NORTHERN ARIZONA UNIVERSITY

School of Informatics, Computing, and Cyber Systems

Umfang - Partial Design Report

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School of Informatics, Computing, and Cyber Systems

EE 486C - Capstone Design

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Introduction:

Our client, Dr. Carlo daCunha stated that a design requirement of the scanning tunneling microscope is sub-nanometer resolution to aid in the understanding of silicon devices on an atomic level, and that the STM stays within the $500 budget. We further discussed the requirements and the hardware options for the STM and settled on a design using an Arduino to collect data of the tunneling current and to control the piezo driver with some code and a quad-channel DAC sending signals to our piezoelectric disc, controlling the scanning process. The Umfang team consists of our Treasure and partial secretary Nicholas Arnold and the Leader and partial secretary Nathan Shoults. As the team lead, Nathan is in charge of circuit design and project management. As treasurer, Nicholas is in charge of the team's budget and ordering parts and will take the lead on soldering and PCB design. Both group members communicate and split the task of assignment completion and submission.

The STM project has been attempted in the past and has had a mechanical engineering team taking the lead on the vibration-damping solution for the STM. The previous work includes the damping solution, a framework in which we are limited to operate, and some obsolete circuit designs. The framework set by previous teams limits us to using a 20mm piezoelectric disc as our scanning mechanism and using the mechanical engineering team's vibration-damping solution.

Problem Statement:

Statement of Needs:

The STM has a few important marketing requirements that need to be met throughout the construction of the project. Firstly, the STM needs to have an efficient design to ensure it is cost-effective, serviceable, and easily assembled. If the STM is over-engineered, the product will have difficulties being adopted and will be overlooked for more simple and easy-to-use products. Secondly, the STM must be accurate in measurements down to the nanometer scale to achieve near-atomic resolution which will require us to source low-noise components and to physically isolate the STM from both mechanical and electrical noise. Accurate and precise imagery is a key selling point of an STM, if the microscope does not take good images, it is a bad microscope and will be overlooked for a product with clearer images. Lastly, the STM must be easy to use which is imperative for the distribution of the product to educators which includes strong documentation, data analysis, post-processing, and software that we choose for scanning. It is paramount that the STM team keeps strong documentation on the components including data sheets and schematics to best serve the customer, and it is the responsibility of the team to create a simple yet effective solution for data analysis that can easily be adopted.

The expectation from the client, Dr. daCunha, is that the team delivers a cost-effective STM utilizing off-the-shelf components in a resourceful manner. It is expected that the STM will be reproducible and have accurate measurements. However, measurements may be low-quality when compared to a more expensive competitor such as Keysight or Nanosurf. It is also expected that the team is punctual and responsive with the client and that the team asks clarifying questions to better understand the scope and objectives of the project. Limitations of the project include the tradeoff between cost and accuracy, since a lot of the higher-quality and accurate components are more expensive, and the lack of precise mechanical equipment such as the etching process for the tungsten tips and the process of inserting and attaching the tip to the piezoelectric disk. Although there are limitations, it is a fun and exciting challenge to be able to work on this project and create an affordable and easy-to-use STM.

Statement of Objectives:

The STM project aims to achieve specific, measurable, and achievable goals to guide the team to successfully construct an affordable STM that can be further used and improved upon for and in future research. The objectives of the project are to construct an operational STM, acquire and analyze STM data, optimize the STM performance, and create thorough documentation and reporting throughout the project.

1. Construct an STM

- Specific: Research and explore the required circuits and components to create an STM, and find affordable components within the project budget to assemble a working prototype, followed by a completed product. Furthermore, the team will research and develop software and protocols for capturing images with the STM that can easily be used by anyone who wishes to use the STM.
- Measurable: The STM will stay within the allotted project budget and be capable of achieving nanoscale resolution to capture fine details of extremely small surfaces and devices.
- Achievable: By the end of the first semester, we will have a prototype to capture a tunneling current without the implementation of the movement with the piezoelectric disk, and by March 2024 we will have a working prototype to optimize and capture images.

2. Acquire and Analyze STM Data:

- Specific: Acquire, process, and analyze data from the STM to create a nanoscale image of a material.
- Measurable: The team will publish images in documentation and on the capstone website.
- Achievable: By the end of the fall semester, the team will be able to scan a stationary tunneling current, and by the end of the spring semester, the team will be able to capture images.

3. Optimize STM Performance:

- Specific: Optimize performance of the STM through post-processing and the isolation of noise.
- Measurable: The STM will be able to achieve nanoscale resolution and photograph the rough atomic structure of graphite, or will be able to take extremely clear and detailed images.
- Achievable: By the end of the fall semester the team will measure a constant tunneling current, and by the end of the spring semester, the team will capture complete images of surfaces.

4. Document and Report:

- Specific: The STM team will create and maintain documentation throughout the project of schematics, assembly notes, problems and solutions, as well as experimental results.
- Measurable: Document all components, circuits, and prototypes with pictures and descriptions.
- Achievable: By the end of the fall semester, the team will create a comprehensive documentation of the work thus far, and this will be extended in the spring semester to include operating instructions.

