NORTHERN
ARIZONA
UNIVERSITY

Department of Mechanical Engineering
Phillip Krigbaum
Clay Culpepper
Alec Markosian
Lucas Abedrabbo
ME-486C - 001

To: Professor Willy

From: STM Capstone Team

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Re: Engineering Calculations Summary

Top Level Design Summary

Our team was tasked with creating and improving a structure for a scanning tunneling microscope, as well as dampening vibrations that may occur around and within the design. We intend to solve our problem with the design that will be shown below and plan to enact vibration-damping techniques to further increase the visual quality of the microscope. The design created by our team (shown below in Figure 1) consists of several subsystems crucial to the functionality of the STM. An exploded view (Figure 2) will show a closer look at each subsystem and how they are incorporated into the design.

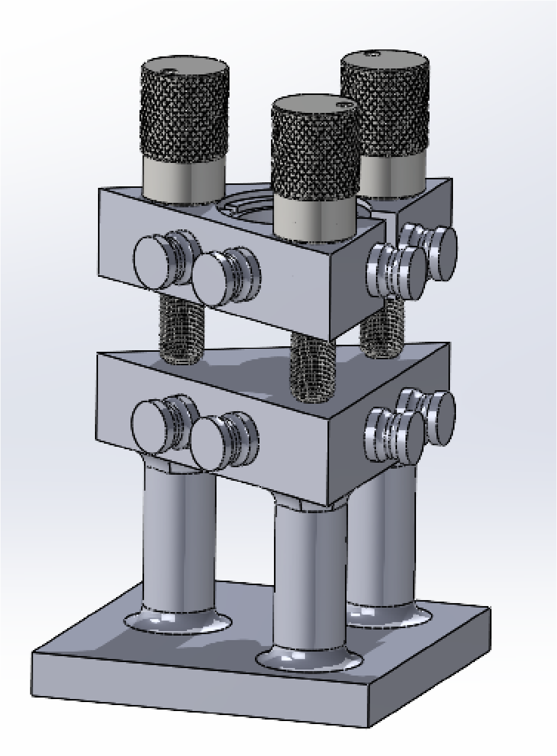


Figure 1: CAD Assembly (Current)

The number 1 in Figure 2 below denotes the top triangle of the structure. The center of the triangle has been designed to contain the piezoelectric sensor needed for imaging, and channels were created to allow for wires to be neatly routed through the structure. The number 3 balloon points to the base platform of the STM, which has been heavily modified throughout the course of the project's development. Columns were added to the base platform to allow the main components of the structure to be lifted off the ground. Although the team previously embedded the base platform and columns in concrete for security and vibration dampening, further changes to the structure's base will likely occur to accommodate for dampening systems added to the design. The balloons numbered 2 and 4 point to pins used to compress the top and bottom triangular platforms together, allowing the piezoelectric sensor to remain a consistent distance from the samples that will reside within the STM. Balloon number 5 points to brass inserts which allow the adjustment screws indicated by balloon number 6 to properly adjust the STM's top platform. The final component to mention is the retaining ring placed into the top triangle, as noted by balloon number 7. This ring will hold the piezoelectric sensor in place when imaging.

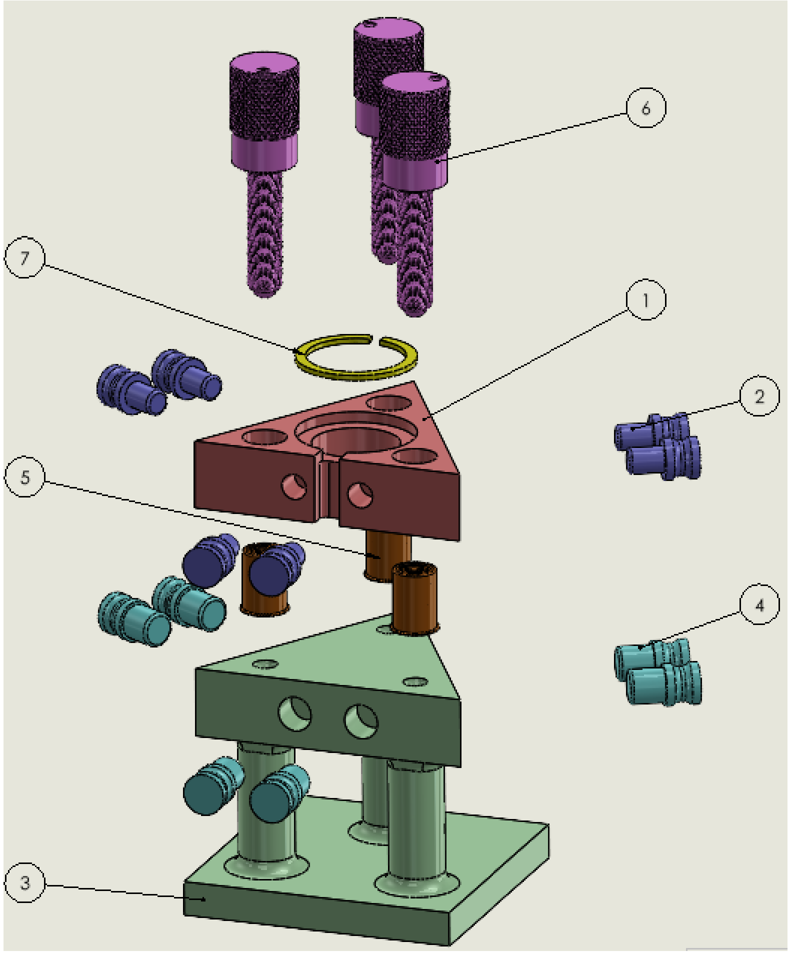


Figure 2: CAD Assembly (Exploded)

