ME366J Mechanical Design Methodology - Personal Notebook
The University of Texas at Austin, Walker Department of Mechanical Engineering

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Semester (YYYY Fa/Sp/Su):	2022 Fall
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Date: 8/26/2022. Topic: Discussion of Gantt Chart and Task List and Team Planning

Yesterday was the first discussion session where the team was formalized. We are a group of 4 and from my understanding, all of us, including myself, are robotics/mechatronics savvy with varying ranges of experience with other aspects of engineering. As for myself, my skills primarily lie in software implementation and working with microcontrollers. An important observation is that none of us are experienced in music or acoustics at a technical level, and thus extra care must be taken to learn and apply acoustics and relevant music concepts with care to not face difficulties with our projects. I have worked with digital signal processing before and hope to use that to find more info on acoustics for music.

As for the task list, I suggested that we take an approach where we gradually become more and more detailed as developments occur over time, without needing to shift deadlines and time expectations. The reason for that is that is quite difficult to predict the exact steps to take. I also agreed with the notation of preserving a sense of flexibility to allow we to 'go back' in time and make any necessary updates for the sake of progress. Task assignments will also be made soon. For now, here's what we have. Google Sheet's formatting glitched the blocks. I plan on trying to fix this over the weekend.

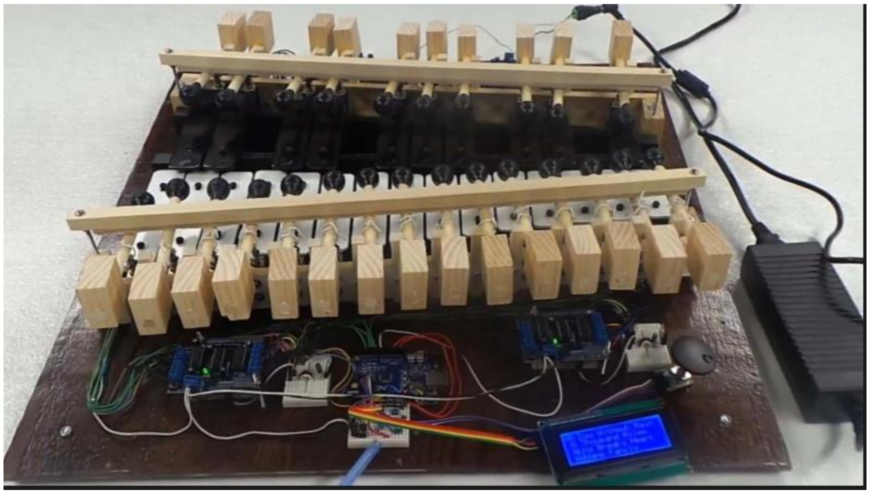
TASK	ASSIGNED TO	PROGRESS	START	END
Project Proposal				
Gantt Chart	All	100%	8/26/2022	8/29/22
Backgroud Research	All	10%	8/26/22	8/29/22
Targets & Questions	All	0%	8/29/22	9/1/22
Go out and Ask	All	0%	9/1/22	9/5/22
Interpret Raw Data	All	0%	9/5/22	9/7/22
Writing	All	0%	9/7/22	9/13/22

For now, the right thing to do would be to carry out some background research to understand the concepts and scale of what I'd be working with. From there, a better understanding of what and who to ask can emerge.

<u>Date: 8/28/2022. Topic: Background Research</u>

I began by trying to search around directly for any music playing robots, hoping to derive any next steps from there. I came across this automated xylophone with rockers and solenoids connected to an Arduino Uno that inputs MIDI files.

This alone provides a strong intuition of what to research: microcontroller selection, power requirements, end-effector selection based on instrument, and I/O techniques.



https://hackaday.com/2022/01/27/robotic-xylophone-makes-music-with-midi-magic/

What stood out most to me was the approach of using MIDI (Musical Instrument Digital Interface) files. This system opens the option of traversing the internet for MIDI files of whatever songs we seek, which is crucial for fulfilling the purpose of having a minimum of 3 playable songs. However, this is not without its issues. I would have to look into modifying the files depending on what instrument is selected and study the process of interfacing midi files with a microcontroller like an Arduino. Luckily, I found a library for Arduino based solutions (https://www.arduino.cc/reference/en/libraries/md_midifile/). With that said, to avoid tunnel visioning down one route, I think it's important to keep my ears open for other possible approaches.

Following more searches and reports on the automation of instruments, an important conclusion that I come to is that the selection of an instrument will without a doubt massively affect the entire course of this project in terms of engineering implementation and criterion fulfillment. The only constant aspect is the use of a microcontroller to input music. Each instrument varies significantly electromechanically. More insights and info are needed to formulate a better sense of direction. To guide my sense of knowledge more, the best of course to follow is to speak with an acoustics expert to gain more insight on music input as well as understanding any challenges or limitations to the automation of specific instruments as considerations for actuation.

Date: 9/2/2022. Topic: Updated Gantt Chart, interview planning

I have helped the rest of my team update the Gantt chart and noticed that a better sense of time was established. Furthermore, it's key to point out that a good chunk of phase 1's work is interviewing people who are directly within the k-12 audience or are affiliated with the topic or the target market/audience itself. As for the rest of the phases these have some high-level tasks. The following shows in image of the phase 1 section of the Gantt Chart, updated on the 1st of Sep.

Linkedin Park
Project Lead

Project Start: 8/26/2022
Display Week: 1

TASK	ASSIGNED TO	PROGRESS	START	END
Project Proposal				
1.Gantt Chart	All	100%	8/26/22	8/29/22
2. Backgroud Research	All	100%	8/26/22	8/29/22
3. Targets & Questions	All	100%	8/29/22	9/1/22
3.1. Questions for K-12 Students	Elliot Turner	100%	8/29/22	9/1/22
3.2. Questions for outreach people	Peter Matthew	100%	8/29/22	9/1/22
3.3. Questions for educators	Elliot Turner	100%	8/29/22	9/1/22
3.4. Questions for musicians	Yifeng Liao	100%	8/29/22	9/1/22
3.5. Questions for robotics experts	Talal Al-Otaibi	100%	8/29/22	9/1/22
4. Go out and Ask	All	100%	9/1/22	9/8/22
4.1. Interview K-12 Students	Elliot Turner	100%	9/1/22	9/8/22
4.2. Interview outreach people	Peter Matthew	100%	9/1/22	9/8/22
4.3. Interview educators	Elliot Turner	100%	9/1/22	9/8/22
4.4. Interview musicians	Yifeng Liao	100%	9/1/22	9/8/22
4.5. Interview robotics experts	Talal Al-Otaibi	100%	9/1/22	9/8/22

Linkedin Park
Project Lead

Project Start: 8/26/2022
Display Week: 1

TASK	ASSIGNED TO	PROGRESS	START	END
5. Formulate House of Quality	All	100%	9/8/22	9/10/22
6. Engineering requirements + spec	All	100%	9/10/22	9/11/22
7. Writing the problem statement	All	100%	9/10/22	9/11/22
8. Writing the proposal	All	100%	9/11/22	9/12/22
9. Review and Submit the Proposal	All	100%	9/12/22	9/12/22

Factoring in scheduling and contacts, we collectively decided that I should reach out to some experts in robotics and more importantly acoustics for the purpose of at least interviewing 10 individuals. To do this, I needed to draft some questions and check back with the team to see if they have any additional questions to ask. During the process, it seemed that it was quite easy to fixate on asking only technical questions, which was not the purpose of these interviews. I decided to lead with some questions related to the audience to avoid fixating on technicality, specifically about robotics for the purpose of outreach as an educational tool.

With the rest of my team members looking into what the k through 12 audience wants, my time should best be spent learning from the hindsight of these experts to create an appealing solution to the audience. I feel it is best to try to reach out to professors, as their teaching experience and technical know-how can be much more informative than I can imagine, especially when it comes to fulfilling the requirement of demonstrating mechanical engineering principles.