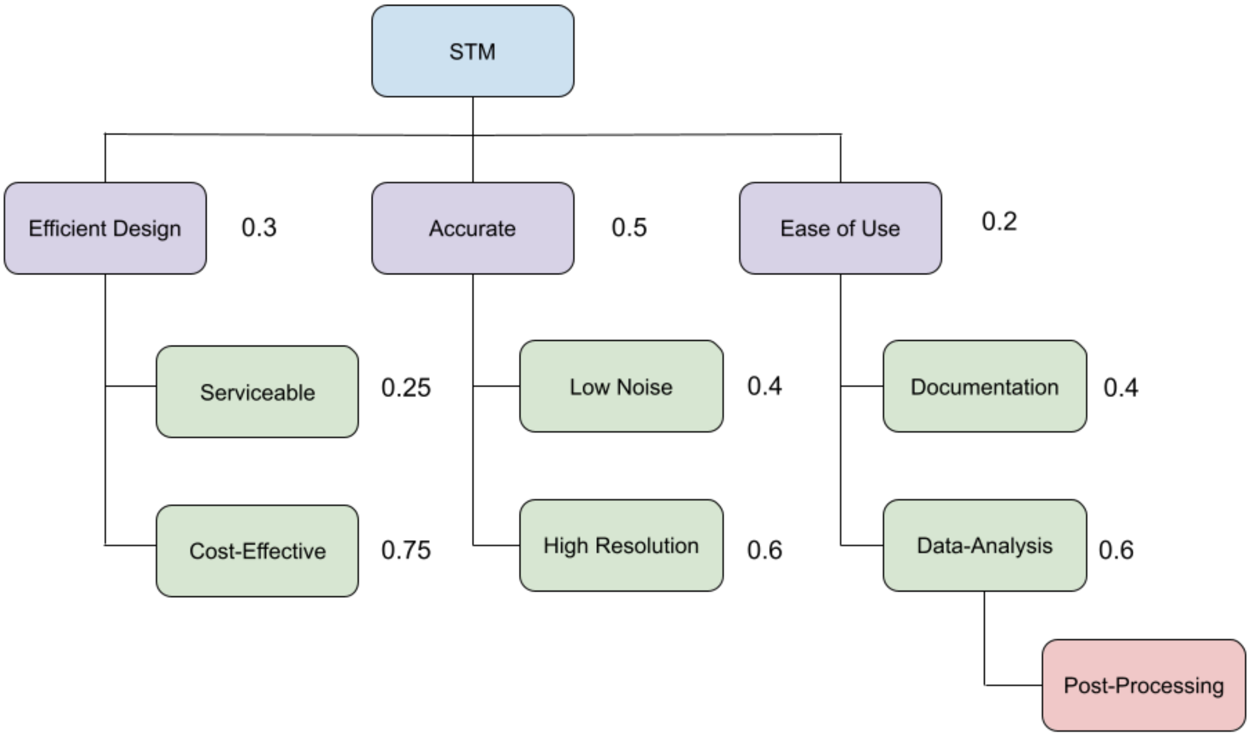


Fig 1: Objective Tree

The objective tree shows our marketing requirements along with the weights associated with each requirement and sub-requirement. As shown by the overarching objective tree, we will be focusing the most on providing accurate measurements with our STM given the budget and restraints that we have followed by creating an efficient and effective design and developing an easy-to-use platform for users of our product. By following this framework, our STM will be able to capture images with high accuracy and will be easy to assemble by the end of the year, which may push some of the ease-of-use features into future work, although the team is confident in the ability to complete all the objectives by the end of the project.

Concept:

We started the project with the idea of an STM unit that will be able to process and display a topographical image of data collected of the tunneling current from the STM. While this is a difficult task, we have come up with some circuit designs and some code to implement stages of the project. We have implemented the transimpedance amplifier circuit, while having a couple of solutions for the feedback loop including both hardware and software solutions.