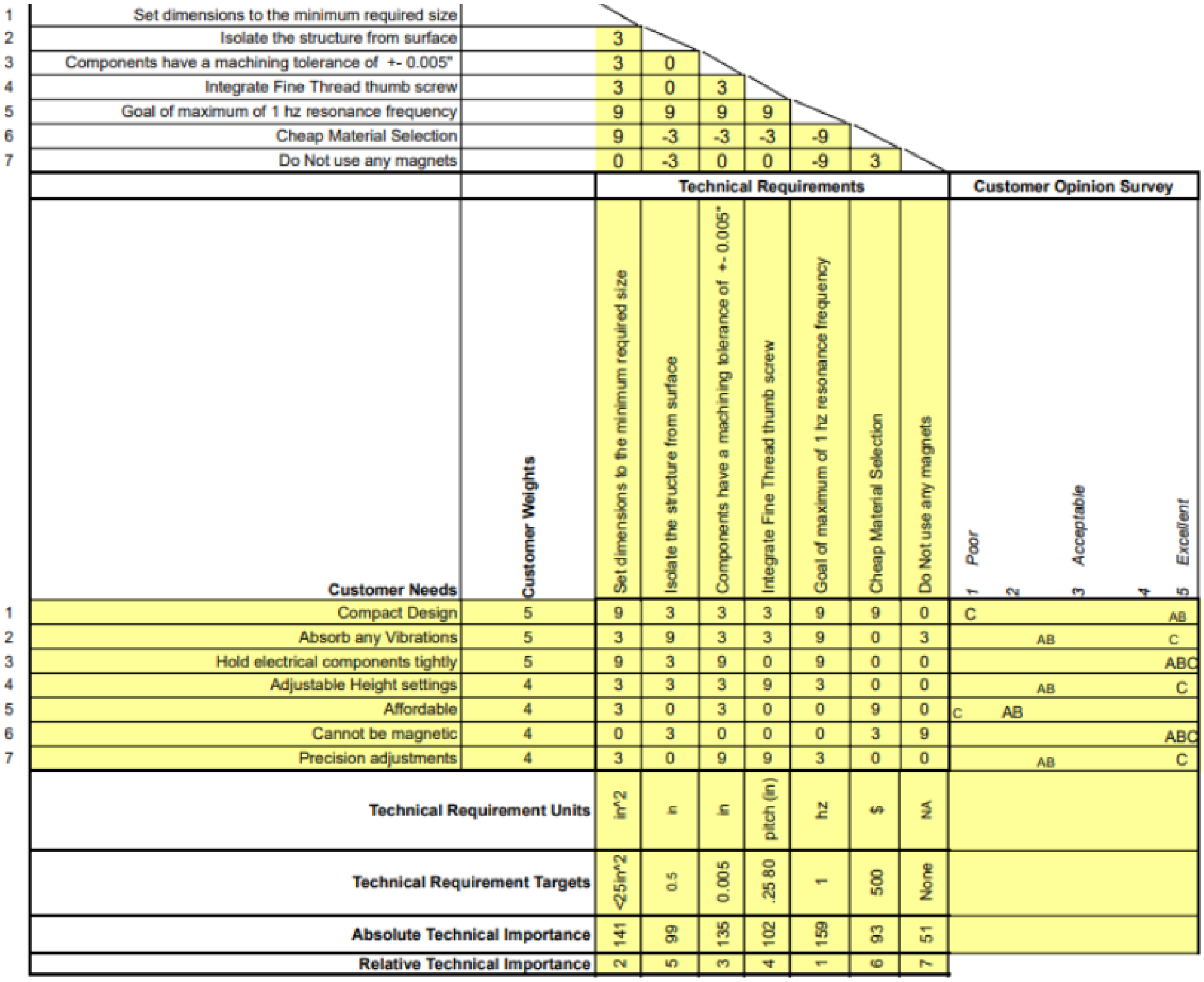
A QFD was also constructed to help list and identify our customer and engineering requirements when designing the STM. The QFD would allow us to rank each of the requirements mentioned above to identify which were most crucial to the design. Customer requirements were first identified to ensure the final product meets the expectations of our client. These included:

1. Compact Design - The microscope must have a compact design and be suitable for use on a benchtop or desktop. (Weighting: 5/5)
2. Absorb any Vibrations: The microscope should be designed to minimize the effects of external vibrations on the sample and the tip. This will allow us to achieve high-resolution imaging. (Weighting 5/5)
3. Hold Electrical Components Tightly: The microscope should be capable of holding and securing the electrical components in place. (Weighting: 5/5)
4. Adjustable Height Settings: The microscope should have adjustable height settings to accommodate various sample sizes and shapes. (Weighting: 4/5)
5. Cost within Budget: The design of this STM should not exceed the budget that was set by the client at the beginning of the project. (Weighting 4/5)
6. Cannot be Magnetic: The microscope should not generate any magnetic field that may interfere with the sample or other nearby devices. (Weighting 4/5)
7. Precision Adjustments: The microscope should be capable of making precise and accurate adjustments to the tip position and the sample stage in all three axes to ensure high-resolution imaging. (Weighting: 4/5)
8. Durable and Robust Design: The design needs to be sturdy and well-built. The end product should have a long lifetime and the customer should not worry that he will break any of our parts. (Weighting 4/5)
9. Reliable Design: The customer should be able to obtain an image every time they attempt to. There should not be any variation in results if the device is used properly. (Weighting 4/5)
10. Safe To Operate: All electrical components should be securely attached to ensure that there is no risk of electrocution. The frame should also be very sturdy to ensure there is no risk of the device tipping onto the client. (Weighting 5/5)

Engineering requirements included within the QFD also kept the client's needs in mind and were built off the customer needs previously mentioned. Requirements that were quantifiable and satisfied the customer's needs are as follows:

1. Set the dimensions of the microscope to the minimum required size of 25 square inches to meet the compact design requirement.
2. Isolate the structure of the microscope from the surface with a minimum distance of 0.5 inches to minimize the effects of external vibrations and fulfill the vibration absorption requirement.
3. Ensure that all components have a machining tolerance of +- 0.005 inches to meet the precision adjustment requirement and ensure high-resolution imaging.
4. Integrate a Fine Thread thumb screw with a pitch of 0.2580 inches to meet the adjustable height settings requirement.
5. Aim for a maximum resonance frequency of 1 Hz to meet the vibration absorption requirement and ensure high-resolution imaging.

6. Select affordable materials that are within the budget of $500 to meet the cost within budget requirements.
7. Avoid using any magnets in the design to meet the cannot be magnetic requirement.
8. Design the microscope with a durable and robust structure to ensure a long lifetime and meet the durable and robust design requirements.
9. Ensure the design is reliable and can provide consistent results by meeting the reliable design requirement.
10. Design the microscope to be safe to operate by securely attaching all electrical components and ensuring a sturdy frame to prevent tipping and fulfill the safe-to-operate requirement.



		1	2	3	4	5	6
1	Set dimensions to the minimum required size						
2	Isolate the structure from surface	3					
3	Components have a machining tolerance of +- 0.005"	3	0				
4	Integrate Fine Thread thumb screw	3	0	3			
5	Goal of maximum of 1 hz resonance frequency	9	9	9	9		
6	Cheap Material Selection	9	-3	-3	-3	-9	
7	Do Not use any magnets	0	-3	0	0	-9	3

			Technical Requirements							Customer Opinion Survey				
	Customer Needs	Customer Weights	Set dimensions to the minimum required size	Isolate the structure from surface	Components have a machining tolerance of +- 0.005"	Integrate Fine Thread thumb screw	Goal of maximum of 1 hz resonance frequency	Cheap Material Selection	Do Not use any magnets	1 Poor	2	3 Acceptable	4	5 Excellent
1	Compact Design	5	9	3	3	3	9	9	0	C				AB
2	Absorb any Vibrations	5	3	9	3	3	9	0	3			AB		C
3	Hold electrical components tightly	5	9	3	9	0	9	0	0					ABC
4	Adjustable Height settings	4	3	3	3	9	3	0	0			AB		C
5	Affordable	4	3	0	3	0	0	9	0	C	AB			
6	Cannot be magnetic	4	0	3	0	0	0	3	9					ABC
7	Precision adjustments	4	3	0	9	9	3	0	0			AB		C
	Technical Requirement Units		in^2	in	in	pitch (in)	hz	$	NA					
	Technical Requirement Targets		<25in^2	0.5	0.005	.25 80	1	500	None					
	Absolute Technical Importance		141	99	135	102	159	93	51					
	Relative Technical Importance		2	5	3	4	1	6	7					

Figure 3: QFD for STM

Summary of Standards, Codes, and Regulations

When considering standards and codes employed in the process of creating the STM, the main codes the project relates to are engineering drawing standards. Because the STM is very low-risk, not many codes apply to designing it other than drawing standards for the individual parts. These standards allow us to not only follow the formatting and design expectations of ASME, but also allow for effective communication of our design to other engineers.