By the end of Sep 1st, here are the questions I came up with:

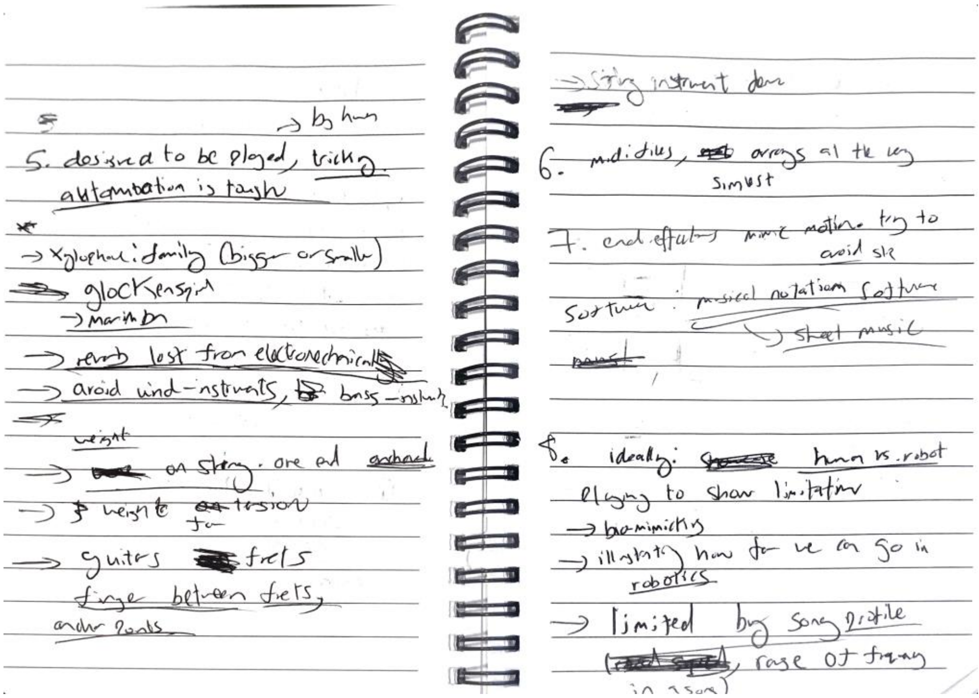
1. What is your background in terms of career?
2. Have you ever tutored, taught, or lectured students from k-12. In acoustics?
3. Follow up on 2: Do you believe that most k-12 students, specifically STEM focused high schoolers, are taught enough about the basics of acoustics? If not, should there be some way to help guide them.

4. Would a project in action, i.e in demo, help a student understand acoustics in comparison to a standard lecture?
5. Which instrument would come to mind for automation?
6. How would you go about inputting music into such a robotic system?
7. Any Software and hardware resources or recommendations? Any materials or end-effectors to avoid based on your experience with acoustics?
8. Any limitations, caveats, or drawbacks to using robotics to play an instrument as opposed to manually playing an instrument? (any aspect)
9. When it comes to seeing an automated instrument as an acoustician, what features would you like to see? How would you ideally expect it to perform?

Date: 9/8/2022. Topic: An interview with Dr. Samuel Wallen

I reached out to as many available professors as possible. In some previous entries, I wanted to uphold the emphasis on interviewing acoustics experts. On the 5th of Sep, I managed to interview Dr. Samuel Wallen over a zoom call for 40 minutes. As a professor of the numerical analysis course I took, I was made aware of his research efforts on acoustics, which is why I contacted him. I took some notes and with Dr. Wallen's consent recorded the interview for archiving and analysis later. At the end of the day, I looked back at what I had to try to pinpoint some key points for the project moving forward. Dr. Wallen's technical know-how with acoustics and experience in outreach events has led to the following observations:

- The content and technicality of an acoustics demo is highly dependent on the audience age given that the topics can be non-intuitive and quite intense with the terms used.
- People in general, not just an audience of kindergarten through high school students, are not taught enough about acoustics.
- There's merit to teaching acoustics for health reasons (eardrums) and communication improvement. Acoustics to bridge science and music is also a great motif for an initiative like this
- Having a sensory and kinesthetic approach to learning is far more effective than lectures. An interactive demo can excite students whilst also keeping them engaged.
- The automation of instruments is tricky given that instruments are ergonomically designed to be played by a human. According to Wallen, the xylophone family is easiest to work with. Wind or brass instruments pose a massive difficulty.
- In terms of software and hardware, midi files are the best bet for inputting, especially if sheet notation music software is paired. End-effectors should try to bio-mimic human input and avoid slip over hard surfaces.
- Emphasis on playing a diverse range of notes to allow more options for songs. Same goes for higher tempo songs. For positive outreach experience, the device should be audible but not too loud.


→ by human
5. designed to be played, tricky
automation is tough
→ Xylophone family (bigger or smaller)
→ glockenspiel
→ marimba
→ reverb lost from electromechanical
→ avoid wind-instruments, brass-instruments
weight
→ on string. one end anchored
→ weight tension
→ guitars frets
finger between frets,
and/or pads
→ String instrument demo
6. midi files, arrays at the very simplest
7. end effectors more motion try to avoid slip
Software: musical notation software
→ sheet music
8. ideally: human vs. robot
playing to show limitation
→ biomimicking
→ illustrate how far we can go in robotics
→ limited by song profile
(range of frequency in a song)

some notes from the interview

<u>Date: 9/11/2022. Topic: House of Quality</u>

I helped review the customer statements from the team to conduct a customer needs analysis and one thing that I noticed was that much of the needs were quite multi-faceted. A lot of them concerned the ability to conduct outreach and focused on the environment in which the device operates in (placed on a desk, compact) and on the dynamics of setting an apparatus up (does it additional funds, time to set up, etc.). Much of the remarks also concerned audio quality (no unwanted disturbances, high range of notes, & tempo). The remarks that heavily define the nature of the final product were weighed heavily. I also tried to take note of the frequency at which statements are present (remarks about pitch were repeated). Once higher-level interpretations of the needs were made, I began formulating an HoQ.

By crosschecking with the customers needs analysis table and in a live Zoom session, the customer attributes section was collaboratively formulated. I came up with the metrics with assigned directions of improvement via some logical thinking and some google searches to see the common standard, especially acoustic metrics such as bandwidth and Tempo. I then mapped the positive/negative correlations between the metrics and the customer attributes. It was interesting but also unsurprising to note that the acoustic metrics drove positively correlated with the performance-based customer attributes but also clearly add to the cost of the system as a more rigorous electromechanical set up needs to be implemented. In the end for the targets, I suggested a tempo of 140 BPM to open the possibility of some hip hop, pop, and rock songs. In addition, a bandwidth of 1900 Hz was selected to allow for a range 100 Hz to 2000Hz to be played, encompassing a guitar's bandwidth and some higher pitches as well for added versatility. Much of the physical metrics were defined by a collective intuition of a portable object fitting a desk.

Positive O, Negative X			Setup Time(min)	Sucessfully Played Songs(#)	Bounding Dimension(ft)	Minimum Guranteed Playtime (min)	Additional Cost to User($)	Maximum Weight (lb)	Volume (ft^3)	Minimum Sound Volume (dB)	Tempo (BPM)	Bandwidth (Hz)	Cost to Make ($)
Direction of Improvement			↓	↑	↓	↓	↓	↓	↓	↑	↑	↑	↓
What	Size	Instrument must Fit on a desk (5)			O				O				
		Instrument can be Carried by One (4)						O					
	Reliability	Reliable Operation (5)		O		O							
	Time	Quick, Easy Setup (4)	O										
		Short Demonstration Duration (5)									O		
	Performance	Sound Quality (4)										O	X
		Loudness (3)								O			X
		Playing Speed (3)									O		X
		Musical range (4)										O	X
		Audience Engagement (4)		O		O						O	
	Cost	No Additional Cost to User (4)					O						
		Low Cost to Make and Maintain (3)									X	X	O
		Target	3	3+	4	5	0	11	5	50	140	1900	250

Date: 9/13/2022. Topic: Engineering Requirements & List

Once the targets from the HoQ were set, it was just a matter of tabulating them to form an engineering requirements list. I helped classify them as demands or wishes. Upon doing so, I realized that much of the requirements under the performance category were more wishes than demands. The reason is that it was crucial to ensure the product's ability in being physically easy to work with in terms of portability and space. Much of the customers' experiences had them emphasize the physical nature and reliable output of the product as the core of a dependable outreach tool, whereas the musical performance metrics add more to the product's viability, but do not single-handedly define the success of it.

