NAU NORTHERN ARIZONA UNIVERSITY

School of Informatics, Computing, and Cyber Systems

Umfang - Report #2

Nathan Shoults, Nicholas Arnold

School of Informatics, Computing, and Cyber Systems

EE 476C - Project Design Procedures

Dr. daCunha, Jack Hardy

December 1, 2023

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Introduction

The members of the Umfang team on the Scanning Tunneling Microscope (STM) project include the team leader, Nathan Shoults, and the treasurer, Nicholas Arnold, with responsibilities of other roles such as secretary being split between the two. As the team leader, Nathan is in charge of circuit design and elements of project management, including client communications and keeping track of the project timeline. As treasurer, Nicholas is in charge of the team's budget and ordering components and is the lead for soldering and PCB design. Both group members split the task of assignment completion and submission.

The client for the STM project is Dr. Carlo daCunha, who has an interest in and use case for the STM in his lab for his graduate students studying the application and exploration of extremely small devices. The purpose of the STM project is to create an affordable STM, which is a microscope used to scan the surface of various materials on an atomic scale by using an atomically sharp scanning tip to measure the variation in the tunneling current between the tip and the material's surface. The goal is to create a usable STM with nanoscale resolution to aid in the research of Dr. daCunha's lab, and to make it affordable and accessible enough for distribution to Northern Arizona public schools.

The STM project has been attempted in the past and has had a mechanical engineering team counterpart 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 limits us to using the mechanical engineering team's vibration-damping solution.

Problem Statement

Statement of Needs:

The STM has three important marketing requirements that need to be met throughout the construction of the project. 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 difficulty being adopted and may be overlooked for more simple and easy-to-adopt products, so it is imperative that our STM be efficient in design. The STM must have accurate measurements to the nanometer scale in order to achieve near-atomic resolution which will require us to source low-noise components and 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, this 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, although 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.

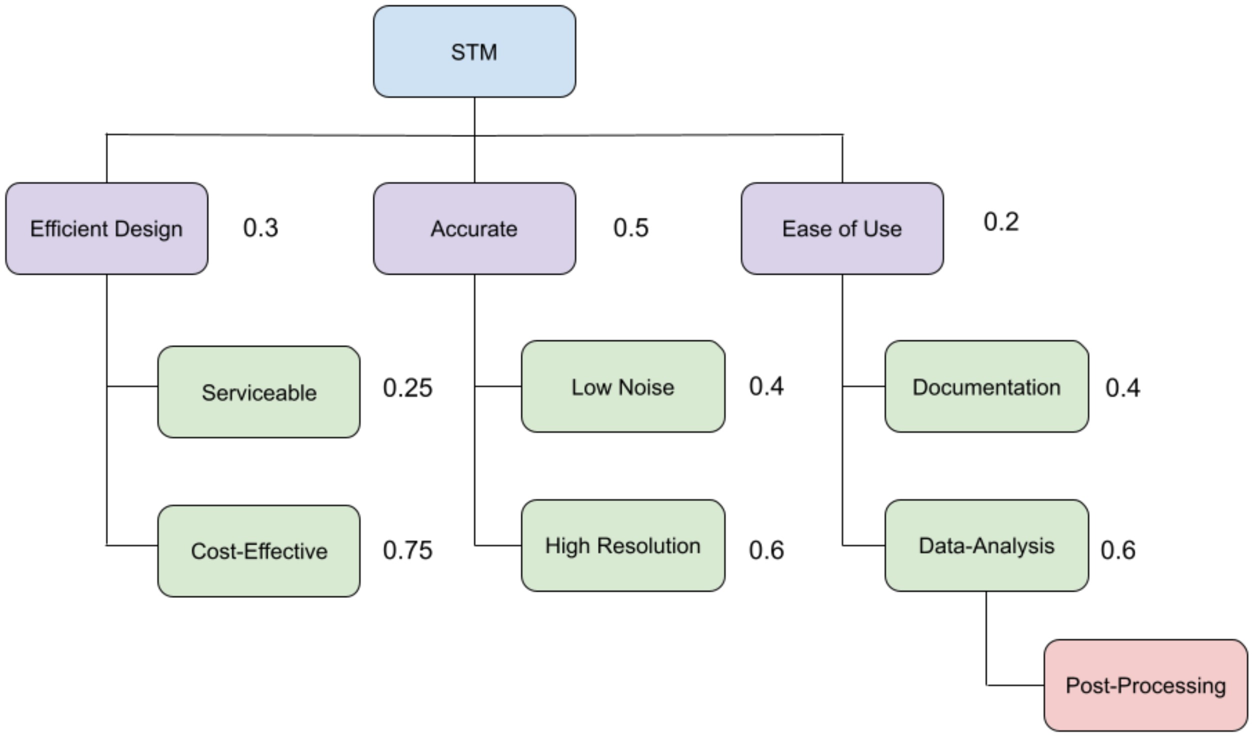

Fig 1: Objective Tree

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 a 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 the future work, although the team is confident in the ability to complete all the objectives by the end of the project.