Standard Number or Code	**Title of Standard**	**How it applies to Project**
ASME Y14.5M-2004	ASME Drawing Standards	Allows our engineering drawings to follow expected ASME standards

Table 1: Applicable Standards and Codes

Summary of Equations and Solutions

The main condition that led to our analysis is the main constraint to limit the resonant frequency of the microscope. This motivated the team to look into vibrations and other components that could help out with limiting the frequency like the material choice in the 3D-printed body of the scanning tunneling microscope. Another condition the team examined was the load the piezoelectric disk could displace with the amount of voltage applied to it. Then the last analysis done was a stress analysis on the fine thread screws to ensure they are strong enough for the load on the microscope.

Analysis 1 - Dampening Systems

The first engineering analysis done last semester was a vibration analysis on the damping systems the team has currently in place and potential damping systems the team could implement. These calculations were done using a handful of equations shown below.

$$\Sigma F = ma \quad (1)$$

$$mx'' + kx = 0 \quad (2)$$

$$x(t) = A\sin(\omega t + \phi) \quad (3)$$

$$\omega = \sqrt{k/m} \quad (4)$$

$$f = \omega/2\pi \quad (5)$$

$$c_{cr} = 2m\omega \quad (6)$$

$$\zeta = c/c_{cr} \; (7)$$

$$f_r = f/2\pi\zeta \quad (8)$$

$$x(t) = Ae^{-ct/2m} sin(\omega_d t + \phi) \quad (9)$$

$$\omega_d = \omega\sqrt{1 - \zeta^2} \quad (10)$$

$$mx'' + cx' + kx = Fsin(\omega_f t) \quad (11)$$

$$x(t) = x_c(t) + x_p(t) \quad (12)$$

$$x(t) = Ae^{-\zeta\omega t} sin(\omega_d t + \phi) + (F/k)sin(\omega_f t - \theta)/(\sqrt{(1 - r^2)^2 + (2r\zeta)}^2 \quad (13)$$

$$r = \omega_f/\omega \quad (14)$$

These equations lead to the creation of the following MATLAB graph that displays the performance of the damping systems the team was comparing shown in *Figure 1: Damping Systems* with the MATLAB code in the appendix of the document.

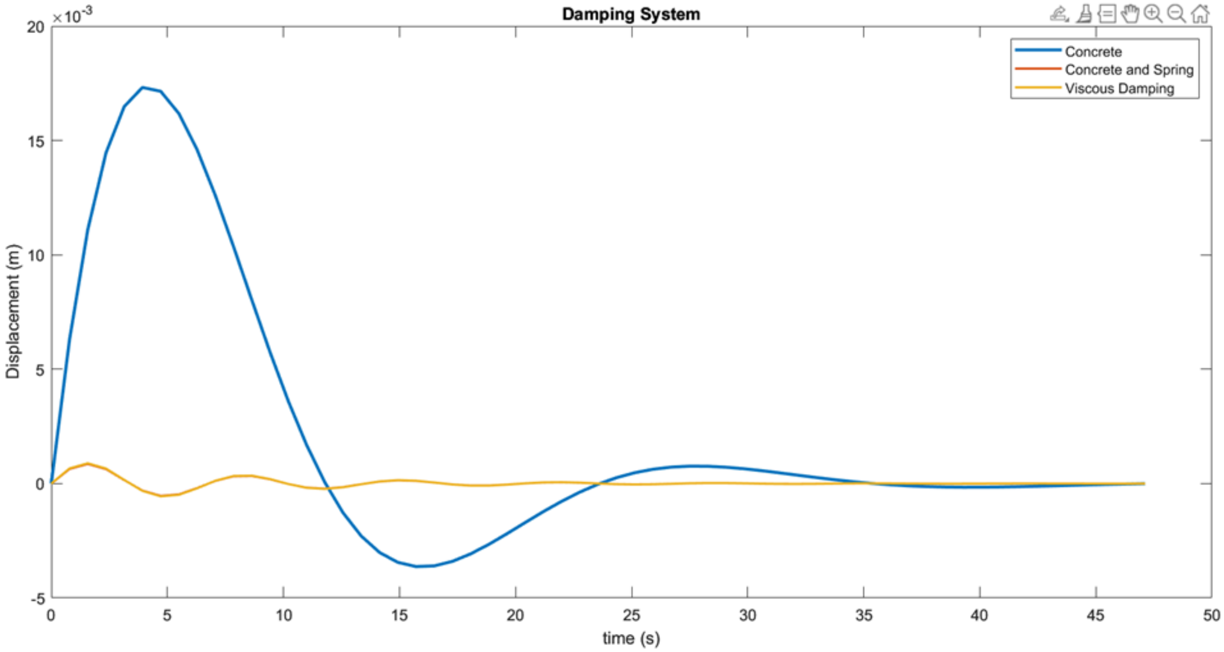


Figure 4: Damping Systems

This graph shows the displacement of the scanning tunneling microscope (STM) over time with the different forms of damping systems. The issue with this calculation is that it is a simplified representation of the STM and to get these results many variables from the equations above were assumed and not accurate to the actual microscope and were simplified to get results. However, the MATLAB graph generated does model a typical curve that damping systems follow and the equations above can be used to find the real frequency of the STM given more knowledge of the subject.