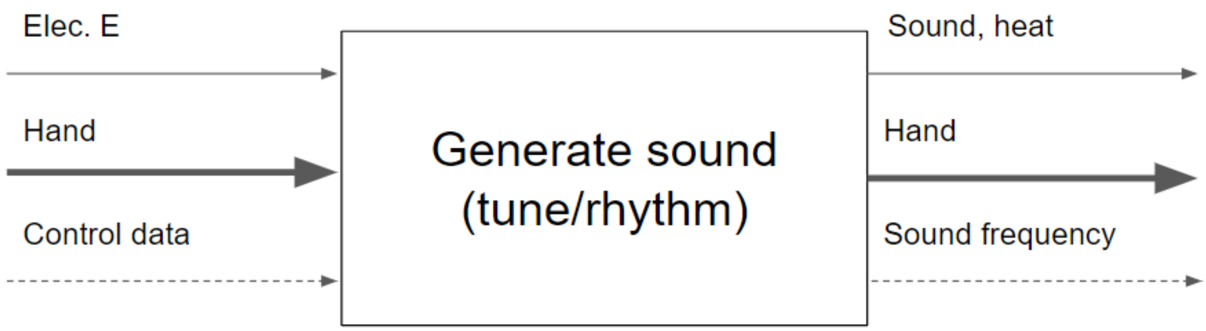
I focused on creating objective verification metrics for the performance-based requirements such as using a tuner for frequency measures, a decibel/sound level meter for audio volume, and using standard audio files at specific BPMs and recording the audio for playback and peak analysis to check for tempo matches or exceeded expectations.

An audio software that I have briefly worked with for acoustic measurements is Audacity.
https://www.audacityteam.org/

I will have to look into and evaluate its viability versus physical instrumentations. It is important that verification techniques aren't just accurate, but also accessible and repeatable for a thorough evaluation.

Date: 9/15/2022. Topic: Functional Model

Collaboratively, generating the black box diagram was not an arduous process. I ensured to pay special information to the fact that there's information/signal flow into the system, which is importing the data to play a song (control data). Information flow isn't material or energetic and so there is plenty of flexibility in how one can go about incorporating this process and thus options are diverse. As such, options to address the high-level process of importing data will need to be carefully examined.



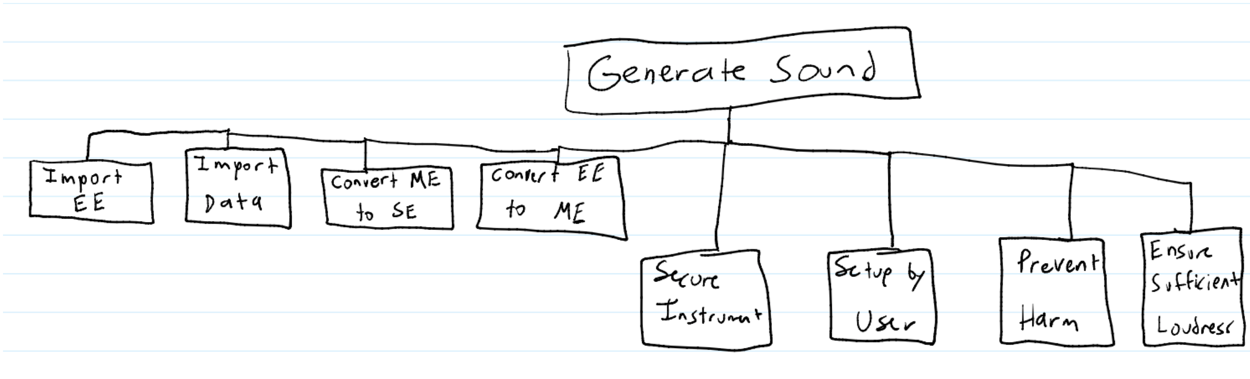
From there, a functional tree needs to be examined, with extra care devoted to using verb-noun formatting. One matter I noticed is that it is easier to make clear distinctions between auxiliary subfunctions and energetic based subfunctions that interact with one another. For example, securing the instrument is really an isolated subfunction that doesn't influence material or energy transformations, but it is a substantial subfunction, nonetheless. The same can be said for any subfunction implementation of preventing harm.

Much of the subfunctions that define 'generate sound' do follow a rather linear path with mostly energy transformations. I I identified the basic subfunctions beginning with importing or supplying electrical energy followed by a series of converting electrical energy to mechanical, then mechanical to sound energy. As a result, it is clear to me that much of the subsystems which map to these subfunctions will be heavy on implementing transformation processes and actuators to fulfill the primary function.

In terms of any subfunctions that work in parallel, I noted that importing the data and supplying electrical energy do work in parallel. Without electricity powering the system, it is difficult to get whatever mechanism to import and process whatever digital or analog data we use. Moreover, I did also notice that the possibility of implementing a microcontroller can best bridge the gap between data importing and ensuring proper control of the actuators to produce music.

Finally, a subfunction to ensure adequate loudness is crucial to account for dissipations and to counteract inadequate sound generation. I also noted that it would be important to make sure that electromechanical components should not be loud so that the acoustic output is not muffled or 'buried' by the movement of non music-generating parts.

The following images shows the subfunction tree that we collectively came up with



Date: 9/25/2022. Topic: Morphological Matrix

The best course of action would be to take the subfunctions identified from the functional model and try to come up with sets of solution ideas mapping to these subsystems. I noticed that a lot of these came down to component selection. Not much emphasis was placed on interfacing these components with one another as that would be far too detailed for this step. Options range in difficulty, usefulness, and complexity but discarding them before rigorously evaluating them later would be myopic and negligent of their value

Continuing based off the idea of importing data, there were plenty of ways to go about this. The first option would be hard to code them onto a microcontroller directly. The more versatile but trickier options would be using a network option: wifi or ethernet to fulfill the same purpose. Finally, using a serial USB or uploading a file through USB drive is what I intuitively came up with first. This step being the first wouldn't really influence the final product much but it will considerably change the levels of software work. My best guess is to avoid the convoluted approach of hard coding or using Wi-Fi all together, but I'd need to consult my teammates.

In terms of electrical to mechanical energy conversions, much of these were derived from prior art research, and I noted down that this is simply a matter of actuator implementation, whether linear kinetic energy or rotational. As such, the options range from stepper motors to solenoids and brushed/brushless dc motors.

As for other contributions, I also added that fulfilling the subfunction of controlling the instrument can range from using a programming wheel which allows the user to mechanically interface with the system to play notes or a wheel which uses variable resistance to configure the driven mechanism (example: potentiometer). The purpose is to promote user engagement, however both approaches seem unwieldy and hard to interface with importing data. It seems both these solutions in this subfunction category involve manual operation of the device. The automatic approach would be to work with the microcontroller. This will likely be the prevalent subfunction solution in use.

The other entries involved the acoustic/sound wave propagation technique, which was collaboratively filled in. Wind instruments were suggested as solution but as per my interview with Dr. Wallen, there is a strong reason to believe that they won't be as effective.

Next step would be to generate concepts.

Morph Matrix

Sub-Functions	Solutions		
Import Data	Serial--USB	Serial--Bluetooth	Network--Ethernet
	Network--Wifi	File--USB Drive	File--Hard Code
Import Electrical Energy	Wired--DC Power	Wired--AC Power	Wireless--Phone Charging Pad
Convert Mechanical Energy to Sound Energy	Pluck--String	Pluck--Thin Metal Sheet	Hit--Wood Blocks
	Hit--Metal Plates	Hit--PVC Pipes	Blow--Flute
	Blow--Recorder	Blow--Harmonica	Blow--Water Bottles
	Rub--Stringed Instrument	Rub--Water Glasses	
Convert Electrical Energy to Mechanical Energy	Stepper Motor	Brushed DC Motor	Brushless DC Motor
	Solenoid	(any motor) + Fan	
Convert EE to ME (optional modifiers)	Modular solenoid housings with 1-step connection	Short stroke solenoids - smaller package and less potential to overcome	
Control Instrument	Mechanical--Programming Wheel that Activates Levers to Play Notes		
	Analog--Electronic Programming Wheel using Resistors to Change Voltage and move an Electrically Driven Mechanism		
	Digital--Microcontroller Controls Motors		
Secure Instrument	Clamp to Table	Weight	Use Glue on Base
Setup by User	Unfoldable elements of product		Product remains assembled or mostly assembled and ready to use at all times
Prevent Harm	Minimize fast-moving parts and/or pinch points: shields, solenoids and servos (one per note, no motion control)	Use bright colors or reflective tape to warn users of possible danger	Slow moving pick for string, fast solenoids for fret
Ensure Sufficient Loudness	Use a diaphragm to amplify sound	Single powerful actuator with motion control to reach multiple notes	Using flexible membranes and fine membranes
	Chosen EE to ME to SE combo sufficient		

