NAU NORTHERN ARIZONA UNIVERSITY

School of Informatics, Computing, and Cyber Systems

MUMMY

Scanning Tunneling Microscope

Final Design Review

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C·Lab

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Introduction

The scanning tunneling microscope (STM) is a useful tool that is used in many fields. This instrument serves the purpose of being able to obtain images of the surface of a material at an atomic resolution. These images can be retrieved by scanning a sharp metal tip over the surface of the material and measuring the tunneling current that is generated between the tip and the surface. The current obtained from this process is then amplified and converted to a voltage that it used to generate an image of the STM. In the case of this specific STM, the goal is to have it used for academic research at Northern Arizona University and potentially contribute to the research of nanoelectronics and semiconductor fabrication and characterization in the complex electronic laboratory.

Problem Statement

The process of building your own STM can vary depending on the methods the team chooses to follow. To ensure the success of this project, the team followed the following steps to approach this project. First, our team will need to create an extremely sharp tip which will be moved around the sample by the piezoelectric scanner up and down, and in zigzag motion as it scans the sample. A PI controller for Z distance correction was also necessary to be able to control how close the tungsten tip of the scanner is to the sample to prevent damage to the tip or the sample. The construction of a transimpedance amplifier is also needed to take the tunneling current which will be on the scale of a few tens of nano Amps as an input and amplify it so it can be converted into an output voltage to be interpretable. All of this needs to be accomplished with a microcontroller script that will monitor the system and allow for corrections to be made. This needs to be interfaced with a computer for communications with the system that will provide the users to control the system and view the scanning signal after processing. Lastly, a mechanical structure is needed for this project which should be able to isolate vibrations, noise and maintain fairly low temperatures.

The current goal of this project is to be able to retrieve an image of a HOPG sample or any other sample that is scanned. Currently, there are no plans for adding additional modes other than scanning the samples that are placed. Potentially, as a future improvement, the STM could be used for nanodevice fabrication, to contribute to the research of nanoelectronics at NAU. The system conditions for our STM are for it to be a functioning device that meets all the requirements and expectations of our client as outlined in the Engineering and Marketing Requirements. This means that it should be capable of obtaining data on the lattice structure of HOPG at ~0.01nm resolution with low noise levels. This system is being built with semiconductor researchers in mind, and will return data in formats that can be used for further investigation and customization--which, ideally, will be done by providing both raw data and a way to process it into an image.

The major constraints of this project are budget, material availability, and programming language for the STM control scripts. The project is limited to a small budget of less than $1,000 to work with, so the system needs to be capable of returning quality data while not being able to use more expensive methods. The system must also be constructed of easily accessible materials to make the STM as accessible as possible to institutions with smaller resources. The STM must also be easily controlled by the user--scripts written in a programming language with easy to understand syntax that is flexible, easily modified, and fast enough to properly control the STM to prevent possible accidents(most notably, scanning tip crash due to large latency due to slow computing speed). All of these constraints have driven the design decisions made for the STM.

Requirements

Engineering Requirements

The client has stated the following requirements as the overall goal for the prototype, however these will be adjusted accounting for the obstacles that may present themselves throughout the project. The team has evaluated the requirements and needs but decided it would not be feasible to weigh each one since they are all essential for minimum success of the project.

- The body should be made of Macor ceramic (or similar) with the smallest dimensions possible.
- The resonant frequency of the mechanical system should be smaller than 1 Hz.
- The voltage amplifiers should produce outputs up to ± 100 V producing a resolution of ~0.01 nm in the Z-direction (this corresponds to ~62.5 μV).

- The noise figure of merit should be smaller than 3 nV/√Hz for the amplifiers.
- Tunneling current is in the order of 1 nA, so a precise and low-noise pre-amplifier should be designed.
- The log-converter connected to this pre-amplifier should have similar figures of merit.

Marketing requirements

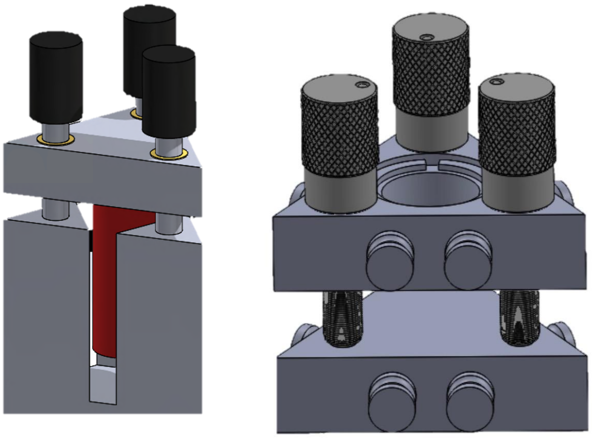
The team will also need to take into consideration the needs for possible future users such as those participating in academic research. the following requirements were determined to be of the most importance:

- Size: the scanning tunneling microscope (STM) should be as small as possible to be able to reduce costs and facilitate transportability.
- Interface: the STM should produce data easily interpretable by academic researchers using the instrument.
- Operating Power: the STM should be able to operate on easily accessible power sources.