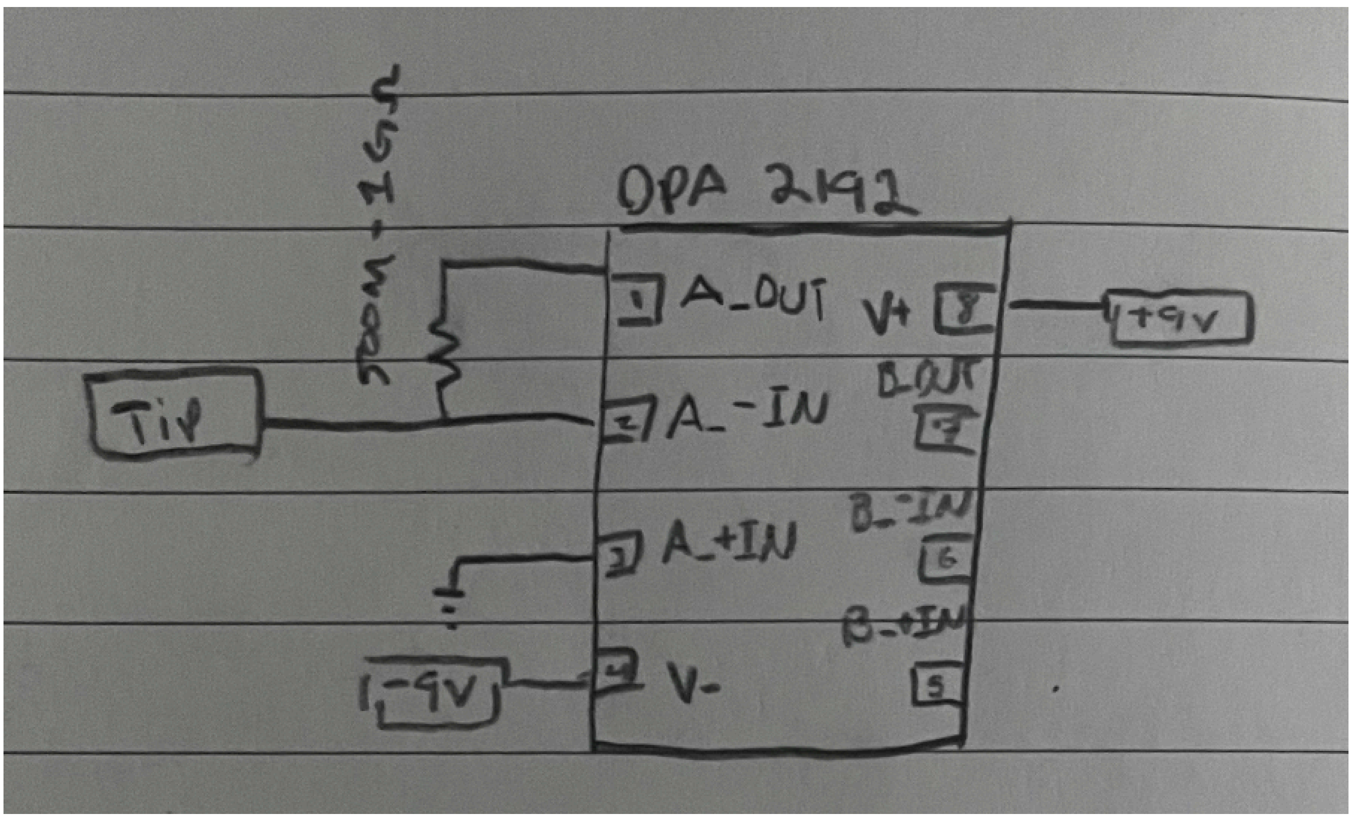


Fig 2: Transimpedance Amplifier Circuit Schematic

Figure 2 shows the schematic of the transimpedance amplifier circuit implemented on an OPA2192 dual op amp component, the op amp is given ±9V as power and as a signal is connected to the atomically sharp tungsten tip. The feedback resistor is between 500MΩ and 1GΩ depending on how much we need to amplify the tunneling current. We later added a 100pF capacitor to this circuit in parallel with the resistor to create a low-pass filter which smooths the voltage and filters out noise. The transimpedance amplifier will amplify the tunneling current given in amps, and will output an amplified signal in volts for data processing by the Arduino.