Date: 9/27/2022. Topic: Concept Generation from Morph Matrix

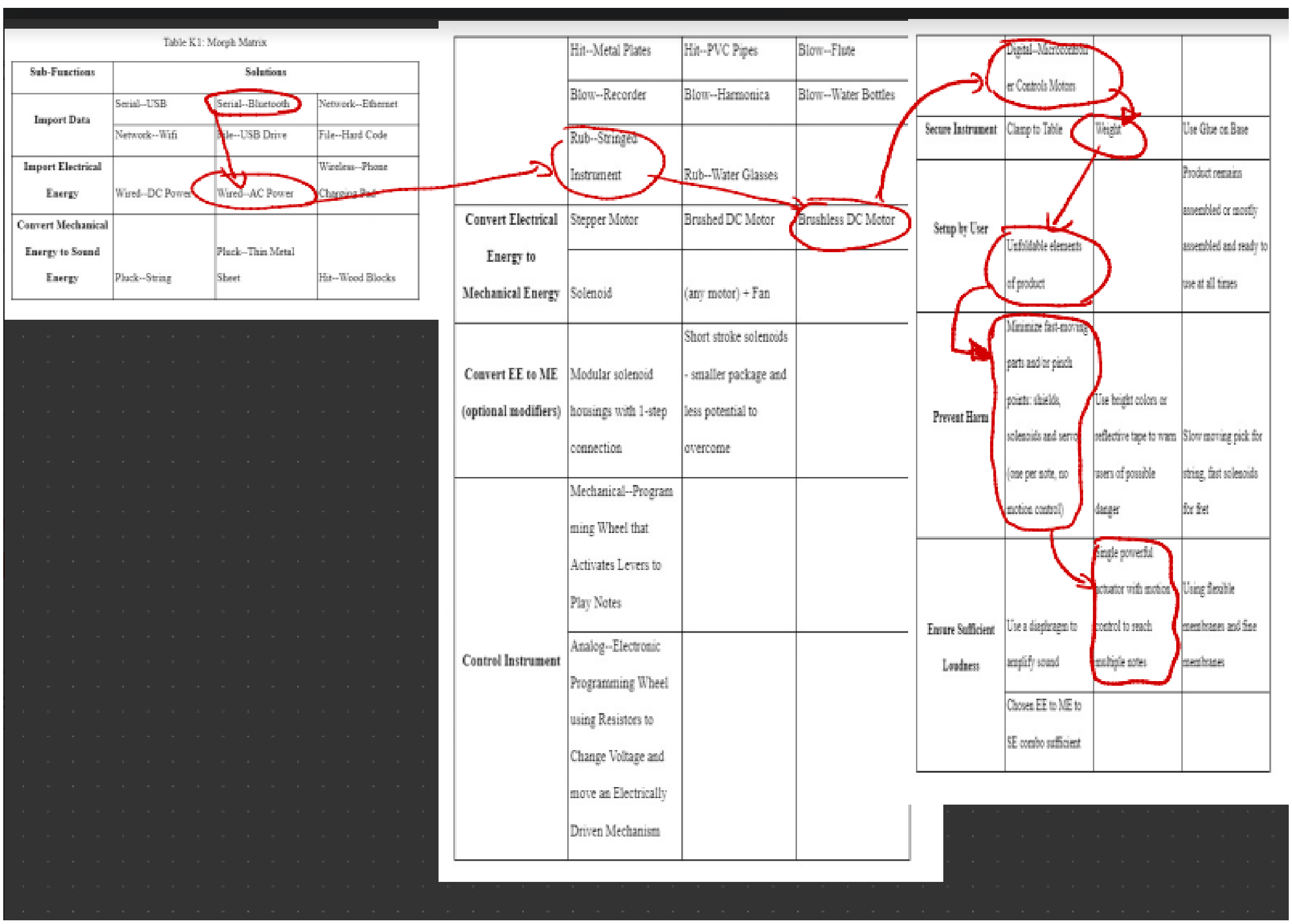


Table K1: Morph Matrix

Sub-Functions	Solutions		
Import Data	Serial--USB	Serial--Bluetooth	Network--Ethernet
	Network--Wifi	File--USB Drive	File--Hard Code
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	Hit--Metal Plates	Hit--PVC Pipes	Blow--Flute
	Blow--Recorder	Blow--Harmonica	Blow--Water Bottles
	Rub--Stringed Instrument	Rub--Water Glasses	
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	Chosen EE to ME to SE combo sufficient		

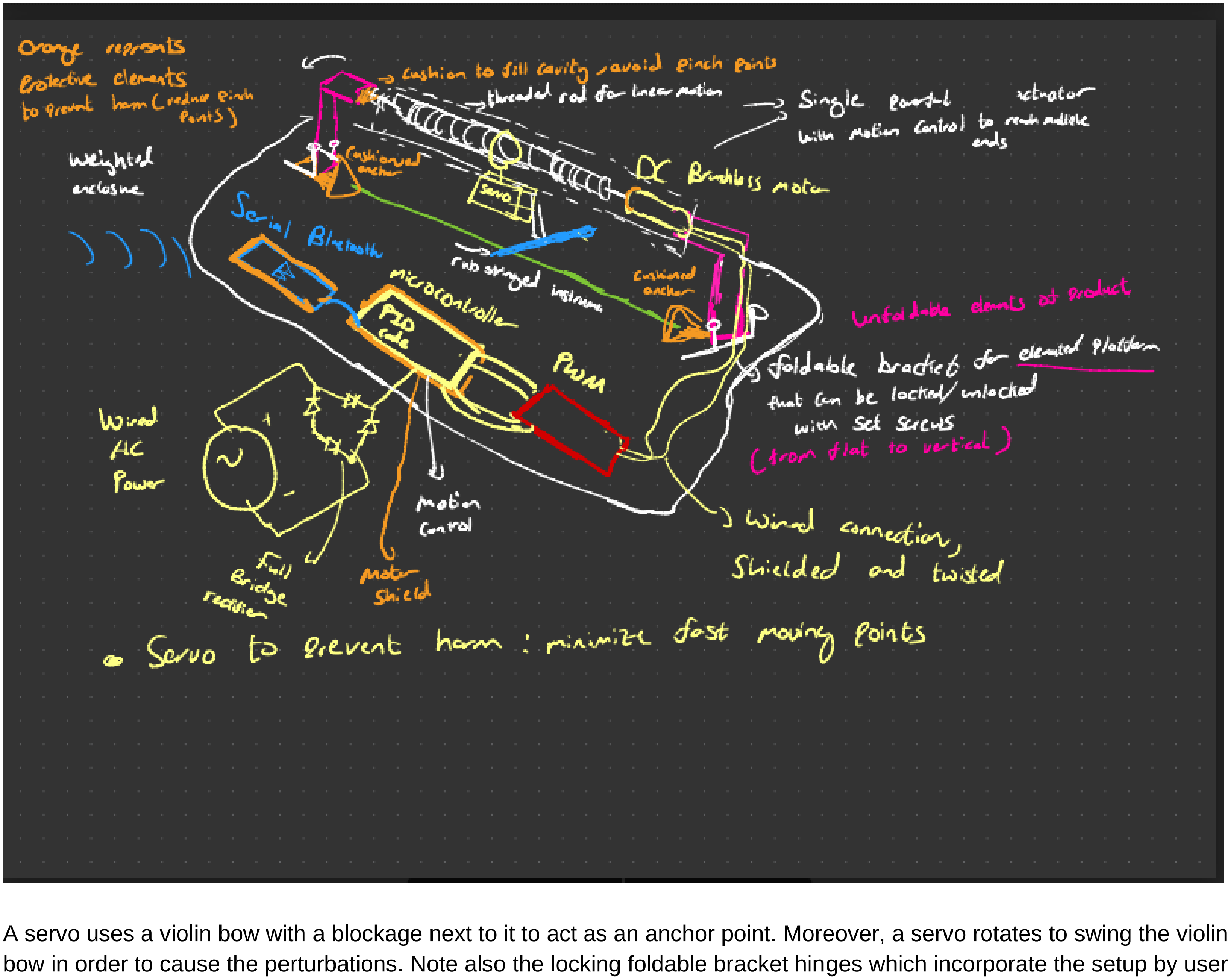
Each team

member traversed through the morph matrix to generate a concept by mixing and matching from different subfunction solutions. The image above shows my traversal.

