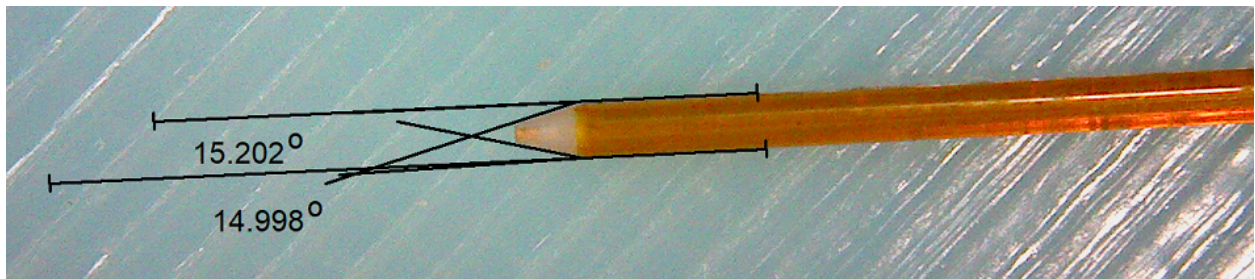
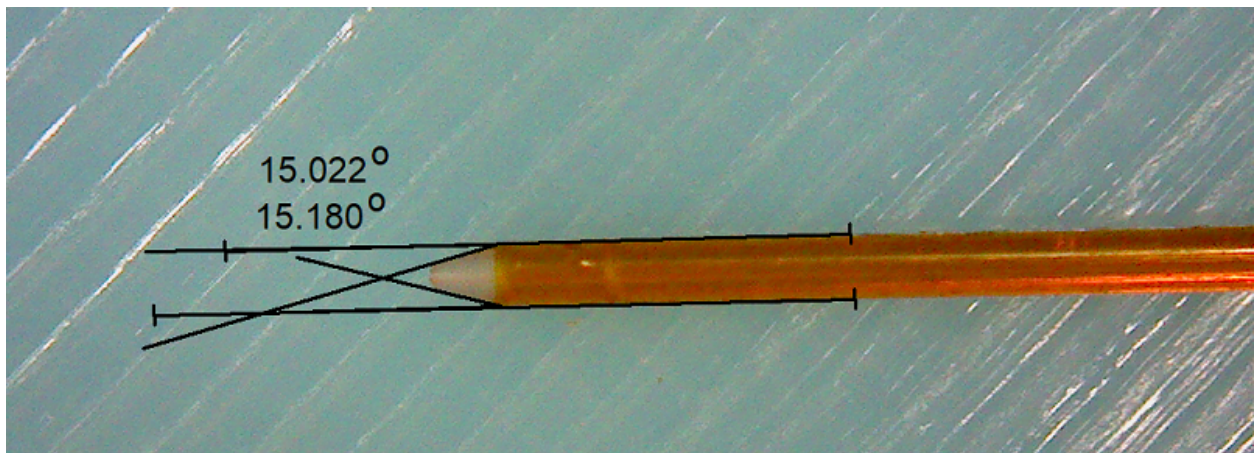
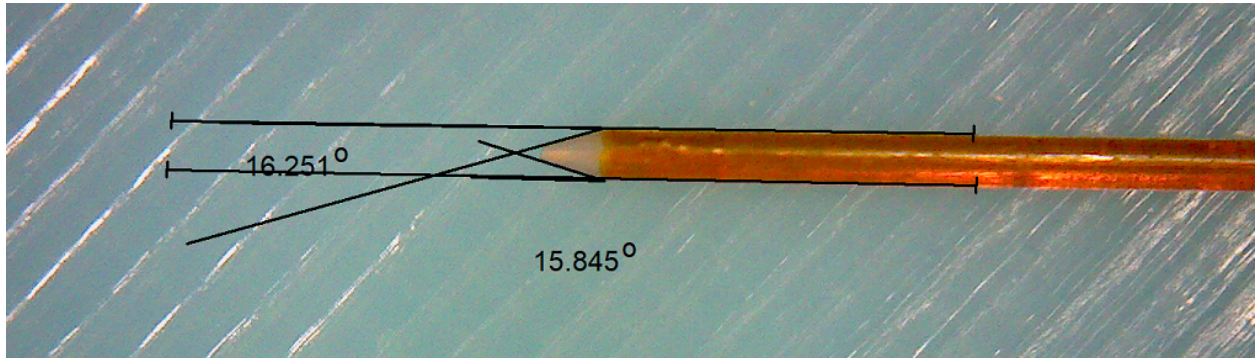
### **DESIGN REVIEW 3 CONCLUSIONS:**

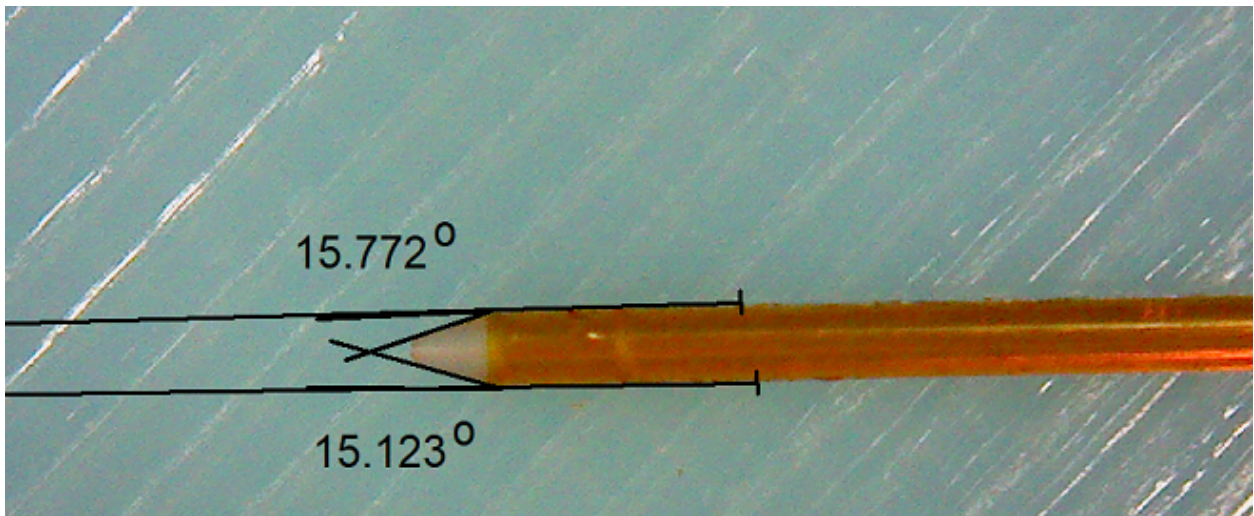
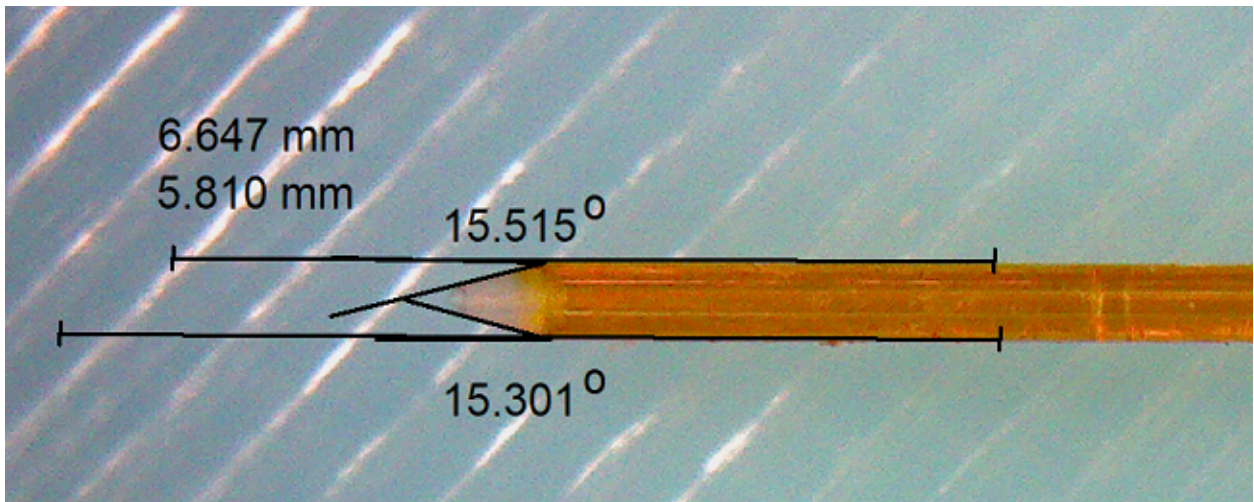
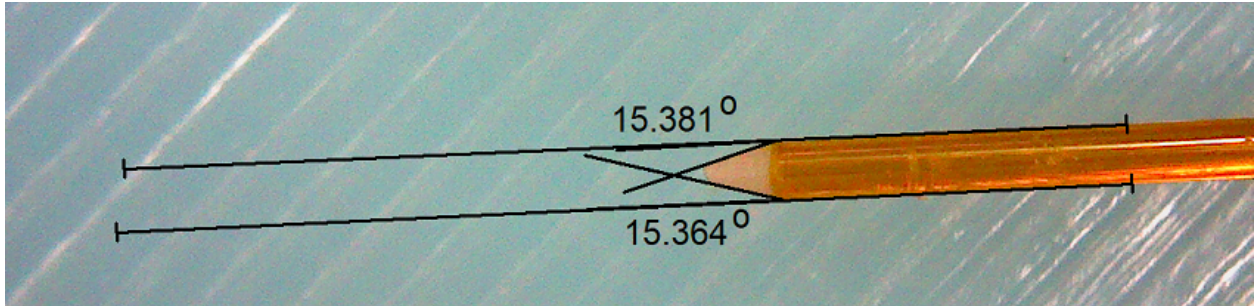