Analysis 2 - Fine Thread Screws

The next area investigated was the STM fine thread screws and how they will perform under stress with the microscope. The equations used to find the performance of these screws are the normal stress and shear stress formulas shown below.

$$\sigma = F/A \quad (15)$$

$$\tau = V/A \quad (16)$$

Using both the dimensions of the fine thread screws to find the area and the material properties of screws to find the force required in shear and normal force to break them. When plugging these in the max force required to break these screws is 9641 Newtons (N) and the torque required to shear the screws is 97650 Newton-meters (N*m). With these results it is unlikely that the microscope will fail due to the breakdown of the fine thread screws since the microscope will not have much pressure applied to it and the material surrounding the screws is 3D printed and will not break down the screws after repeated use.

Analysis 3 - Piezoelectric Disk

The third analysis done last semester was looking at the piezoelectric disk responsible for moving the scanning tip of the microscope and looking at the required amount of voltage to displace the scanning tip. The equations used to calculate this are shown below.

$$E = S/d \quad (17)$$

$$S = (1/Y)T = sT \quad (18)$$

$$T = F/A_p \quad (19)$$

$$f_{bl} = d_{33}Y^{E}{}_{3}(A_p/t_p)v \quad (20)$$

$$s_{33}{}^{E} = 1/Y_3{}^{E} \quad (21)$$

To move the piezoelectric 0.10 μm it requires 6.0415 volts and results in a force of 200 Newtons. This is an expected outcome since piezoelectrics are known for producing a lot of force for the amount of displacement. These calculations will be used to help design the structure to make sure the structure can handle the force produced.

Analysis 4 - Material Selection

The fourth analysis that we completed was the analysis of the material that the body would be made out of and how that would affect the vibrations being transferred to the scanning tip. Our client wanted to 3D print the body of the STM so all of the materials that we analyzed are plastics that can easily be printed using a 3D printer. The formulas that we used to check the vibrations going through the body are:

$$f = \frac{\omega}{2\Pi} \qquad (22)$$

$$\omega = \sqrt{\frac{k}{m}} \qquad (23)$$

Using these formulas and the known mass of the plastics we were able to create a graph (Figure 5) that compared PLA, PETG, and ABS (printed from a resin printer). This graph compared the natural frequencies of the material based on the infill of the print.

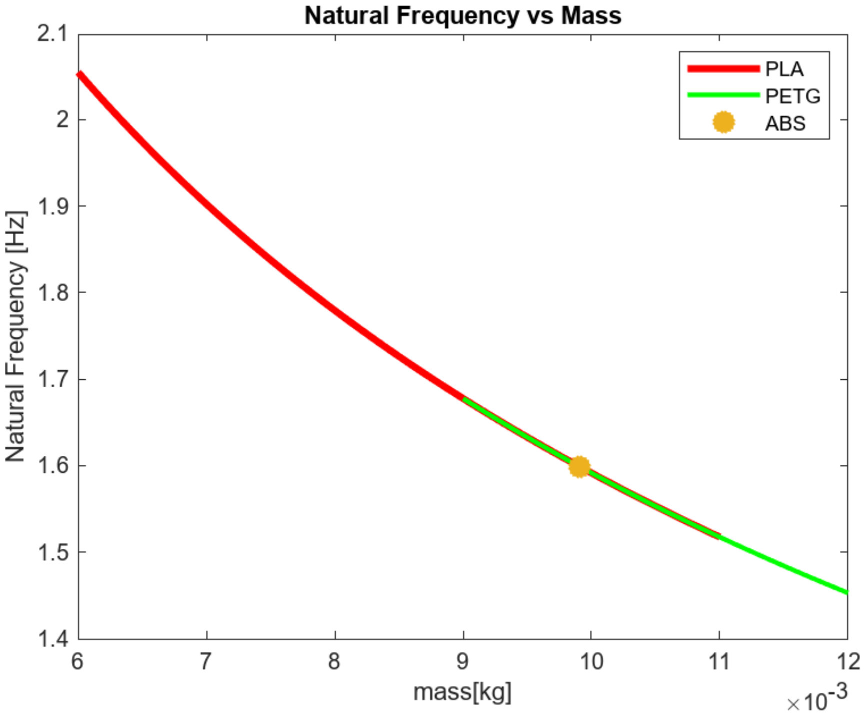


Figure 5: Material Vibration Analysis

The MATLAB script for these calculations can be found in Appendix B. There are some errors in these calculations due to the fact that some of the variables needed to be assumed rather than known. To find the exact natural frequency of our model we will need to pull the model into ANSYS or another similar software. These software are capable of taking the design of our model into consideration. However, the MATLAB calculations gave us a good enough understanding to move forward with the project before fine-tuning the end product. We were able to conclude that PLA would be a good material for the body of our system. It performed well enough in the vibration analysis and has many other advantages over the other materials. The biggest advantage that PLA has over the other materials is the ease of manufacturing. Our client wants to make this STM easy for anyone to make and using PLA ensures that anyone can print the body with a basic 3D printer.