The attempt with mine is to create a compact yet highly effective device that reduces setup time. By inputting in AC power and stepping it down and passing through a rectifier source, one would not need to supply their own power (i.e simply use a socket). In addition, by using a bluetooth module with code from a library such as arduino, using a usb drive to manually upload a file would be avoided. My rationale is that it introduces a little bit of complexity for much more ease of use. From there, emphasis was placed on controlling the instrument with a microcontroller connected to a DC brushless motor for fast and precise continuous motion. To ensure sufficient loudness the DC brushless motor would be paired with a servo which are both PID controlled to ensure that a string would be perturbed properly to generate sound. In order to ensure that the system has high bandwidth, the end-effector would rub against the string much like a violin for faster vibrations. For ease of setup, there will be elements that can unfold. Also, I noticed that the much of the electronics can be loose, so using a weighted platform to hold them together can ensure easier setup and carrying, whilst also ensuring nothing falls apart chaotically.

In terms of specifics, a thread rod would be used as a linear guide rail for electrical to linear kinetic energy by proxy of using a DC brushless motor.

The following shows the final sketch:



A servo uses a violin bow with a blockage next to it to act as an anchor point. Moreover, a servo rotates to swing the violin bow in order to cause the perturbations. Note also the locking foldable bracket hinges which incorporate the setup by user subfunction, which is an auxiliary one. Finally, note the PWM which is used in conjunction with the microcontroller running PID to achieve optimal control of the actuators.

Overall, my insight shows that this might be a costly solution with plenty of electronics and wires that need to be managed. It is component heavy and so I'm not sure that it's the most viable solution. However, it will have to be compared with the rest of the solutions in order to arrive at a consensus.

Date: 10/01/2022. Topic: Criteria, Back-of-envelope Calcs, & Justifications

Before creating a Pugh chart and ranking the concepts, a set of criteria must be established. I wanted to ensure that the criteria can be applied to each solution so that fair comparisons of the viability of each solution with respect to one another can be made. These criteria as I've read must have correspond to the engineering requirements in some capacity. To create effective comparisons without using too much time, the obtained metrics had to be quantifiable and quick to approximate based on simple information without needing to resort to highly rigorous techniques with information that is not present yet. These metrics should be provide a holistic overview of each concept's feasibility from cost to performance and overall structure to best match target audience expectations.

As a result, the selected criteria were mass, size, bandwidth, cost, and educational value. Mass, cost, and size can all be roughly approximated by first compiling a preliminary list of parts, mostly from McMaster and Amazon. Here's what I decided:

- The larger components such as instruments and other platform/chassis-based parts will mostly make up the volume. Small electronics and other small components embedded within won't have of an effect on volume. To be conservative, ½ an inch or a full inch can be added to each dimension as a ballpark estimate. The final volume is taken to be a conservative cuboid estimate of height times width times depth.
- As for mass, this is best done by taking the sum of the weights of individual components
- As for cost, each component's price was determined by finding the cheapest listing that is repeated more than once, regardless of brand or color, etc.

In terms of educational value, I created a basic survey where participants rate each concept from 1-5 after showing them images of the concept and explaining the gist of each concept. From there the question is asked:
"Based on what you see and understand, which of the concepts seems to the best in terms of teaching you basic mechanical engineering principles?"

The idea is to contact 15 high school students from the same group spoken to from the project proposal. Each concept's rating will be summed across all 15 students. In other words, students arranged by row and concepts by column, where the final row shows the total points accrued by each concept. The primary insight with this approach is to try to convert a rather qualitative criterion to a numerical description.

In terms of bandwidth analysis, the following was done:

- Concepts 1 through 3 rely on pre-existing instruments. Concept 1 using a harmonica and concepts 2 and 3 being different iterations of a xylophone setup. To obtain the bandwidth for these two instruments, charts were looked up to find the lowest and highest frequencies based on the playable notes. From there, I subtracted the highest lowest frequencies as a theoretical approximate to the range of frequencies obtained by a human playing these instruments./
- As for concept 4, the following image best describes the process.

violin: by testing the thinnest string, using a digital tuner

f_{lowest} : 422 Hz

$f_{highest}$: 2551 Hz

bandwidth = 2551 Hz − 422 = 2129

I used a friend’s violin and went to the thinnest string corresponding to the highest frequency. From there, my friend would play the highest note while I recorded this with a digital tuner phone app. The same was done with the lowest frequency possible. This would be the fastest way to find a rather generous estimate of concept 4’s bandwidth as it is loosely based off a violin’s operating principle.

Finally for concept 5, the roller-plucker uses a moving anchoring point (the wheel being the moving anchor), and basic acoustic theory means that the fundamental vibration mode frequency of the closed-closed standing wave can be obtained using an equation that relates frequency to the tension in the string, its length, and mass per unit length.

Roller-Plucker (guitar string)

$$f = \frac{\sqrt{\frac{T}{m/L}}}{2L}$$

guitar estimate

$T = 200\,N$ $\qquad \frac{m}{L} = \frac{4\times10^{-3}\,kg}{m}$

$L = 0.3m$ $\qquad L = 0.05$

$$f_{min} = \frac{\sqrt{\frac{200}{4\times10^{-3}}}}{0.6} \qquad f_{max} = \frac{\sqrt{\frac{200}{4\times10^{-3}}}}{0.1} = 2236\ Hz$$

highest length

372.7 H

bandwidth = 1863.39 Hz

It was difficult finding the exact tension used in a guitar string on average but 200N is close to what some sources cite for an E4 note, so I used that. The dimension of the string would be 0.3m and the selected mass per length is around 4 g/m to account for thicker (higher gauge) strings.

The bandwidth is close to the target of 1900 Hz at 1863Hz, but the key insight is that this value is a rough approximate and the apparatus can be tuned by modifying string parameters. Also, this frequency only

considers the fundamental vibrational mode (1st overtone). I will ensure extra caution later down the line with trying to meet the bandwidth if this concept is selected.
With the calculations outlined, the concept metrics will be obtained before carrying out a Pugh Chart tabulation and analysis. They will be tabulated and listed for future reference and appendix placement.

<u>Date: 10/06/2022. Topic: Pugh Chart</u>

With all necessary data obtained, a Pugh chart analysis can be carried out with all 5 concepts. I expressed doubt in the viability of concept 1 and the team luckily agreed. Generally, using pneumatics sounds far more troubling and harder to achieve. Being the only wind instrument from the list, it seemed like setting it as a datum would be a good start to see how the remainder of the concepts would stack up against it.

Here are the tabulated results I compiled by referring to the calculations

Pugh Chart with Concept 1 (Automated Harmonica) as Datum

	Concepts				
	1	2	3	4	5
Criteria	Automated Harmonica	Solenoid Xylophone	Stepper Xylophone	DC Motor Controlled Violin Bow	Roller-Plucker
Cost ($)	0	1	-1	-1	-1
Size (in^3)	0	1	-1	1	1
Mass (lb)	0	-1	-1	-1	1
Bandwidth (Hz)	0	1	1	1	1
Educational Value	0	1	1	1	1
Sum of +	0	4	2	3	4
Sum of -	0	1	3	2	1
Total	0	3	-1	1	3

In terms of quick comparisons, the stepper xylophone seems like a better performer, but holistically is weaker. From this datum, it seems that the solenoid xylophone and roller-plucker seem to be the top performers for different reasons.

The team came to the consensus that splitting the tie can best be done by setting each one to be the datum. My intuition also does agree that they're the best of the 5 concepts.

Pugh Chart with Concept 2 (Solenoid Xylophone) as Datum

	Concepts				
	1	2	3	4	5
Criteria	Automated Harmonica	Solenoid Xylophone	Stepper Xylophone	DC Motor Controlled Violin Bow	Roller-Plucker
Cost ($)	-1	0	-1	-1	-1
Size (in^3)	-1	0	-1	1	1
Mass (lb)	1	0	1	1	1
Bandwidth (Hz)	-1	0	0	-1	-1
Educational Value	-1	0	-1	1	1
		0			
Sum of +	1	0	1	3	3
Sum of -	4	0	3	2	2
Total	-3	0	-2	1	1

The harmonica and stepper xylophone are the lowest scorers compared to the solenoid xylophone, whereas concepts 4 and 5 seem to be holistically worse. With that said, it does seem that the violin bow does seem to be holistically a decent performer but it is the priciest concept by far as I predicted. It totaled to be $244, a value quite close to the $250 budget (and this is only with a rough approximation).