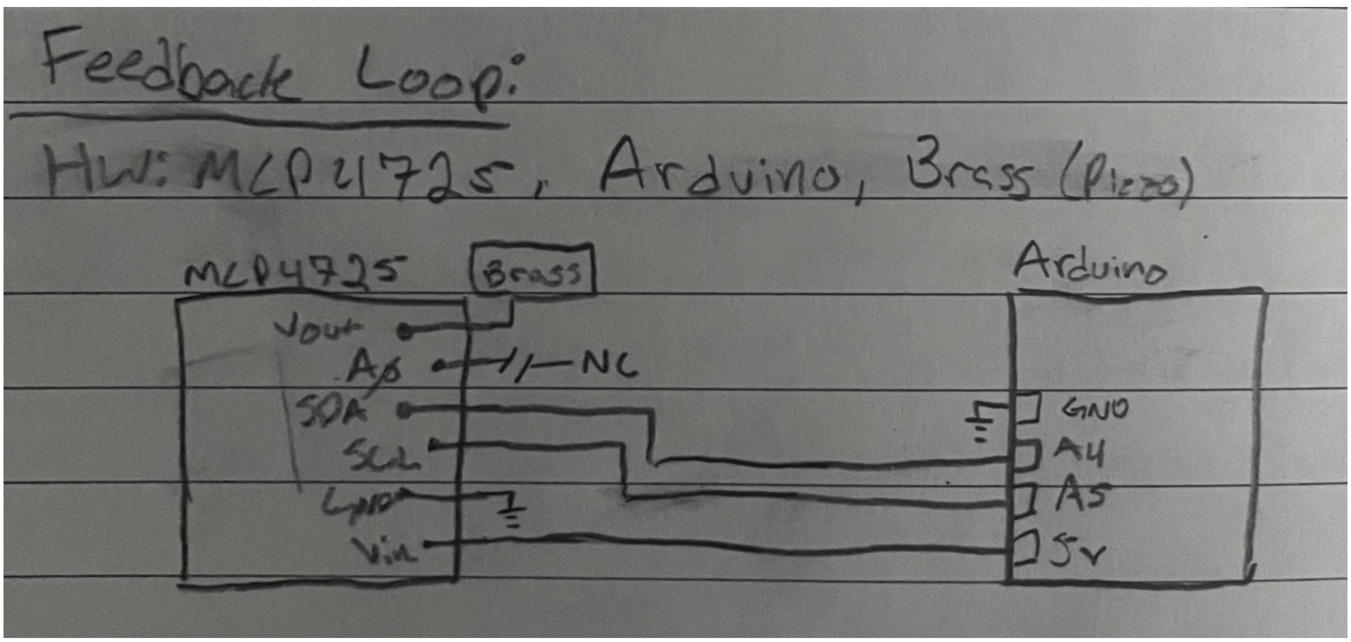


Fig 3: Software Feedback Loop/DAC Wiring Diagram

Figure 3 shows the wiring diagram from the MCP4725 DAC to the Arduino board showing the I^2C connection protocol. With this DAC and the arduino, we are able to connect the output of the DAC to the brass of the piezo disc and send a voltage to flex the piezo disc dynamically given feedback through our feedback loop code. The code is based upon the equation $V_{out}[n] = A * V_{out}[n - 1] + B * (V_{in} - SP)$ with SP being the set point at which we want the piezoelectric disc to equalize at. The idea is that as the approach the tungsten tip, the tunneling current will go up exponentially, so to not crash the tip we implement this feedback loop to ensure that when the tunneling current raises, the piezoelectric disc is flexed to avoid touching the material we are scanning. This will provide us a strong datapoint between the tip and the material while keeping the atomic sharpness of the tungsten tip.

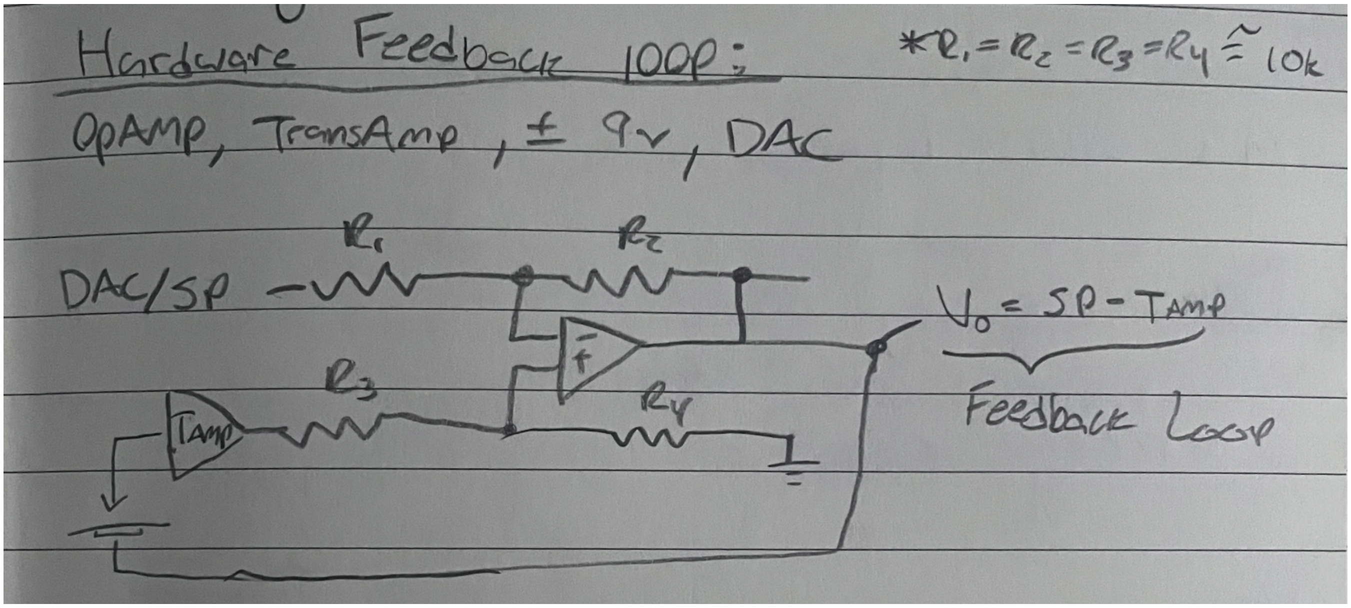


Fig 4: Hardware Feedback Loop Schematic

Since we have been having difficulties with the software based approach to the feedback loop, our client Dr. daCunha suggested that we implement a simple hardware subtractor to act as our feedback loop. This eliminates a lot of the difficulties associated with the software approach such as real-time reaction and software debugging. We hope that once we implement this hardware feedback loop, we can move on toward manipulating the piezoelectric disc's quadrants with the piezoelectric driver.