Factor of Safety

Sub-system	Part	Load Case Scenario	Material	Minimum FoS
Component Body				
	Adjustment Screws	Adjustment Screws are placed with the load running through the axis of the screw	18-8 grade stainless steel thumbscrews	9773.13
	Adjustment Screws	Twisting the screw with resistance being put on the screw which would cause the bolt to shear from the torque	18-8 grade stainless steel thumbscrews	
	Upper Spring Stud	Point load from rubber bands running perpendicular to the central axis of the stud causing the stud to shear	PLA	
	Lower Spring Stud	Point load from rubber bands running perpendicular to the central axis of the stud causing the stud to shear	PLA	
Vibration Dampening				
	Hanging Tension Springs	Point load hanging axially from spring	Music-Wire Steel	

Table 2: Factor of Safety

After conducting our research and analyzing the different components of our build, we did have to make some alterations to our original design. We found that the load being placed on the adjustment screws would have no effect on the screws; however, we did find that the studs that the rubber bands are mounted to are very close to their max load. As a temporary resolution to this, we increased the size of the studs in order to strengthen them. Moving forward we are going to replace the 3D-printed studs with stainless steel bolts. This will greatly improve their strength and will no longer be a point of failure.

We also learned from our analysis that moving forward the body should be 3d printed out of PLA due to its ease of printing and natural frequency. We are currently designing our vibration dampening structure and the analysis done on the different types of damping will help us move forward. Understanding that viscous dampening is the most effective form of dampening allows us to focus our research on this form of vibration dampening.