Proposed Solution

Mechanical Structure

A mechanical engineering (ME) team joined the project in February, and have been working on optimizing the design of the mechanical structure we made last semester. The original design of the structure needed to be modified in order to adjust to the change in the piezoelectric scanner that would be used (figure 1). The team had originally planned to add springs that would help keep the two pieces together, but after discussions with the ME team we concluded that the use of elastic bands to secure the top of the structure to the bottom and provide a layer of vibrational isolation, and uses two anchor points per elastic that are larger. Additionally, due to the 3D printed model being so lightweight, the bottom piece was attached to a concrete block to prevent unwanted movement and limit vibration.



(a) *(b)*

Figure 1. a) Initial design of the mechanical structure adjusted to fit the tube scanner. b) Final design of the structure.

Electronics

The team built a transimpedance amplifier which was able to take the tunneling current in the scale of nano Amps to be amplified and outputted as voltage. The preamplifier uses a TL071 op-amp due to its low-noise and low input bias current capabilities. In order to have a gain on the current to voltage, the feedback resistance used was 100 MΩ. Due to the output voltage being negative, an inverter was added to the output of the amplifier to obtain positive voltage output that can be read by the digitally implemented amplifier. From further testing during the integration process, the output current contains high electrical noise which causes the signal to be affected due to the current input being very low.

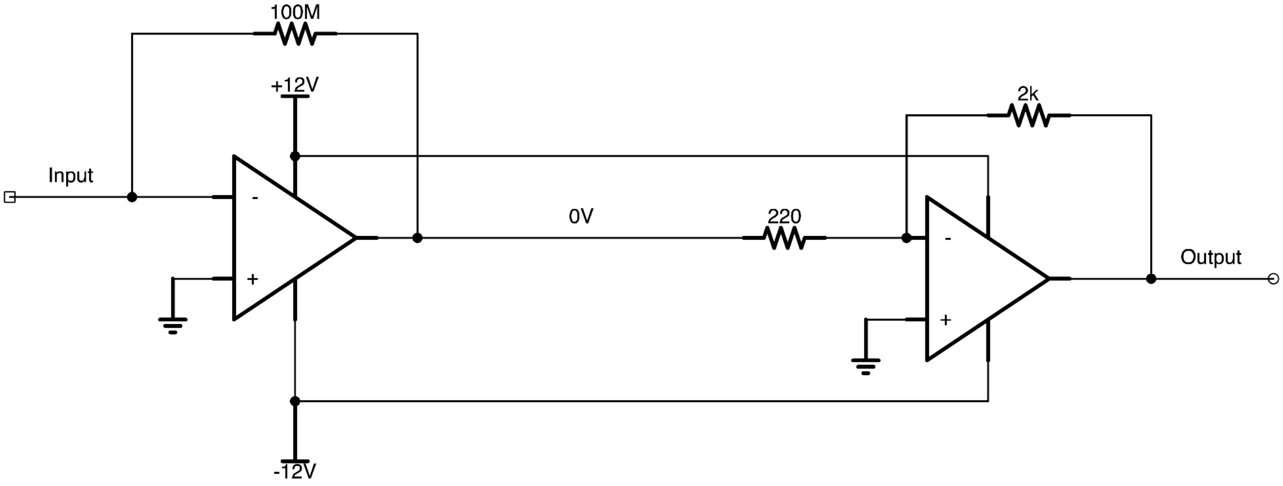


Figure 2. Final design of the preamplifier including the inverter added in the output.

The team also started construction of a high voltage amplifier, but due to long shipping times for SMD component protoboards and delays and campus closures because of snow, we were not able to finish construction of the high voltage amplifier. To prevent falling further behind in our schedule, and with guidance from our client, the team decided to change the piezoelectric driver used to move the scanning tip from a tube scanner to a disk scanner as it can be driven using significantly lower voltages than the tube scanner, with about 0.16 microns of displacement per volt. [1] This changed the circuitry for connecting to the driver slightly, but the function and general idea is largely the same; the silver electrode on the top of the disk will be divided into four sections(one for each axis, ±x and ±y) and the back is also connected to ground. Z displacement will be driven by applying an equal voltage across all quadrants of the silver electrode, and lateral(x and y) displacement will be driven by applying a voltage differential between opposing quadrants.

Figure 3. X and Y displacement (top) and Z displacement (bottom). From Alexander 2013 [1].