The piezoelectric driver is a portion of the STM that will control the scanning through code from the Arduino and a quad-channel DAC with two inverted signals. The piezoelectric driver works based on the concept of cutting the ceramic into four quadrants and applying controlled voltages to each quadrant to flex it in a certain ±XY coordinate direction to take a scan of points to contribute to a topographical map of the atomic surface of our material.

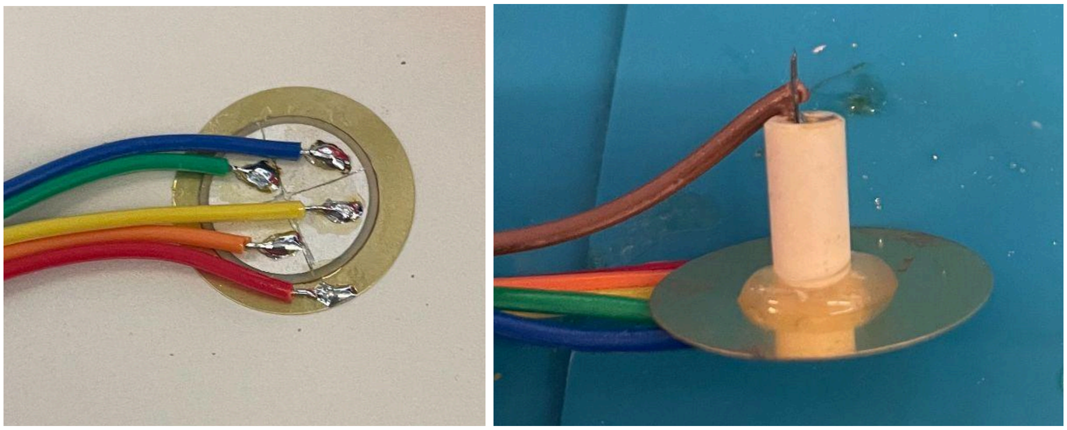


Fig 5: STM Scan Head Assembly

The STM scan head assembly is a physical piece of hardware that contains the tungsten tip and the piezoelectric disc cut into four quadrants and wires connected to the four quadrants, the tip, and the brass of the piezoelectric disc. The scan head assembly starts out with the ceramic holder attached to a wire with the tungsten tip heated and placed into the hot solder. The tip holder is then glued to the bottom brass of the ceramic. It is important that the tungsten tip is electrically isolated from the ceramic of the piezoelectric disc to eliminate as much noise as possible, which is why we went with ceramic for the tip holder rather than a metal counterpart. We did not 3D print the tip holder either because of problems with heat and melting.

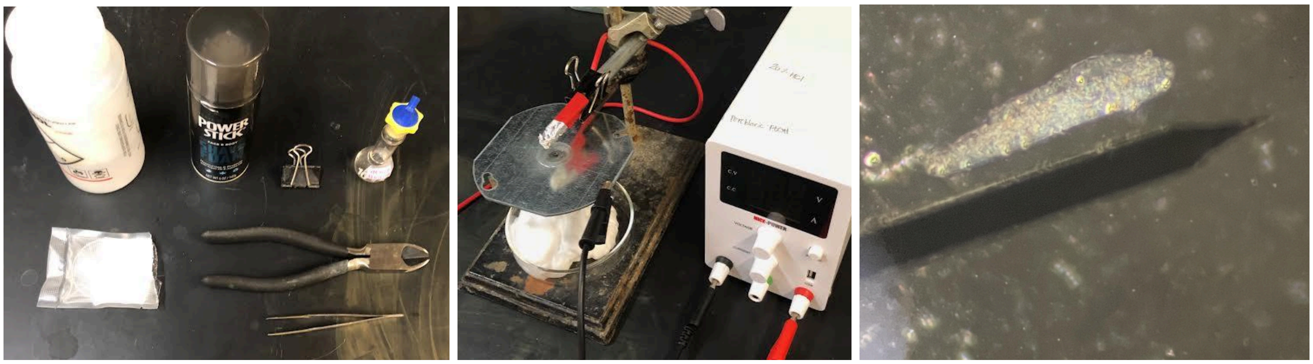
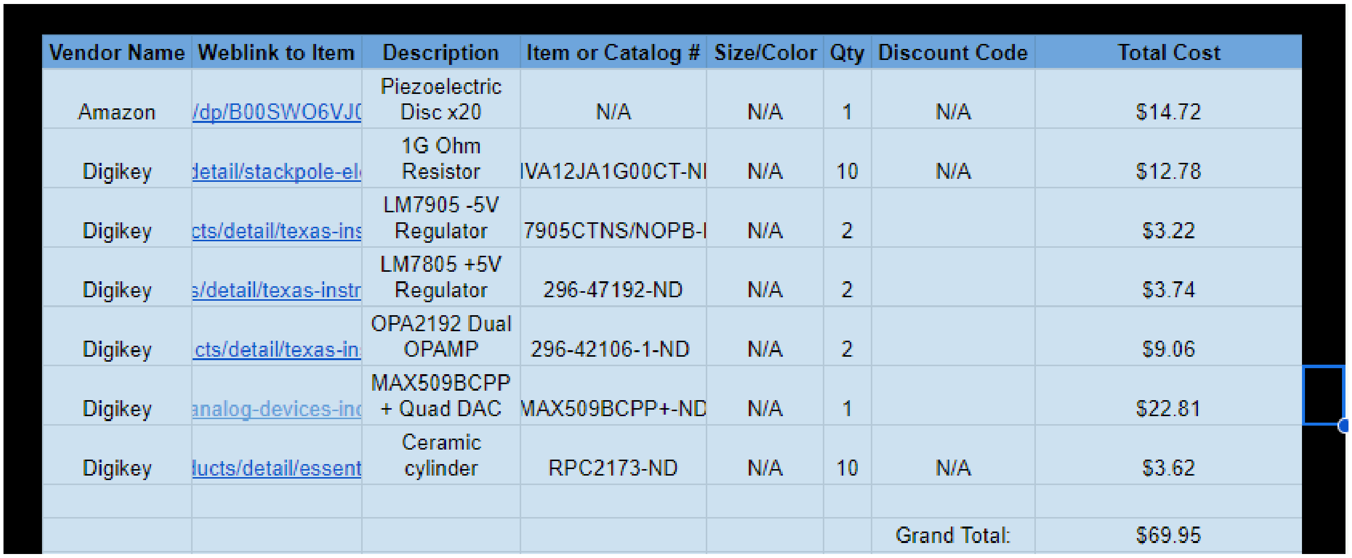