System Requirements

The system requirements for the STM fall into two categories, technical and functional requirements, which are overarching requirements of the STM, and hardware, software, and performance requirements, which are smaller-scale requirements like hardware components and software tools.

Technical and Functional Requirements:

- Resolution and Sensitivity: The STM should be able to achieve nanoscale resolution, with an atomically sharp tip capable of detecting atomic-scale variations of tunneling current
- Scanning Range: The STM should have a scanning range large enough to scan a variety of materials at varying sizes
- Imaging Modes: Support different modes such as constant tip height and constant tunneling current modes to provide different perspectives and images of the same material.
- Data Acquisition and Analysis: Have an easy to use and well documented software and method for data acquisition and image processing.

Hardware, Software, and Performance Requirements:

- Hardware Components: The STM requires a piezoelectric disc, atomically sharp tip, a feedback control system, and various ICs that will make up circuits for the preamp and piezoelectric driver.
- Software Tools: The team will utilize Arduino, Raspberry Pi, and MATLAB and research other software tools to best implement image processing for an easy to use STM.

- Performance: The STM should be able to scan images across multiple time frames, ranging from an hour up to a full day. The STM components will need to withstand prolonged on-time use.
- Durability: The STM should be able to withstand multiple scans without damaging the tip or otherwise being compromised mechanically or electrically.

		Data Collection	Processing Language	High-Resolution	Low-Noise
		+	+	+	-
Data Collection	+		-	+	+
Processing Language	+			-	-
High-Resolution	+				+
Low-Noise	-				

Fig 2: Engineering-Engineering Tradeoff Matrix

In evaluating engineering-engineering trade-offs, the team will consider factors of resolution, sensitivity, performance, and post-processing. For example, increasing sensitivity may come at the cost of reducing the scanning range. Additionally, the software we use for post-processing and data analysis will directly impact the usability and user-friendliness. The STM team will carefully assess these trade-offs to optimize the system's performance and accessibility.

		Data Collection	Processing Language	High-Resolution	Low-Noise
		+	+	+	-
1. Accuracy	+	+	+	**+**	**+**
2. Efficient Design	+	+	+	**-**	**-**
3. Ease of Use	+	-	+	-	-

Fig 3: Engineering-Marketing Tradeoff Matrix

This matrix compares engineering decisions with marketing requirements. The team will evaluate how engineering decisions related to data collection, processing and analysis, precision, and noise will impact the marketing requirements and client's concerns during the project it is important to note that the more priority the team places on accuracy, the more difficult it will be to stay within the budget and create an efficient design for the STM since higher accuracy will require more complex circuits and solutions.

					+			
				+		N/A		
			-		N/A		+	
		Data Collection		Processing Language		High-Resolution		Low-Noise
		+		+		+		-
1. Accuracy	+	+		+		+		+
2. Efficient Desig	+	+		+		-		-
3. Ease of Use	+	-		+		-		-

Fig 4: House of Quality

The house of quality analysis serves as a visual representation of the impact that the engineering requirements have on each other, and how that ultimately impacts the marketing requirements. For example, more data collection is required for higher resolution, which will be a large plus for accuracy, but would come at the cost of ease of use. In a real-world scenario, the higher the resolution and the more data points the STM has, the longer the STM will take to scan, leading to multi-day scans.