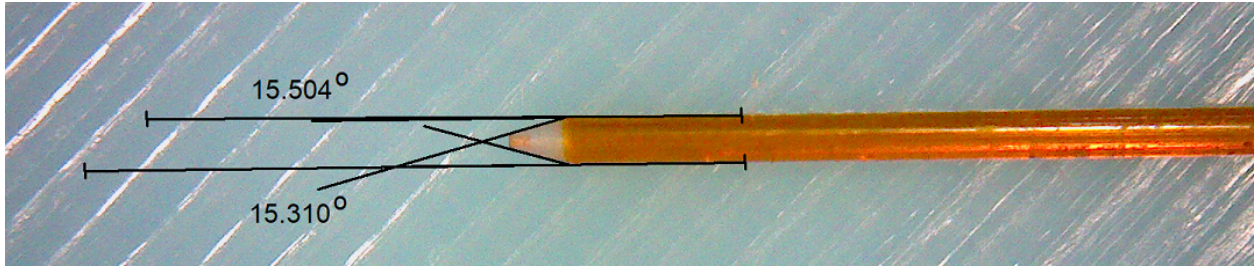
To summarize the work we have completed since Design Review 2, we have selected, purchased, acquired, machined and assembled many of the important subsystems critical to the functionality of our design, and are in progress of the verification and validation steps