Flow Charts and Other Diagrams

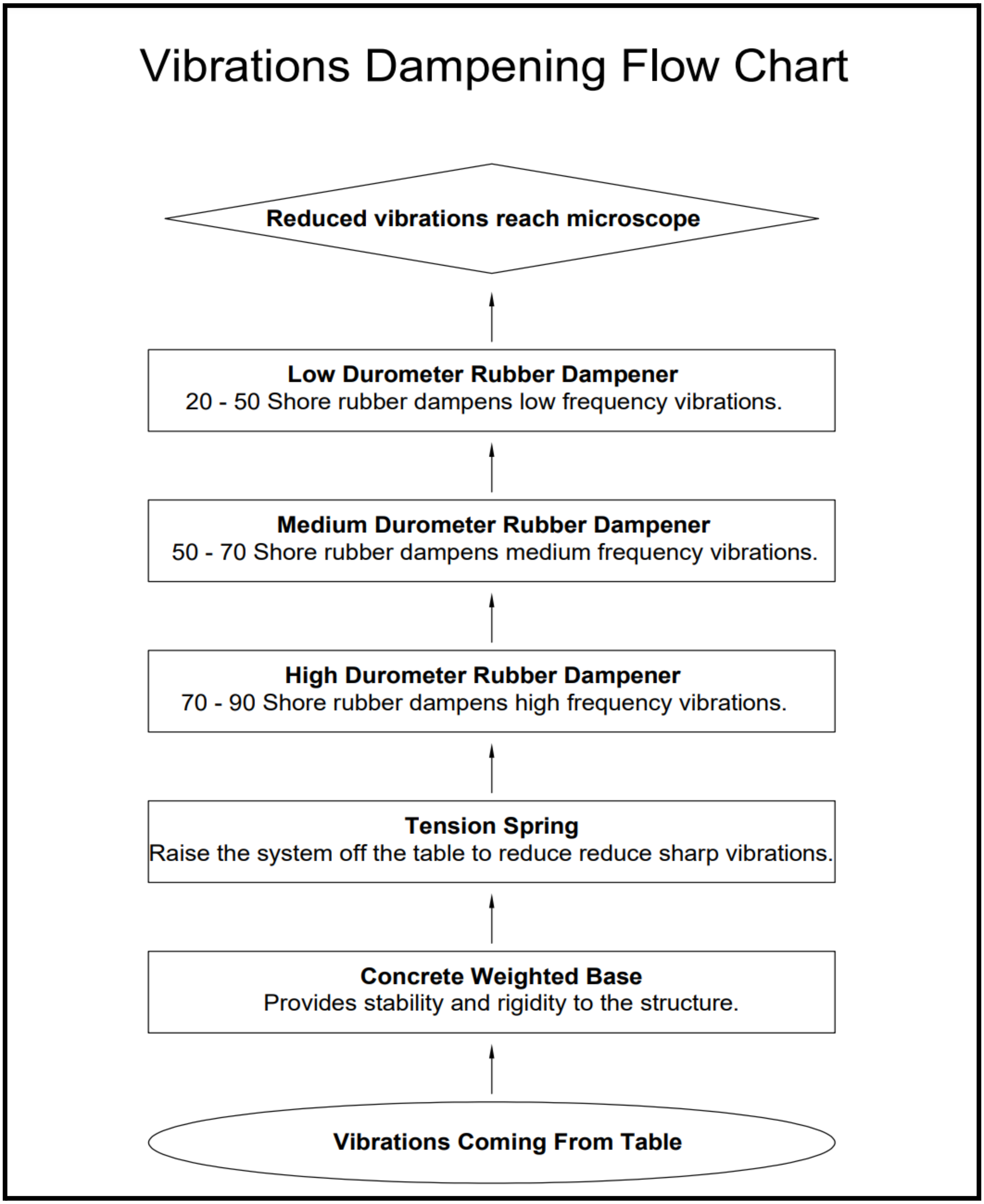


Figure 6: Vibration Dampening Flow Chart

Figure 6 shows how our team is mitigating vibrations from being transferred from the table the microscope is sitting on to the microscope itself. This flowchart starts with the table that the microscope will be mounted to where the vibrations will be coming from. The first item the vibrations will meet is a large concrete block to help give the entire system a stable and rigid structure to be mounted to. Our microscope will then be mounted onto three tension springs that will suspend the system from large shakes and vibrations. After the spring there will be a stack of steel plates that will be separated by pieces of rubber with different durometers to reduce vibrations of different frequencies. This flowchart shows in what order the vibrations will stop.

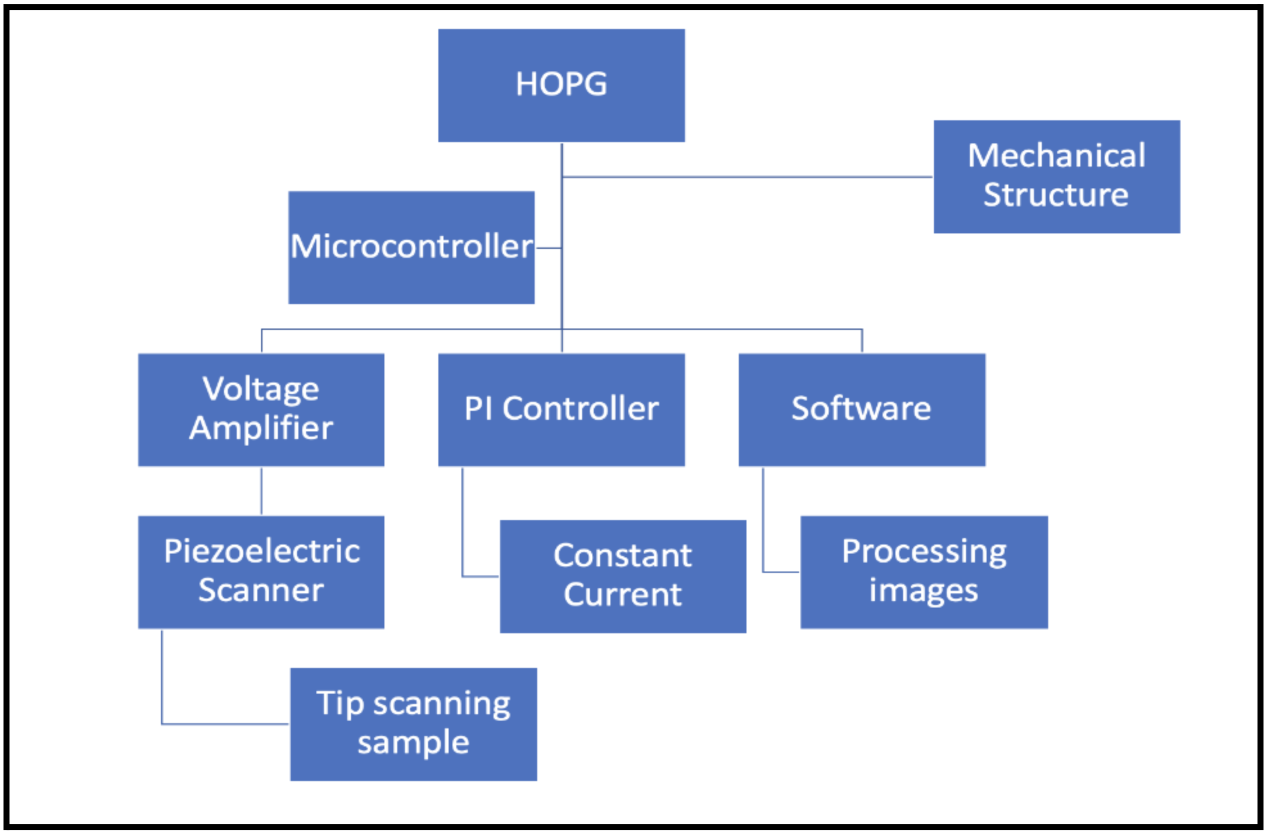


Figure 7: Electronic Flow Chart.

Figure 7 shows the electronic side of the STM. The electronics are designed by the electrical engineering team. Even though our team is not directly designing the electronics it is very important that we the mechanical engineering team understand how they work and what each part accomplishes. This flowchart shows how each component interacts with each other. The microcontroller is in the middle because it oversees how all the other components communicate and interact with each other. This flowchart lays out the basics of how this microscope works and is useful in understanding operations as well as diagnosing problems.