Fig 6: Tip Etching

The synthesis of the atomically sharp tungsten tip has been assisted by Ms. Madison King in the chemistry department who has been crucial in the success of this process. We ideally want an atomically sharp tip in order to be able to point and scan at atoms directly rather than having a tip multiple atoms wide and scanning the average value for those multiple atoms resulting in a blurry image. The tip etching process involves cutting a piece of tungsten wire, securing it in the setup shown in the middle figure, filling the petri dish with shaving cream to catch the falling half of the tip, and applying voltage to a membrane of sodium hydroxide solution which surrounds the tip, chemically etching it until it separates. When the tungsten separates, it will yield two atomically sharp tips.



Vendor Name	Weblink to Item	Description	Item or Catalog #	Size/Color	Qty	Discount Code	Total Cost
Amazon	/dp/B00SWO6VJ(	Piezoelectric Disc x20	N/A	N/A	1	N/A	$14.72
Digikey	detail/stackpole-el	1G Ohm Resistor	VA12JA1G00CT-NI	N/A	10	N/A	$12.78
Digikey	cts/detail/texas-ins	LM7905 -5V Regulator	7905CTNS/NOPB-I	N/A	2		$3.22
Digikey	s/detail/texas-instr	LM7805 +5V Regulator	296-47192-ND	N/A	2		$3.74
Digikey	cts/detail/texas-in	OPA2192 Dual OPAMP	296-42106-1-ND	N/A	2		$9.06
Digikey	analog-devices-inc	MAX509BCPP + Quad DAC	MAX509BCPP+-ND	N/A	1		$22.81
Digikey	lucts/detail/essent	Ceramic cylinder	RPC2173-ND	N/A	10	N/A	$3.62
						Grand Total:	$69.95

Fig 7: Bill of Materials

Figure 6 shows the current bill of materials that we have purchased and are using. It is important to note that not all of the purchases that we have made are on this BOM since we are not using some of the components that we bought. It is also worth mentioning that we are going back and forth with using the ±5V regulators and are currently considering not using them for the final design. Some of the materials are also not on the BOM since we are able to synthesize them with resources on campus such as the tungsten tips. Ms. Madison King in the chemistry department has been kind enough to assist us with the etching of the tungsten and provides the materials required for this process.

Project Management:

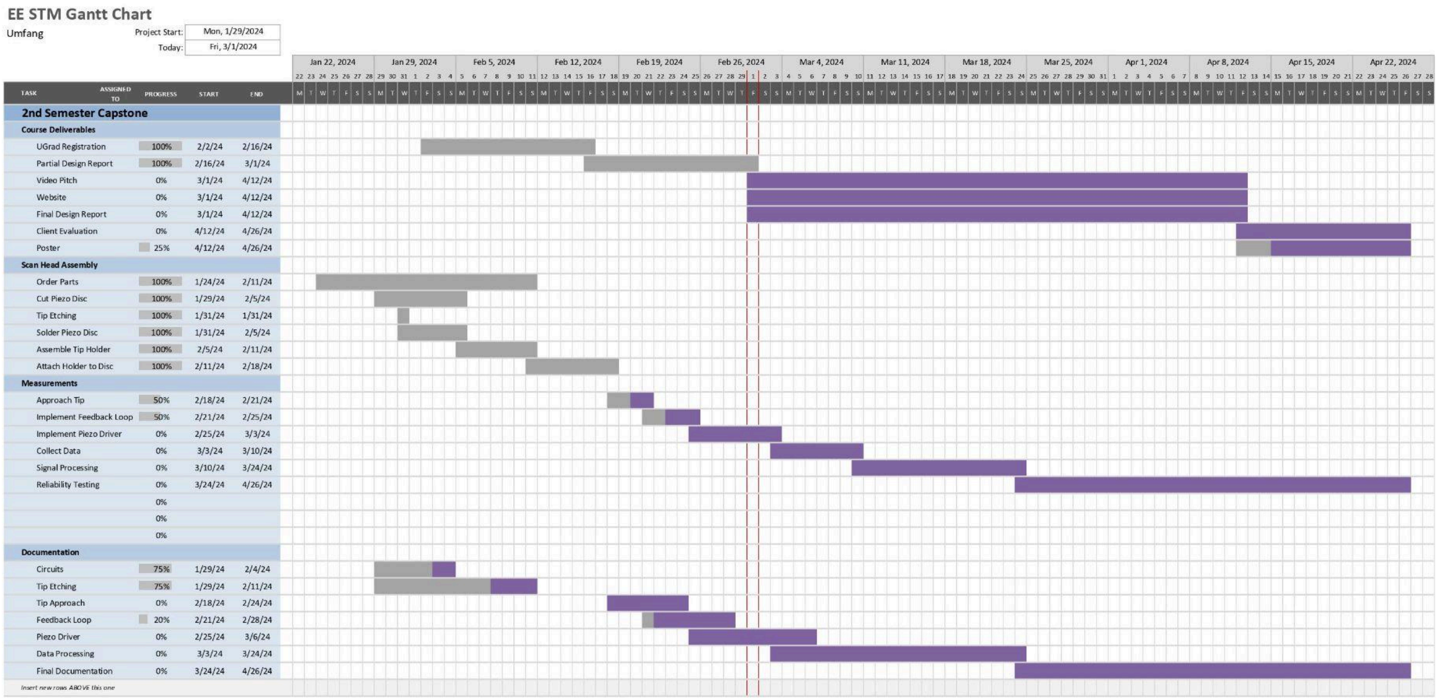


Fig 8: Gantt Chart

The Gantt chart is used to track the progress of the project timeline. The chart is split up into four parts, the EE486C course deliverables, hardware assembly, measurements, and documentation. As shown in the Gantt chart, we are behind on the documentation and the measurements. This is because we are currently having a difficult time debugging and implementing the feedback loop in order to properly approach the tip. We are up to date on the course deliverables and need to finish up some documentation to be on track to execute a sprint once we successfully implement the feedback loop.

EE STM Work Breakdown Structure and PERT Chart

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ID	Activity	Description	Deliverables	Duration (Days)	People	Resources	Dependencies
1	Course Deliverables						
1.1	UGrad Registration	Register for the undergraduate symposium		15	Both		
1.2	Partial Design Report	Complete the partial design report as outlined in the course deliverables	Turn into Canvas	15	Both		
1.3	Video Pitch	Create a video pitch for the STM	Turn into Canvas & Ugrad Registration	43	Both		1.2
1.4	Website	Update and finalize the website with documentation and accurate descriptions of the project	Updated website & turn into Canvas	43	Nick		
1.5	Final Design Report	Complete the final design report as outlined in the course deliverables	Turn into Canvas	43	Both		1.2
1.6	Client Evaluation	Client evaluation of the STM			Client		
1.7	Poster	Create a poster showcasing the STM and our work	Turn into Canvas and present at Ugrad Symposium	15	Both		1.4
2	Scan Head Assembly						
2.1	Order Parts	Order parts for the STM Scan Head Assembly	Bill of materials (BOM)	19	Nick		
2.2	Cut Piezo Disc	Cut the piezo disc into four quadrants	5x Cut Piezo Discs	8	Nick	Box Cutter	2.1
2.3	Tip Etching	Chemically etch the tungsten tips for atomic sharpness	4x Tungsten Tips	1	Both	Chemistry & Madi	2.1
2.4	Solder Piezo Disc	Solder wires onto the four quadrants of the piezo disc	1x Wired Disc	6	Nick	Soldering Station	2.1
2.5	Assemble Tip Holder	Attach the tungsten tip and a wire to the ceramic holder	1x Tip Holder	7	Nick	Soldering Station	2.3
2.6	Attach Holder to Disc	Attach the tip holder assembly to the piezoelectric disc	1x Scan Head Assembly	8	Nick	Soldering Station	2.5
3	Measurements						
3.1	Implement Feedback Loop	Write a feedback loop in Arduino that uses a DAC and the transimpedance amplifier to adjust the height of the piezo disc while we approach the scan material	Code in Documentation	4	Nathan	Arduino	2.6
3.2	Approach Tip	Approach the tungsten tip to the material slowly with the feedback loop		5	Both		2.6
3.3	Implement Piezo Driver	Write code to interface with the four output DAC and move the piezoelectric disc along a plane to begin scanning	Code in Documentation	8	Nathan	Arduino	3.1, 3.2
3.4	Collect Data	Collect data from the scan and output it to an excel document	Excel Sheet	8	Nathan/Both	Excel	3.3
3.5	Signal Processing	Input that excel document into MATLAB and process the data into a heightmap that is understandable	MATLAB prrogram	14	Nick	MATLAB & Excel	3.4
3.6	Reliability Testing	Test for reliability and see where we can make improvements on the design		34	Both		3.5
4	Documentation						
4.1	Circuits	Write documentation on the circuits used in the STM	Documentation	7	Nick	Pictures & Data	
4.2	Tip Etching	Write documentation on the tip etching process	Documentation	14	Both	Pictures & Data	2.3
4.3	Tip Approach	Write documentation on the tip approach process	Documentation	7	Both	Pictures & Data	3.2
4.4	Feedback Loop	Write documentation on the feedback loop implementation	Documentation	8	Nathan	Pictures & Data	3.1
4.5	Piezo Driver	Write documentation on the piezo driver implementation	Documentation	11	Nathan	Pictures & Data	3.3
4.6	Data Processing	Write documentation on the data processing in MATLAB	Documentation	22	Nick	Pictures & Data	3.5
4.7	Final Documentation	Finalize the documentation, check for errors, tidiness, and make sure it looks nice	Documentation	33	Both	Pictures & Data	4.6