The thin tungsten wire tip needed to be extremely sharp, which is why it has to through an electrochemical etching process which was completed in collaboration with the chemistry department. The process for completing this was to prepare a solution of 1 M KOH and coat the hole on the stainless steel plate with that solution . Next, the wire was inserted through the hole to then apply the positive terminal to that plate and the negative to the end of the wire. The set-up of this process can be seen in figure 4. Once the wire was etched, the bottom tip would fall onto a soft surface and be stored in a container to prevent it from oxidizing.

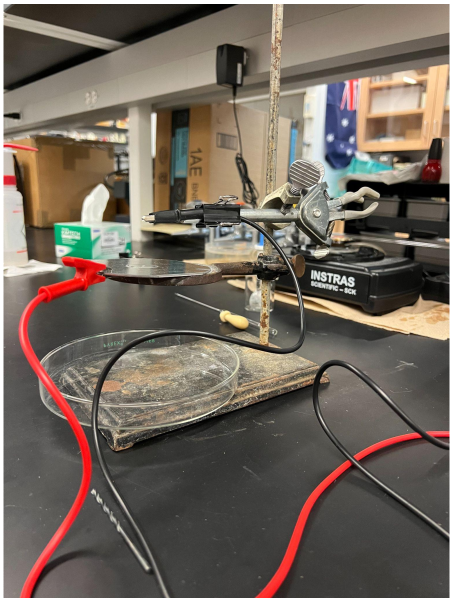
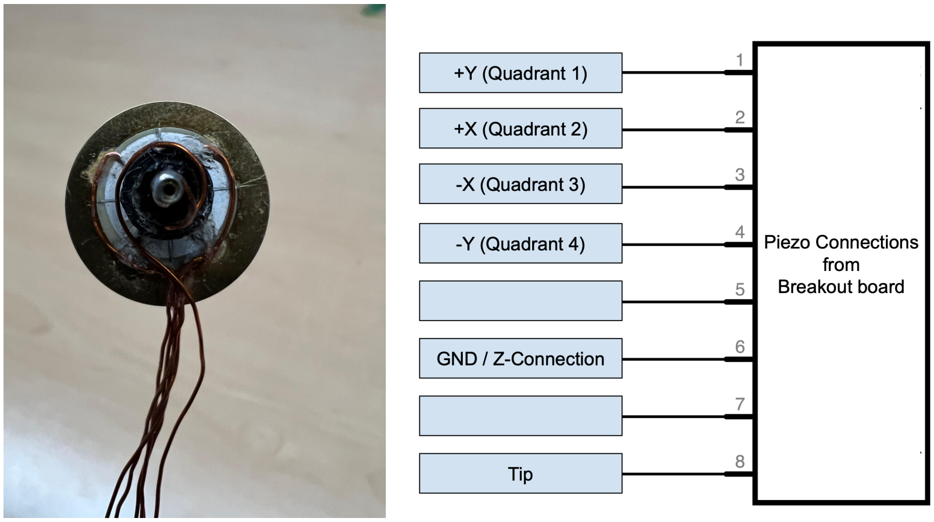


Figure 4. Final set-up of the electrochemical etching process done to sharpen the tungsten wire tip.

The piezo disk scanner originally only contained one quadrant so to adjust this, the disk's electrode needed to be divided into four quadrants but scratching it with a precision knife or box cutter. The four quadrants need to be equally divided to ensure the movements of the piezo are equal. To ensure the electrodes are completely separated, an ohm meter was used to test that there were no shorts between the electrodes. Once this testing process was completed, the connections to the piezo were made with conductive silver paint to avoid damaging the ceramic on the piezo. Additionally, super glue was used to keep the wires in place due to the silver paint not being able to hold on to the wires on its own. In this case, the Z axis was on the stainless steel disk therefore a wire was attached to the back side of the piezo. To finish this process, the tip holder was added to the center of the disk, over the ceramic. The holder was composed of a leftover peg from the mechanical structure, and a pin from the IC socket was inserted in the center of the peg. When inserting the tungsten tip to this holder, silver paint was used once again to make electrical contact with the wire. Our team found it essential to keep all wires organized which is why they were all soldered onto a PCB protoboard (figure 5b).



(a) (b)

Figure 4. (a) Piezo disk with tip placement holder showing how quadrants were separated, wires were attached with silver paste, and tip holder placed on the center of the disk. (b) Diagram showing the pinout of the wiring from the piezo disk.