Functional & Behavioral Analyses

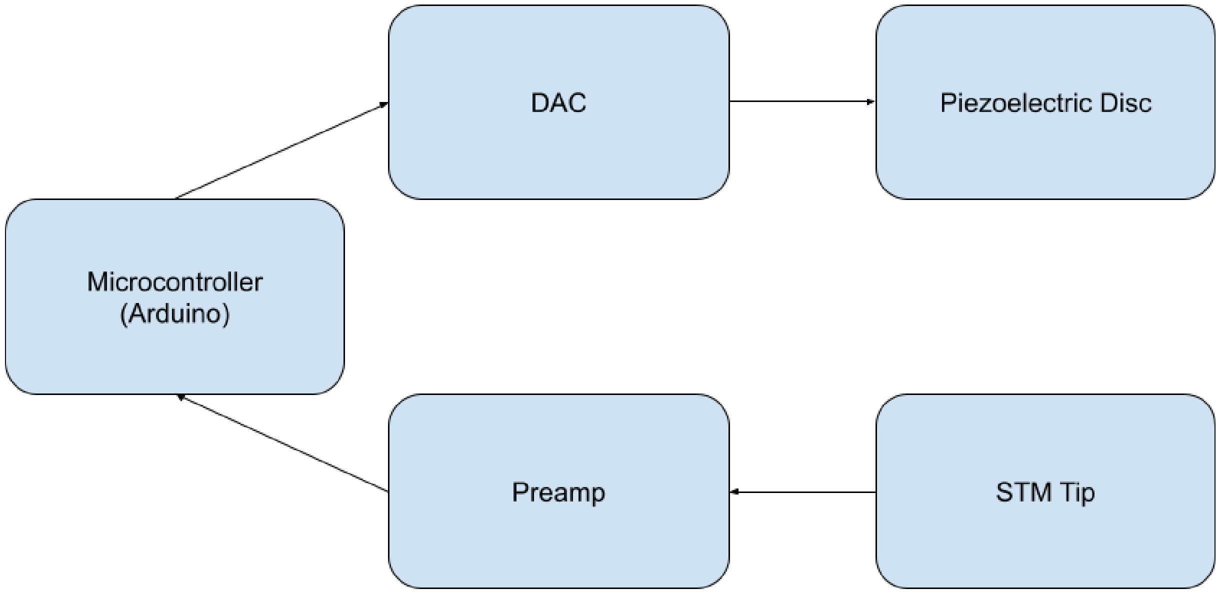

Fig 5: STM Flowchart

The STM is made up of five main modules that interact with each other, the STM tip, the preamp, the microcontroller, the DAC, and the piezoelectric driver. The STM tip is how the team will measure the tunneling current, applying a voltage between the tip and the material will create a tunneling current that grows exponentially the closer the tip is to the material allowing us to map the variations. Currently, the STM tip has been difficult to mount to the piezoelectric disc, and we need to keep electrical isolation in mind. Some ideas we have to improve the tip mounting are to use hot glue to secure the tip in the holder, and epoxy to secure the tip holder to the disc. We can also use enamel paint to electrically isolate the disc from the tip. Lastly, we need to electrically connect the tip to either five volts or ground, and it is difficult soldering to a thin tungsten tip, to solve this problem we are looking into small washers we can secure in the tip holder to help administer the solder. The tunneling current we get from the tip will be in the ballpark of nanoamps (10^{-9}A) that cannot be read directly by the

Arduino so we need to utilize a transimpedance amplifier (transamp) to both amplify the tunneling current and output the value as a voltage that can be read by the Arduino. The team's current iteration of the transamp utilizes a low-noise precision OPA192 opamp along with a nine-volt power supply to amplify the current. This introduces a new limitation in that we cannot amplify the current past eight volts reliably or else the power supply will be saturated, so the team needs to ensure that the max amplification is under eight volts. The team has not been able to test the transamp with the tungsten tip, but the amplifier has been tested with a simulated tunneling current of negative five volts across a gigaohm resistor which yielded promising results. The microcontroller has three main functions, it will take in and record data from the transamp and will send signals to the DAC to control the piezoelectric driver. The team has a lot of work to do with the software of the microcontroller, a feedback loop needs to be implemented for the STM tip, the software for controlling the DAC needs to be explored and developed, and the software for recording the tunneling current needs to be written. The DAC that we chose for prototyping is the MAX509 since it is a through-hole component and has an 8-bit resolution which will make it easier to experiment with. Since the DAC only has an 8-bit resolution, this limits the overall resolution of the STM to 256x256 data points so the team needs to be careful with the voltage steps to achieve nanoscale resolution. The piezoelectric driver is what moves around the tungsten tip and is controlled by the DAC and microcontroller. The piezo disc is cut into four quadrants and positive and negative X and Y along with a positive Z voltage are applied to flex the disc. The team has not experimented much with the piezo disc, but there are concerns about electrical isolation and noise. These five modules all operate alongside each other and the team is working vigilantly toward the completion and integration of all these individual modules together.

Conclusions

Thus far in the fall semester of the capstone course, the STM team has accomplished the following:

- Flowchart/State diagram for the STM that shows how the components of the STM work together.
- Circuit design and simulation for the preamp, power supply, and inverter for the piezo-driver.
- Ordered and assembled the circuits for the preamp, power supply, and inverter.
- Atomic tungsten tip fabrication.
- Mechanical design for attaching the tungsten tip to the piezoelectric disc.
  - Maintains electrical isolation between tip and piezoelectric disc.

Before the winter break the team needs to do the following:

- Update and organize the STM documentation to include all progress up to this point.
- Update and organize the capstone website to reflect the progress this semester.

The further work for the spring semester will be to:

- Implement tip feedback loop
- Finalize the piezoelectric driver
  - Implement DAC
  - Write software for driver
- Acquire and analyze data from the Arduino
- Create software within MATLAB to process data
- Finalize circuit design and begin PCB design
- Optimize noise isolation and STM performance

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