of our project, while finalizing and manufacturing other parts of our design. We are very pleased with the progress that has been made thus far, and are extremely optimistic that we will be able to display and deliver a promising design and prototype to our sponsors by the deadlines set out for us.

## L. Validation

Images here

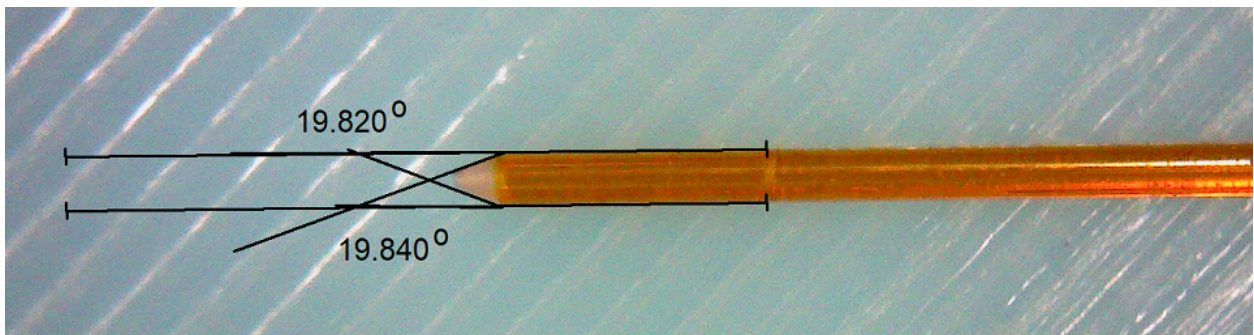
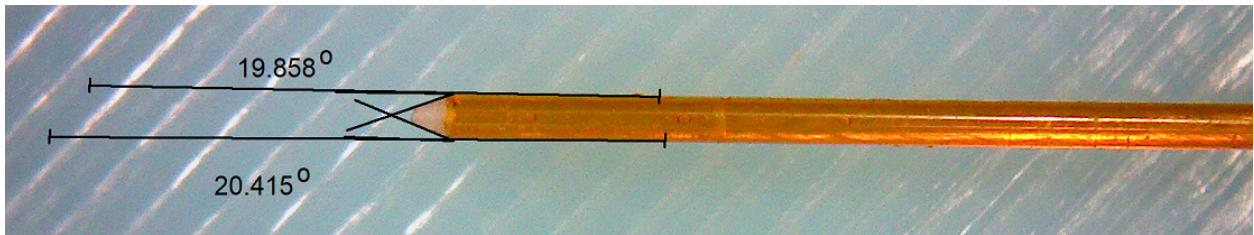
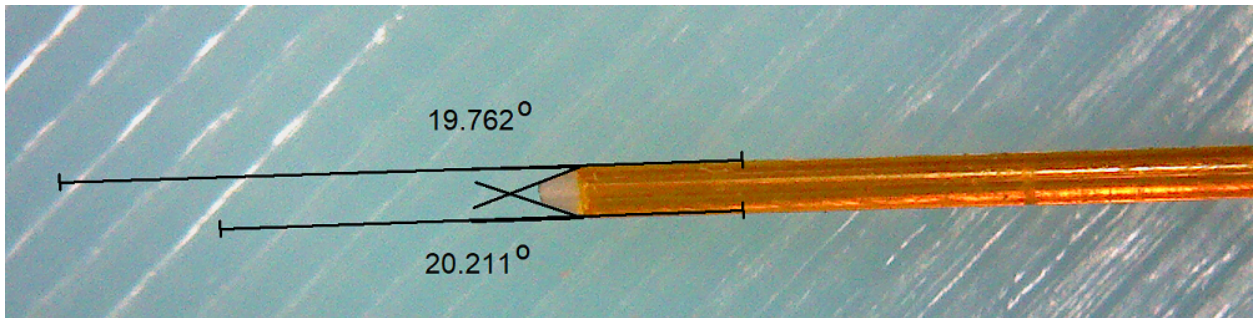
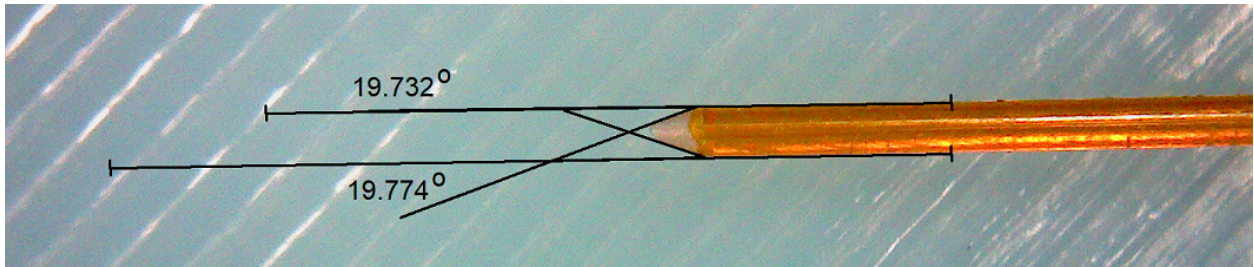
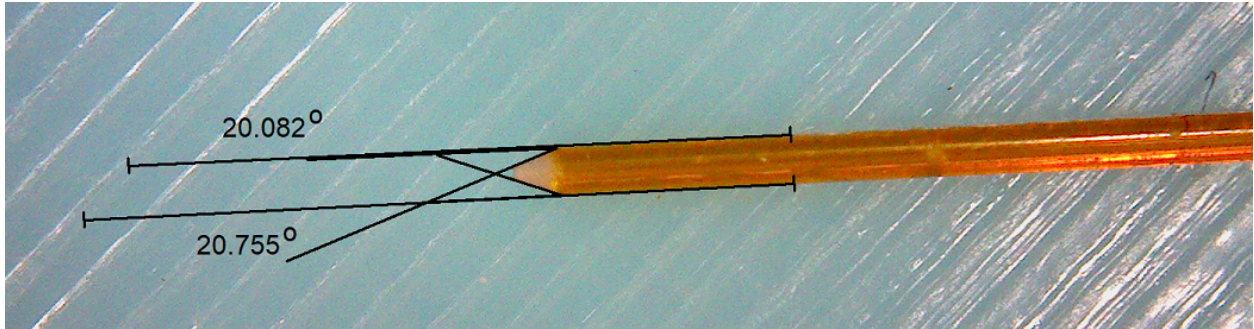
15 Degrees





20 Degrees





**35 Degrees**