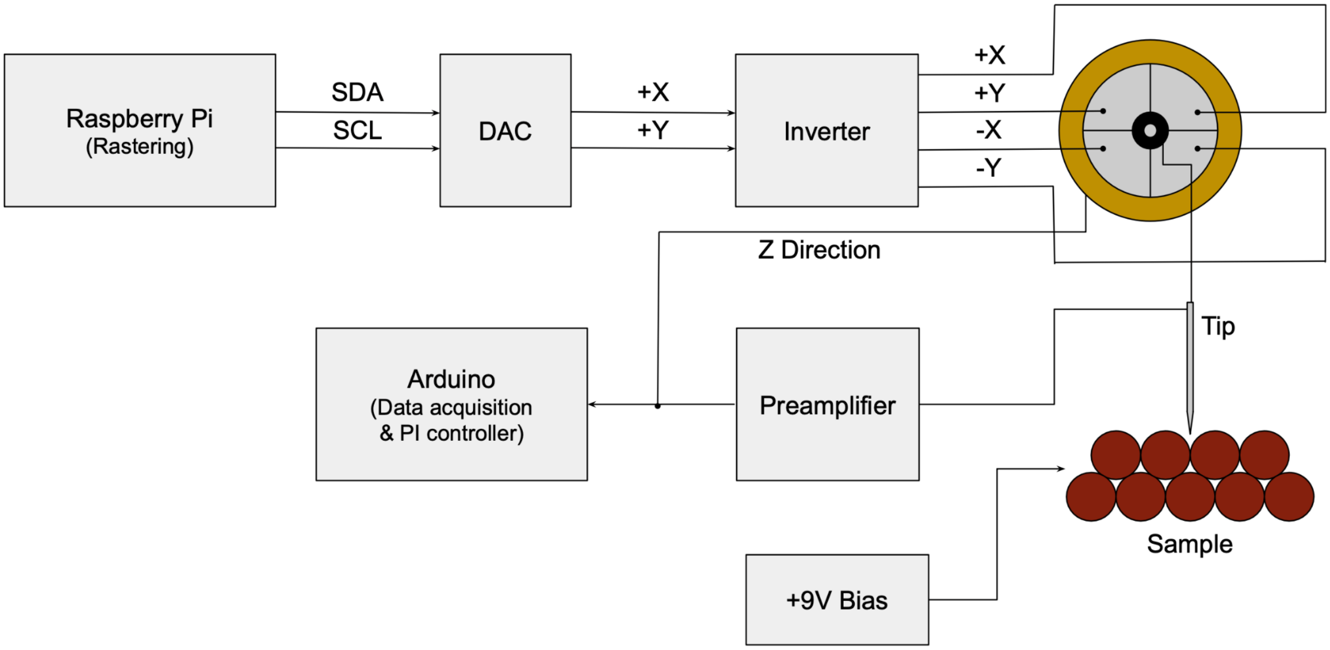


Figure 5. Block diagram showing how all submodules perform together once integrated.

Software

Software was created for rastering the tip of the microscope over the surface of the sample--see Appendix A for the full rastering code. It generates signals that sweep from 0 to 3.3 volts in a zig-zag fashion and outputs the signal to a 4 channel, 12 bit DAC connected to a Raspberry Pi--on which the rastering code is executed.

Software was created for data acquisition of the sample. The code uses an analog to digital converter (ADC) attached externally to the system through a breadboard in order to convert the analog signal of the z voltage on the piezo (height) to a digital signal that the computer can use. See Appendix B for the data acquisition code.

The PI controller was also implemented digitally and is included in the script used for data acquisition. The script calculates the proportional and the integral of the output from the preamplifier and then sums those two values. That sum is then passed to the data acquisition part of the Arduino code and to the DAC connected to the Arduino to serve as the Z driving signal for the piezo buzzer. As was stated in the previous paragraph, this code is included in the second half of Appendix B.

Testing

Testing occurred separately for each submodule and then once again as each module was integrated into the overall system. The team used this approach to be able to easily locate and isolate problems as they occurred to make the troubleshooting process faster. The submodules that were tested were the preamplifier, the PI controller and data acquisition script, and the rastering script.

For the preamplifier, the circuit was connected to a function generator and a series of resistors to simulate a tunneling current of ~1 nA. The output of the preamp was measured to see if it amplified the signal by the correct amount. The op amps used were also tested for noise using a voltage follower circuit(see figure 5 for output for the TL071CP).