To get a better picture, here is the final Pugh chart with concept 5 (Roller-Plucker) set as a datum.

Pugh Chart with Concept 3 (Roller-Plucker) as Datum

	Concepts				
	1	2	3	4	5
Criteria	Automated Harmonica	Solenoid Xylophone	Stepper Xylophone	DC Motor Controlled Violin Bow	Roller-Plucker
Cost ($)	-1	1	-1	-1	0
Size (in^3)	-1	-1	-1	-1	0
Mass (lb)	-1	-1	-1	-1	0
Bandwidth (Hz)	-1	1	1	1	0
Educational Value	-1	-1	-1	-1	0
					0
Sum of +					0
Sum of -					0
Total	-5	-1	-3	-3	0

The results are quite clear. Holistically, the remainder of the designs seem to be worse in almost all criteria with respect to concept 5. It is the lightest of designs and also volumetrically the smallest while also having the largest educational value from the survey results.

It is lower than the xylophone bandwidths and is not the cheapest option (that would go to the Solenoid Xylophone), yet it does seem that this concept's properties are well within or near the criteria. With more fine tuning, a design based of this concept can be well-adapted to meet all the criteria and engineering requirements.

I made sure that a key step would be to map the frequency of the fundamental overtone as a function of the mass per length, overall length gauge, and tension in order to really maximize the bandwidth potential to be able to play as widest a range of songs as possible. Carrying out this step does pave the path for one to understand how the final design should end up being. By introducing these constraints, efforts to design and prototype a final product can reduce ambiguity and ensure satisfaction of the criteria. The next step is to build a low resolution prototype of concept 5 for additional insights.

<u>Date: 10/10/2022. Topic: Low resolution Prototype</u>

Results from the pugh chart show that the roller-plucker design is the most viable option. The only course of action left for the design review is to create a prototype. Realistically, our budget is more than 5 dollars. This suggests that we should use nothing more than a few basic scraps. I looked at the concepts and realized that the roller plucker is nothing than a bunch of extrusions and a few revolutions to CAD. By 3D printing the main frame piece, we'd effectively almost be done with the prototype and just need to assemble the pieces. While having a low-resolution prototype allows for quicker results, introducing some detail, and allowing some pieces to move gets the team access to additional insights (we get to point out kinematically poor aspects that are hard to work with for sound production). Peter, Elliott, and Yifeng agreed. Andrew added that we should replace electronics and additional assembly-related pieces with cardboard. I assisted with designing the main frame piece as seen below using fusion 360. We'd attach a knob and a plucker to attach, tighten and pluck the string. I selected the frame to roughly be about 123mm (edge to edge). It was here where the compactness vs. bandwidth tradeoff would be quite apparent, and at the time I wasn't really sure if we a string gauge small enough and a tension high enough can result in an operating instrument that will not snap. It was clear that experimentation was needed. At the very most, a preliminary test can be conducted with the low res prototype, but it is likely that a selection to a longer neck is needed.

Figure: Low res prototype frame

The final design assembly of the low res prototype below alongside the built version. I assembled the system with no more than some preexisting m3 screws, bolts, and nuts, and one 10mm bearing, ensuring the need to not purchase any more. I also helped cut some cardboard to act in place of a raspberry pi pico.

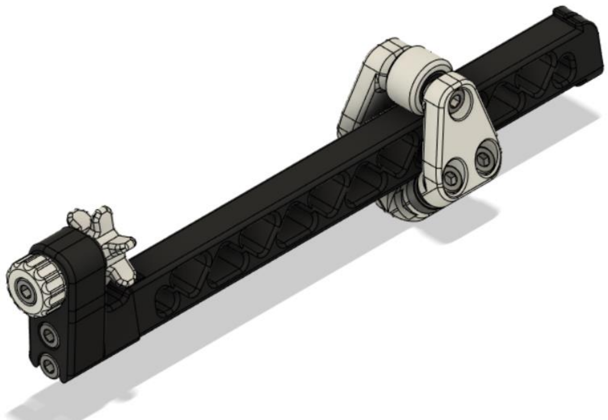


Figure : CAD'd assembly of low-res

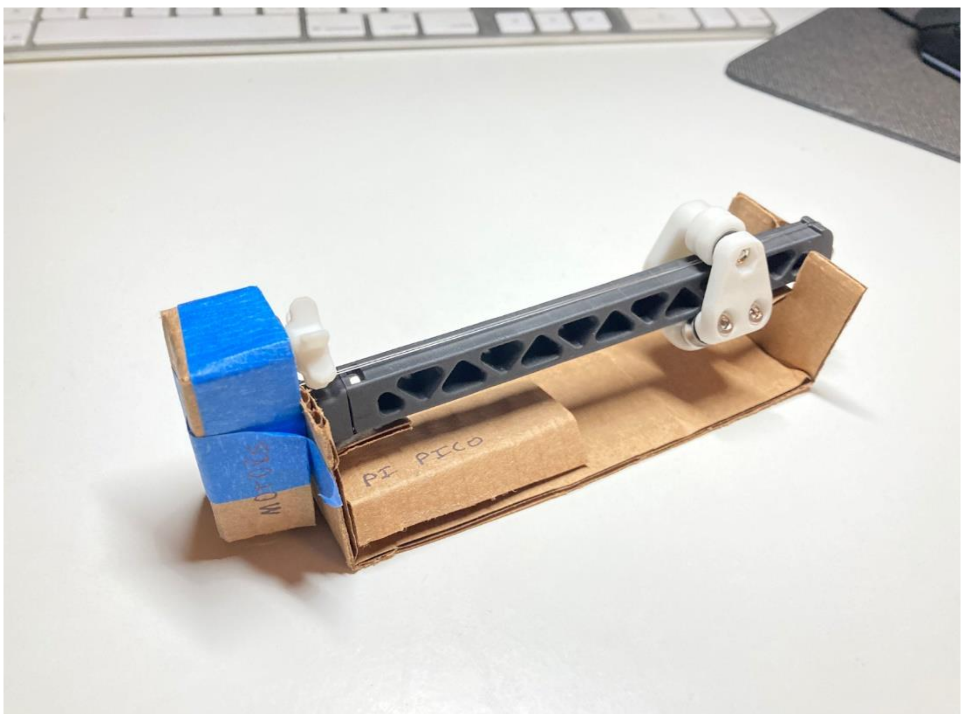


Figure : Low res prototype

Elliott attached the string, but the spoked plucker would not make a sound loud enough when manually turned. As a matter of fact, I plucked it myself and the sound generated was noticeably louder. Also, the multiple spokes can actually pluck more times than needed if the plucker shaft rotates too much. To ensure adequate plucking force without creating multiple unwanted plucks, it is important to select a plucker horn with 'one spoke'. This will be investigated further and optimized down the line.
It seemed the low-res prototype is proving quite useful.

Date: 10/15/2022. Topic: Bill of Materials, Budget, and feedback from low-res

Based on the low-res prototype's function, I drafted a preliminary bill of materials with budget requirements to kickstart a basic idea of what the final budget will be and what parts are expected. I gauged the team opinion and we decided to collectively stick with metric M3 fasteners, which will help standardize the process. Also, I predict that emphasis on fastener mechanical properties would not pose a problem. As a result, I decided to find a well price hex-head assortment kit on amazon and placed it in the bill of materials. To be cautious, I made the assumption that we will use all pieces just to avoid underestimating the final budget. The google sheet screenshot below displays the bill.