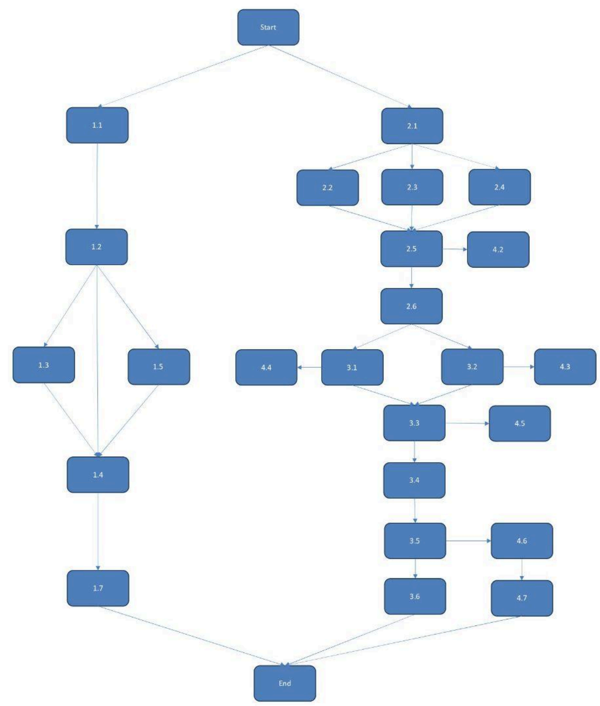

Fig 9: Work Breakdown Structure and PERT Chart

Figure 6 shows our work breakdown structure, which details who on the team needs to complete which requirement along with giving prerequisite objectives required to move on to the next objective spawning out PERT chart which gives a highly visual diagram of the WBS. The PERT chart shows that #2 objectives (hardware assembly) are required before the #3 objectives (measurements) and the #1 objectives (course deliverables) run concurrently with the #2 and #3 objectives.

Testing:

All of the parts of the project have been completed separately and now we are working through integrating all of them together. Some common issues we have run into are handling the atomically sharp piece of tungsten and preventing ruining the tip with accidental crashes, making sure wires are connected with the correct polarity to prevent short circuiting the electronics. We have rewritten the two main scripts many times and will continue to iterate and depending on time will turn to focus on making the user interaction as smooth and easy as possible. Current ideas on this include but are not limited to; LCD for displaying different modes or displaying what step the STM is currently working on, or possibly a loading bar to show how long the scan is going to take. Buttons and rotary encoder for selecting different operations like setup and shutdown operations to prevent accidental tip crashing. With the mechanical engineering team we helped them do some validation testing on their mechanical vibration isolation system. Their data showed a potential harmonic in the 15 Hz range that could affect the scanning process but that was during testing in extreme vibration simulated by banging at certain frequencies. We will not be banging the table when we want to scan. We will also not be scanning during an earthquake so it should not be a serious issue.

Conclusion:

In conclusion, our senior project on the development of a cost effective scanning tunneling microscope (STM) under the guidance of Dr. daCunha has been a long and challenging journey. Our primary objective was to design an STM capable of achieving sub-nanometer resolution while still adhering to our budget of five hundred dollars. Unfortunately the ME team had rather expensive purchases for the damping solution but fortunately we were provided with almost everything we needed for the circuitry already by Dr. daCunha. Our approach involved thorough discussions with Dr. daCunha on the precise requirements of the things we would be building. After arriving at an understanding of the chemistry, physics, and basic electrical engineering needed to design the parts of the STM we immediately began iterating every component of the machine. We first started with the transimpedance amplifier to convert the very small current signal to a higher voltage signal for the Arduino analog pin or a separate more accurate ADC to be hooked up to later. We also went through the chemical etching process to bring a small piece of tungsten wire to an atomically sharp tip. We then worked on the feedback loop needed to control the height of the tip from the substrate we are measuring. Then finally we created the scanning portion of the project with the MAX509 DAC and an arduino. We are still working through integration hell and polishing things up and will continue to do so until time runs out.