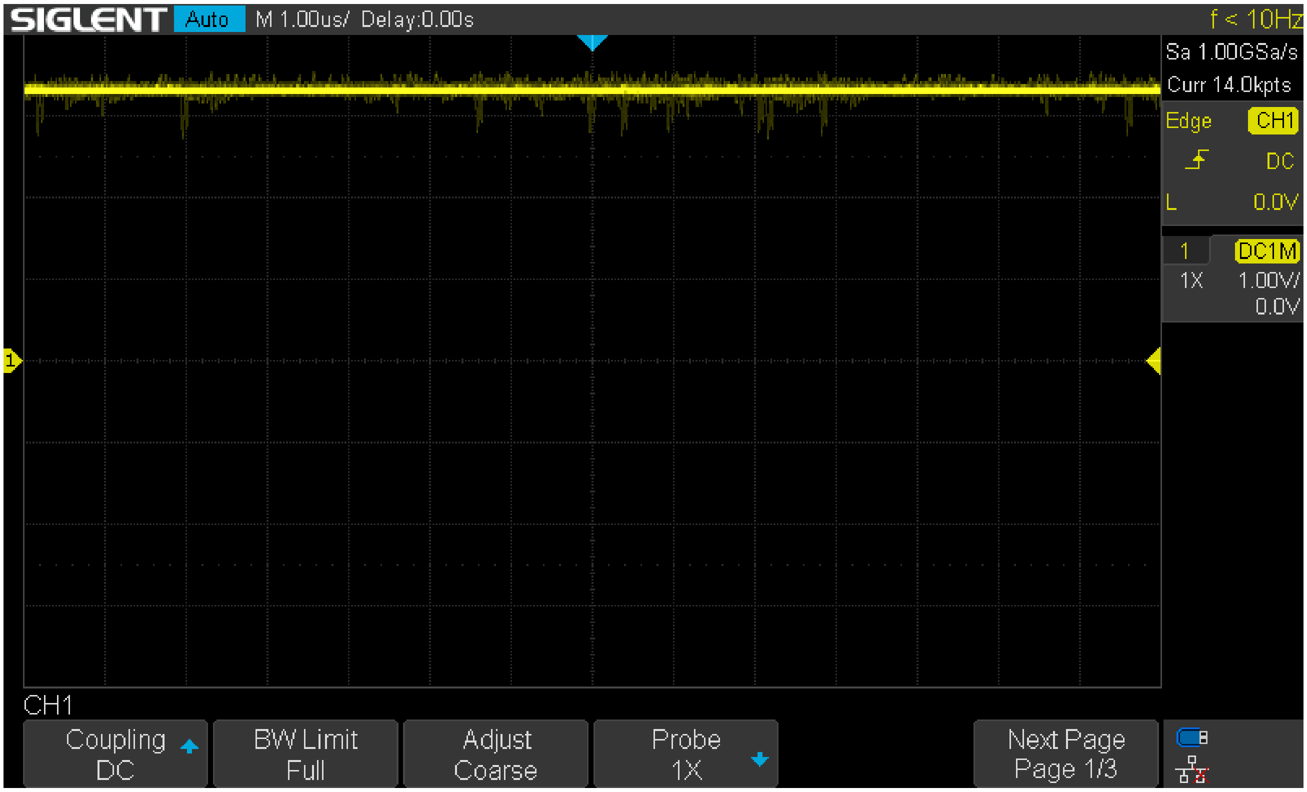


Figure 6. O-scope output of a voltage follower circuit using the opamp used for the preamplifier.

The PI controller was tested first by printing out the values it produced to a serial monitor to check it was producing the desired output given a certain input from the function generator. This was done for the analog version of the PI controller, and will also be completed for the digital version of the PI controller. The data acquisition part of the code was also tested at the same time because it’s needed to print the output of the PI controller to the serial monitor; the saving function was also tested by seeing if Excel would receive values from the Arduino, and print them out to an Excel spreadsheet.

The rastering script was tested by running it on the Raspberry Pi and measuring the output using an oscilloscope. In order to pass its test, the rastering code needed to both produce the correct signals, and also not produce so much noise--via the inverters used to create the -X and -Y signals-- that it would obscure the rastering signal. Below are pictures of the output of the rastering script measured using the oscilloscope before(figure 6) and after(figure 7) lowering the power supply output from ±15 V to about ±8.65 V to lower the noise produced by the power supply--which seems to be the cause of the noisy output of the inverters.