	A	B	C	D	E
1	Materials	Price / Unit	Quantity	Cost ($)	Status
2	GT2 Idler	2	1	2	Received
3	GT2 Timing Belt	6	1	6	Received
4	GT2 Pulley	2	1	2	Received
5	Steel Strings	2	1	2	Received
6	Single String Pickup	8	1	8	Received
7	Brushed DC motor with gear box and encoder	50	2	100	Received
8	Bearings	15	1	15	Received
9	Screws	15	1	15	Received
10	Py Pico Controller	5	1	5	Received
11	L298 Motor Driver	6	1	6	Received
12	M3 Hex Head Fastener Assortment Kit	9	1	9	Received
13	ESP8266	8	1	8	Received
14					
15			Total	176	

Preliminary BoM

For now we were not sure if one or two controllers will be needed to power the plucker and roller independently. For now, I assume both will be used. The budget totals $176, exceeding the $150 provided by the mechanical engineering department. I ensured that the team is comfortable splitting the remainder $26. Luckily, we were, so our worst case estimate is doable by all of us. I noticed by keeping as many static parts, as possible and using bearings where needed, 3D printing will significantly minimize budget expenditures. All of us have 3D printer access and the skillset, so this seems viable as a plan to follow through with.

On the 13th of October, we presented our low-res prototype to Dr. Seepersad and Elena. I noticed that it seemed that using a PID-tuned DC brushless motor will not be the wisest course in action in the shortest amount of time, given that tuning the motor is time consuming especially when trying to perfect the note intended. We also collectively discussed the use of a high speed overhead servo with a single horn to pluck the string; this seemed like a good option.

With regards to the DC motor, I was not initially convinced that a stepper motor was that fast of an option, but then reading about the ability for some steppers to reach high pulses/sec using discretized steps made it quite appealing to work with, especially in open-loop, which can save me a lot of development time. After the milestone review, we then discussed how the roller will be propelled. My initial idea was a rack and pinion approach but simply put, I and everyone agreed on a pulley and idler approach. By using an appropriate pulley and timing belt, slip issues can mostly be mitigated. A large enough pulley and idler can ensure linear velocity is adequate.

Overall, for now, I pinpointed 3 primary issues to address; stepper speed and acceleration limits, how to get the servo to pluck properly, and most importantly, the right string configuration.

I decided that Yifeng and I will experiment with a string configuration.

Date: 10/19/2022. Topic: String Experimentation – “The Diddly Bow”

We ordered an electric guitar string set for $12.19 and an electric pickup for $9.99. I discussed with the team and here’s my experiment (I decided it needs to be crude for the sake of time but effective enough for insights).

1. Get a long wooden board (allegedly some 2 x 4s at TIW) and some nails.
2. For the sake of sizing compactness, cut no more than 0.6 meters of string.
3. Wrap a guitar string around one nail and torsion it as much possible until firmly attached.
4. Hammer the nail into the 2 x4
5. Retrieve a glass bottle with a substantial radius and place it sideways near the end of the other side of the string.
6. Pass the string over the wall of the bottle, then wrap the other end of the electric string around and then nail it.

The image shows what the final apparatus should appear like.

Figure: ‘Diddly Bow’ experiment

Now the experiment was to cycle through the different string diameters (gauges). We roughly tried to coil each string type the same number of times to account for tension but this was hard to quantify. I pinched different measured lengths after annotating the board with a marker. James used PanoTuner to measure the frequencies between 0.1 and 0.5m. The approach was to try to find a bandwidth as close as possible to 1900Hz. This is basically a matter of subtracting the highest observed frequency minus the lowest one. By using this setup, the attempt is to emulate a closed-closed boundary condition for a perturbed standing wave. I assumed that my estimates are simply the fundamental harmonic frequency (see page 13)

There is a major issue however. Generally, frequency drops in an inverse proportion to length (with root tension/[mass/length]) as a scaling constant. We'd need a remarkably small string gauge length or very high levels of tension to achieve the intended bandwidth. By opting to make our own instrument, it can be observed that following standardized tuning options will not work).
For now, I suggested to try to shoot for a bandwidth that can encapsulate one octave, and we targeted a range of 440Hz to 880Hz for an effective bandwidth of 440Hz. When I used a D-4th string with a 0.026 inch cross-sectional diameter, this was achieved.

A primary insight is that even with additional tuning, the 1900Hz bandwidth may far too ambitious but that doesn't necessarily impede the possibility of playing 3 songs.

Date: 10/22/2022. Topic: Software/firmware associated tasks for Plucker & Roller: Stepper Motor

We decide to collectively meet on Saturdays for 2-4 hours in the mornings for software testing and component design assembly. This will help keep efforts and synergized so that software matches hardware configurations.

In terms of hardware, Andrew suggested a transition to using an esp32 which is a far more powerful microcontroller when comparted to an Arduino Uno. This allows us to carry out serial commands and operations on both plucker and roller with one microcontroller rather than 2, which minimizes expenditures and space for electronics, ensuring that we meet customer needs without drastic change.

I realized that rather using the espressif IDE, a library can be installed onto a laptop or PC to use the ESP32 with arduino's IDE, heavily reducing development time by virtue of familiarity. Then it was a matter of selecting libraries that act as driver software to the stepper motor. An example is FastAccelStepper, which I decided to not continue working with as documentation for the esp32 is limited and it was difficult to get the stepper to spin upon arriving.

On the 21st, the neck/frame with pulleys and roller was assembled by other group members. It was up to Elliott and I to configure the motor for roller motion. Image shown below

As of right now, this is the stepper motor architecture:

- .ino files to execute the final script
- .h files with forward declarations to ensure all functions are defined and compiled easily and variable initializations
- .cpp files with C++ files outlining the functional subroutines to get the stepper motor to run.

For now, placeholder servo functions have been as a means to outline function. I am not too well-versed in Git, so I am emailing files to Elliott so as to not waste time.

```
#include "stepper.h"
#include "servo.h"
#include "serial_cmd.h"

void setup() {
  stepper_setup();
  servo_setup();
  serial_cmd_setup();
}

void loop() {
  stepper_tasks();
  servo_tasks();
  serial_cmd_tasks();
}
```

Figure : Final Arduino file to be executed with all tasks and header files (firmware.ino)

```
#ifndef STEPPER_H
#define STEPPER_H

#include <Arduino.h>
#include "bsp.h"

typedef struct MOVE {
  unsigned int position;
  unsigned int acceleration;
  unsigned int velocity;
} MOVE;

void stepper_setup();
void stepper_tasks();
void stepper_move(MOVE move);
bool stepper_move_complete();

#endif
```

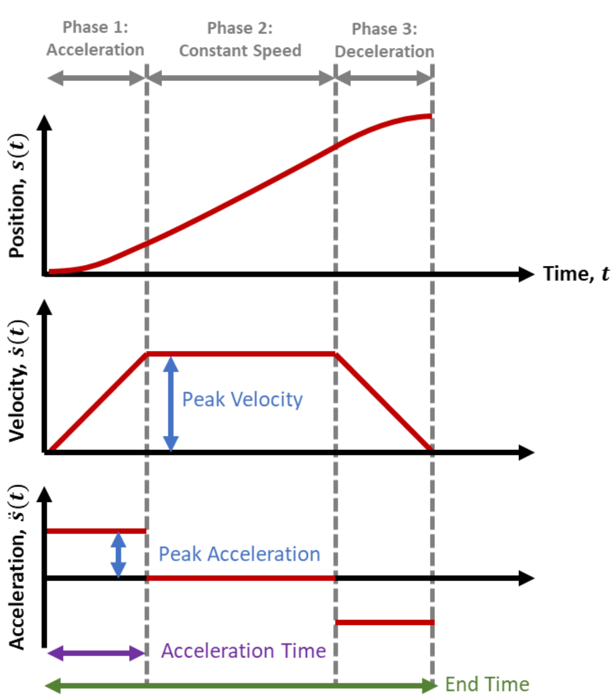
Figure : All forward declarations and initializations for stepper.h, note the integer quanities of position,velocity, and acceleration

```
void stepper_move(MOVE move) {
  move_distance = move.position - current_position;
  if (move_distance < 0) {
    move_direction = -1;
    move_distance *= -1;
  }
  else {
    move_direction = 1;
  }
  move_acceleration = move.acceleration;
  move_velocity = move.velocity;
  current_stepper_state = starting;
}

bool stepper_move_complete() {
  return (current_stepper_state == waiting);
}
```

Figure 1: Move and complete functions in stepper.cpp files coded so far

Two key observations can be made. Firstly, by keeping the servo plucking processes independent from the stepper, the operation of one does not rely on the operation of the other. As a result, debugging one can be done independently of another, allowing for a more incremental approach to ensuring proper operation of the system as opposed to having to overhaul the entire code.