Moving Forward

Moving forward, our team will be focusing our efforts on vibration testing and mitigation, as well as building the final design. The steps required to accomplish these goals are to finish our full CAD assembly. Once the full CAD assembly is complete, Phillip and Lucas will be running that assembly through the ANSIS software to get a vibration analysis. Once the vibration analysis has been completed, Clay and Alec will analyze the results to make decisions on what parts of the assembly can be improved. From there, the team will regroup to implement the changes into our final design. Once the final design has been completed, our team will use an Arduino to measure the vibrations being passed through our damping system. From here, our team will meet with our client to discuss our results and see if the design meets his expectations.

Appendix A - Vibration Dampening Analysis

```
%Concrete
A = 0.03367;
c = 3;
m = 11.34;
omega = 0.297;
damping = 0.445;
omega_d = omega*sqrt(1-damping^2);
t = 0:pi/4:15*pi;
f = A*(exp((-c.*t)./(2.*m))).*sin(omega_d.*t);
plot(t,f,'LineWidth',2)
title('Damping System')
xlabel('time (s)')
ylabel('Displacement (m)')
hold on
% Concrete and Spring
A1 = 0.001065;
omega1 = 0.939;
damping1 = 0.141;
omega_d1 = omega1*sqrt(1-damping1^2);
f1 = A1*(exp((-c.*t)./(2.*m))).*sin(omega_d1.*t);
plot(t,f1,'LineWidth', 1.5)

% Concrete, spring, viscous fluid
 A2 = 0.0011;
 omega_f = 1.065;
 k =10;
```

```
F = 1;
r = .5325;
comp = A2.*exp(-damping1.*omega1.*t).*sin(omega_d1.*t);
particular = (F/k).*sin(omega_f.*t)/(sqrt((1-r^2)^2+(2*r*damping1)^2));
f2 = A2.*exp(-damping1.*omega1.*t).*sin(omega_d1.*t)+particular;
plot(t,f2,'LineWidth',1.5)
legend('Concrete','Concrete and Spring', 'Viscous Damping')
```

Appendix B - Material Selection Analysis

Formulas

Natural Frequency

= the angular frequency of the object

Angular Frequency

k = the spring constant for the system

m = mass of the system

Assumptions

k is a constant 100N/m (This value needs to be tested to verify accuracy)

Cubic infill pattern

Analyzing Top Triangle

Vibration Calculations

```
clc;clear;close all;
k = 1; %N/m
min_mass_PLA = 6; %mass when infill is set to 1% [g]
max_mass_PLA = 11; %mass when infill is set to 100% [g]
min_mass_PLA = min_mass_PLA/1000; %[kg]
max_mass_PLA = max_mass_PLA/1000; %[kg]
mass_PLA = min_mass_PLA:.00001:max_mass_PLA;

ang_freq_PLA = sqrt(k./mass_PLA); %angular frequency of system [Hz]
Nat_freq_PLA = ang_freq_PLA./(2*pi); %Natural Frequency of system [Hz]

min_mass_PETG = 9; %mass when infill is set to 1% [g]
max_mass_PETG = 12; %mass when infill is set to 100% [g]
```

```
min_mass_PETG = min_mass_PETG/1000; %[kg]
max_mass_PETG = max_mass_PETG/1000; %[kg]
mass_PETG = min_mass_PETG:.00001:max_mass_PETG;

ang_freq_PETG = sqrt(k./mass_PETG); %angular frequency of system [Hz]
Nat_freq_PETG = ang_freq_PETG./(2*pi); %Natural Frequency of system [Hz]

ABS_density = 1.17; %[g/cm^3]
ABS_density = ABS_density*(100^3)/1000; %[kg/m^3]
Volume = 8468.80;%mm^3
Volume = Volume/1000^3; %m^3
mass_ABS = ABS_density*Volume; %kg

ang_freq_ABS = sqrt(k/mass_ABS); %angular frequency of system [Hz]
Nat_freq_ABS = ang_freq_ABS/(2*pi); %Natural Frequency of system [Hz]

plot(mass_PLA,Nat_freq_PLA,'r','LineWidth',3)
hold on
plot(mass_PETG,Nat_freq_PETG,'g','LineWidth',2)
plot(mass_ABS,Nat_freq_ABS,'*',LineWidth=8)
hold off

xlabel('mass[kg]')
ylabel('Natural Frequency [Hz]')
legend('PLA','PETG','ABS')
title('Natural Frequency vs Mass')
```

Strength Analysis

```
Tensile_PLA = 40000000;%N/m^2
Tensile_PETG = 45000000; %N/m^2
Tensile_ABS = 22000000; %N/m^2
Surface_A = 748.62; %mm^2
Surface_A = Surface_A/1000; %m^2

Maxforce_PLA = Tensile_PLA/Surface_A;
Maxforce_PETG = Tensile_PETG/Surface_A;
Maxforce_ABS = Tensile_ABS/Surface_A;

bar(1,Maxforce_PLA)
hold on
bar(2,Maxforce_PETG)
bar(3,Maxforce_ABS)
legend('PLA','PETG','ABS')
ylabel('Max Force (N)')
title('Material Strength')
```