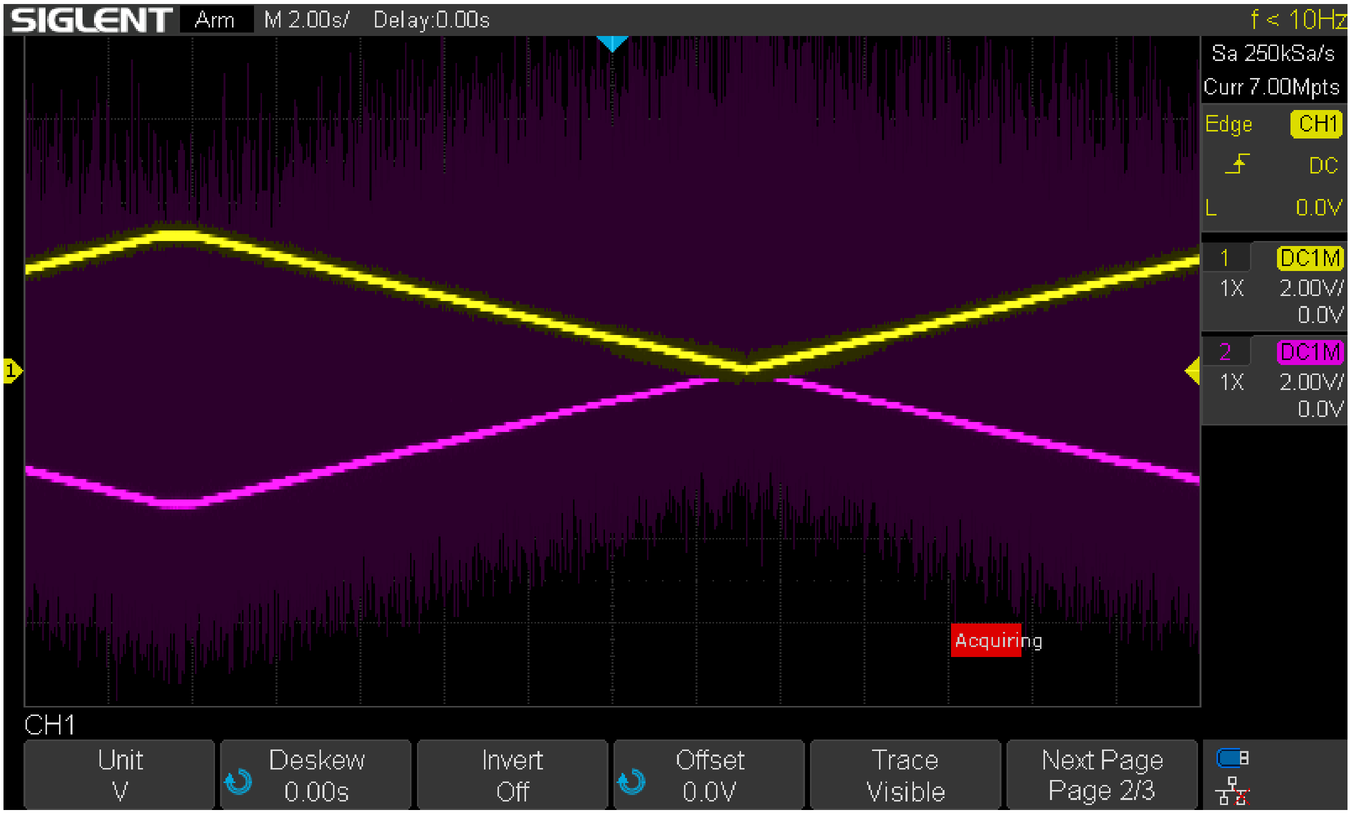


Figure 7. O-scope output of the rastering signals before noise correction.

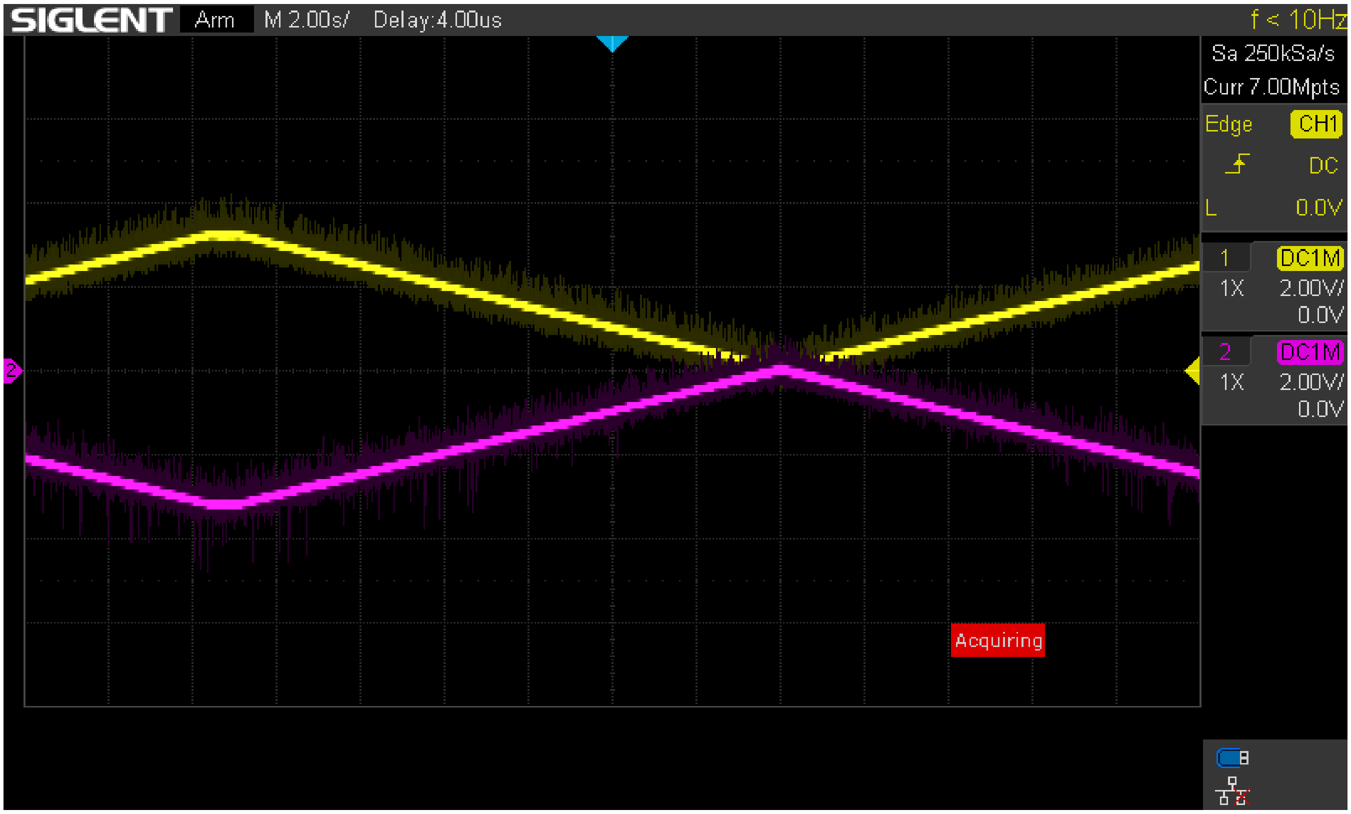


Figure 8. O-scope output of rastering signals after noise correction.

Future Work

Further testing and troubleshooting for each subsystem needs to be completed to reduce the noise produced by the preamplifier, as well as further development of an image processing script. After eliminating the source of noise in the preamplifier--which is likely due to the opamp used in the circuit--data collection and processing can begin and will likely result in the production of the first image captured using the STM. Currently, there is only existing software capable of retrieving raw data, which means that further work would involve being able to produce images from that data. Some other suggestions provided by the client are to place the preamplifier as close to the STM as possible to make the connection of the tip as short as possible. Additionally, a faraday cage can be implemented around both components to act as a shield and protect the circuit from external interference such as electromagnetic field which could be a source of electrical noise.

Further development of the physical structure also needs to be completed; this will be done by the Mechanical Engineering team assigned to this project. A vibrational analysis will be performed of the physical structure and changes made to ensure that the vibrational modes seen in the structure will not lead to mechanical vibrations interfering with the data output of the STM.

Conclusion

The team was able to produce the design and architecture for an inexpensive scanning tunneling microscope and began the assembly and testing of each sub module and the integrated system. This design is an open-air system, thus reducing the price of production by not relying on the use of a vacuum chamber. The piezoelectric actuator used for the design is an easily accessible piezo buzzer that is driven using low voltages and is used for the positioning of a tungsten scanning tip--chosen for its strength and ability to not tarnish in the open-air at room temperature. The only analog circuit used in the whole system is the preamplifier, which utilizes an electrometer grade op-amp in a transimpedance amplifier to both amplify the tunneling current signal and convert it to a voltage signal that can be read by an Arduino and recorded in an Excel spreadsheet for post-scan processing and image production. Due to noise produced by the preamplifier

Appendix A

Rastering code written in Python:

```
from adafruit_extended_bus import ExtendedI2C as I2C
import adafruit_mcp4728
import numpy as np
import time

i2c = I2C(1)
dac = adafruit_mcp4728.MCP4728(i2c,0x60)

x = 0
y = 0

yinc = 5
xinc = 5
XMAX = 65534 #maximum DAC output = VDD
YMAX = XMAX

#reset DAC
```

```
dac.channel_a.value = 0

dac.channel_b.value = 0


t_end = time.time() + 60*3 #timer, takes current time and allows for following loop to run for onlt the time aloted

while time.time() < t_end: #runs up to x = 50505 & y = 65...

    x += xinc

    if x > XMAX or x < 1: #if x reaches limit or is less than 1...

    xinc = -xinc #reverse x


    y += yinc

    if y > YMAX or y < 1: #if y reaches limit or is less than 1...

    yinc = -yinc #reverse y


    dac.channel_a.value = x #set channel a to x value

    dac.channel_b.value = y #set channel b to y value

    print([x,y])#print x and y values


#reset DAC

dac.channel_a.value = 0

dac.channel_b.value = 0
```

Appendix B

Code for data collection and PI control, written in C/C++. for Use on an Arduino Uno

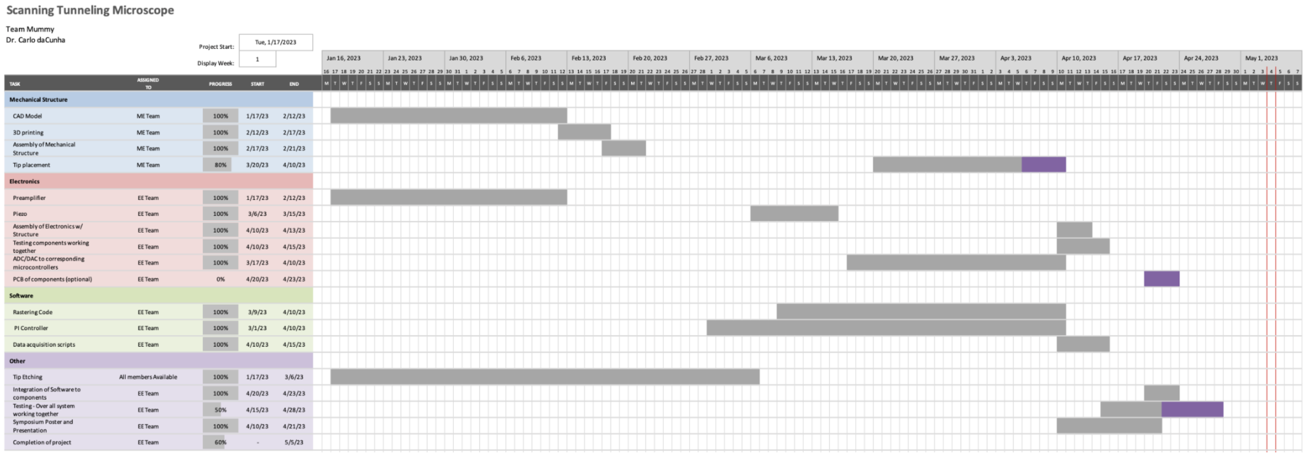
```
#include <Adafruit_MCP4725.h>//12 bit DAC

#include <Adafruit_ADS1X15.h>//ADC

#include <Wire.h>


Adafruit_ADS1115 ads1115;//Construct an ads1115

Adafruit_MCP4725 mcp4725;//construct an mcp4725


const int bias = 8;//pin for sample bias output


void setup() {

  // put your setup code here, to run once:


  Serial.begin(9600);//init serial comm at baudRate = 9600

  pinMode(bias,OUTPUT);//outputs 5V dc


  ads1115.begin();//Initialize adc

  mcp4725.begin();//initialize dac
```

```
}


void loop() {
  // put your main code here, to run repeatedly:


  //set bias
  digitalWrite(bias,HIGH);


  //adjust input gain to get range of ± 256 mV with a resolution of 7.8125uV
  ads1115.setGain(GAIN_SIXTEEN);


  ///////////////////PI control///////////////////////


  int z = 0;//z driver signal
  int Prop = 2;//proportional constant
  int Int = 1e-10;//integral constant


  while(1) {


        //get preamp output and call it "ampOut"
        int ampOut;
```

```
    ampOut = (ads1115.readADC_Differential_0_1());//adc resolution is 16 bits

    int err;

    err = ampOut - 128; //preamp output minus the set point. first try 2^7


    //calculate the proportional of the preamp output and the integral of the previous z value and add them

    z = (err*Prop)+(z*Int);


    //write z to the dac

    mcp4725.setVoltage(z, false);


    //output z signal value:

    int results;

    results = z;

    Serial.print(results*3);//output in mV

    Serial.println();


  }

}
```

Appendix C

Gantt Chart used to ensure the team stayed on schedule throughout the project.



Scanning Tunneling Microscope

Team Mummy
Dr. Carlo daCunha

Project Start: Tue, 1/17/2023
Display Week: 1

TASK	ASSIGNED TO	PROGRESS	START	END
Mechanical Structure				
CAD Model	ME Team	100%	1/17/23	2/12/23
3D printing	ME Team	100%	2/12/23	2/17/23
Assembly of Mechanical Structure	ME Team	100%	2/17/23	2/21/23
Tip placement	ME Team	80%	3/20/23	4/10/23
Electronics				
Preamplifier	EE Team	100%	1/17/23	2/12/23
Piezo	EE Team	100%	3/6/23	3/15/23
Assembly of Electronics w/ Structure	EE Team	100%	4/10/23	4/13/23
Testing components working together	EE Team	100%	4/10/23	4/15/23
ADC/DAC to corresponding microcontrollers	EE Team	100%	3/17/23	4/10/23
PCB of components (optional)	EE Team	0%	4/20/23	4/23/23
Software				
Rastering Code	EE Team	100%	3/9/23	4/10/23
PI Controller	EE Team	100%	3/1/23	4/10/23
Data acquisition scripts	EE Team	100%	4/10/23	4/15/23
Other				
Tip Etching	All members Available	100%	1/17/23	3/6/23
Integration of Software to components	EE Team	100%	4/20/23	4/23/23
Testing - Over all system working together	EE Team	50%	4/15/23	4/28/23
Symposium Poster and Presentation	EE Team	100%	4/10/23	4/21/23
Completion of project	EE Team	60%	-	5/5/23