Secondly, when running the system in open loop, it is important to ensure the system doesn't miss the intended position, but it is also important to ensure an operation fast enough otherwise the performance benchmark behind the customer needs will not be met. Moreover, to also account for stepper slip, I suggest an implementation of trapezoidal trajectory tracking. From my advanced mechatronics notes, the system adheres to a maximum acceleration and max velocity to create a velocity-time graph that accelerates linearly to the max velocity, remains at that max velocity and then decelerates linearly until the path is reached. This should address some of the issues.

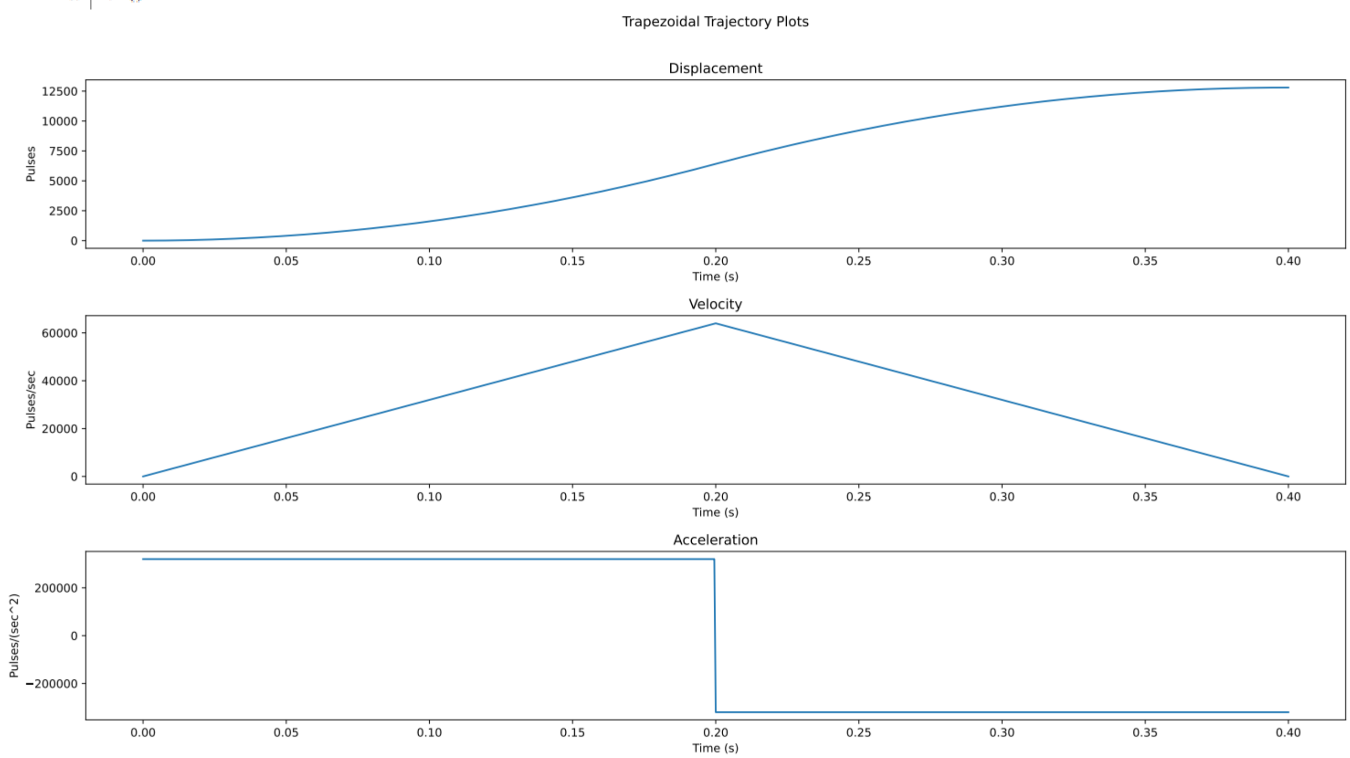


Date: 10/24/2022. Topic: Simulating trapezoidal trajectory in Code + Homing the roller

As a preliminary simulation to try to ensure that an algorithm for trapezoidal trajectory is to be implemented, I coded a python script of a trapezoidal trajectory with plots to then use as a baseline for the .cpp Implementation I simulated an input of 320,000 pulses/sec^2, a max velocity of 64,000, an end distance of 12,800 pulses, sampling at 2000 Hz (similar to a case in a book I found).

```python

import numpy as np
from numpy import array
from numpy import sign
import matplotlib.pyplot as plt



def f(i,x2,a_max):
    if sign(x2[i]) != -1:
        val = -0.5 * (x2[i]**2)/(1*a_max)
    else:
        val = -0.5 * (x2[i]**2)/(-1*a_max)
    return val

def trap_traj(a_max,v_max,x_end,f_s):
    dt = 1/f_s
    i = 0
    x_t = 0 # initialize as x_start
    v_t = 0 # intialize initial velocity
    x1 = [x_t - x_end]
    x2 = [v_t]
    a = [0]
    tol = 1e-11
    while(True):
        x2[i]
        if x1[i] < f(i,x2,a_max):
            if x2[i] < v_max:
                a[i] = a_max
            else:
                a[i] = 0
        else:
            if x2[i] > -v_max:
                a[i] = -a_max
            else:
                a[i] = 0

        x2.append(x2[i] + a[i]*dt)
        a.append(a[i])
        x1.append(x1[i] + x2[i+1]*dt)
        i +=1
        if x2[i] == 0 and abs(x1[i]) < tol:
            break
    disp = [i + x_end for i in x1] # convert to displacement reading instead of tracking error
    velo = x2
    acc = a
    vec = np.array([disp,velo,acc]) # x1, x2, and acceleration points
    return vec


```

```
def main():
    output = trap_traj(320000,64000,12800,2000)

    disp = output[0]
    velo = output[1]
    acc = output[2]
    time = np.arange(0,len(disp),1) * 1/2000 # index * sampling perior

    np.savetxt('trajectory_disp.txt', disp, delimiter = '\t')

    fig, axs = plt.subplots(3)
    fig.suptitle('Trapezoidal Trajectory Plots')
    plt.subplots_adjust(left=0.1,bottom=0.1,right=0.9,top=0.9,wspace=0.4,
                hspace=0.4) # plot spacing


    axs[0].plot(time,disp)
    axs[0].set_title('Displacement')
    axs[0].set_xlabel('Time (s)')
    axs[0].set_ylabel('Pulses')

    axs[1].plot(time, velo)
    axs[1].set_title('Velocity')
    axs[1].set_xlabel('Time (s)')
    axs[1].set_ylabel('Pulses/sec')


    axs[2].plot(time,acc)
    axs[2].set_title('Acceleration')
    axs[2].set_xlabel('Time (s)')
    axs[2].set_ylabel('Pulses/(sec^2)')
    plt.show()



main()
```



Note that an optical trapezoidal trajectory can be triangular.
With this acquired confidence, an implementation in C++ can be carried out.

As for setting 0 position to avoid propagating error, Elliott has implemented a bump switch that the roller impacts. Simply put, this roller causes a digital signal to be picked up by the esp32 by virtue of a completed circuit. When this switch is pressed, the position is reset to 0. This ensures the right notes are played so that the songs do not worsen in audio quality over time. There is also a home function that moves the system towards the bump switch until the switch is bumped into (from there, the roller stops).

It is quite important to acknowledge that a huge part of acoustic difficulties really can be attributed to the roller.

Date: 10/31/2022. Topic: Milestone review 2 feedback

We managed to implement a functioning roller system. Feedback consisted of implementing the pick-up and the servo for sound generation. To keep up the cadence, Yifeng would model an electric pickup holder. In addition, Peter and Andrew would focus on creating a supporting frame and getting the servo in operating order and in good placement. I noticed that servo movement and clicking can get picked up by the pickup so it would need to kept far away enough and electrically shielded+ grounded.
The functioning roller system would need to be interfaced with the use of serial commands in order to respond to each note selection.

Prior to completely finalizing the roller system, experiments should be carried out to understand what parameters can optimize the system for the best performance. It is important to find out what aspects reduce or improve performance so that the design and final assembly can account for any possible modifications made. Moreover, it's important to ensure that the servo and pickup placement do not contradict any attempted tweaks and improvements.

To perform the experiment, we conducted 8 individual experiments and repeated each one 3 times, for a total of 24 experiments. Each experiment studied each factor at its high and low states and then studied its response to both response variables.

Ideas for experiment from discussion:

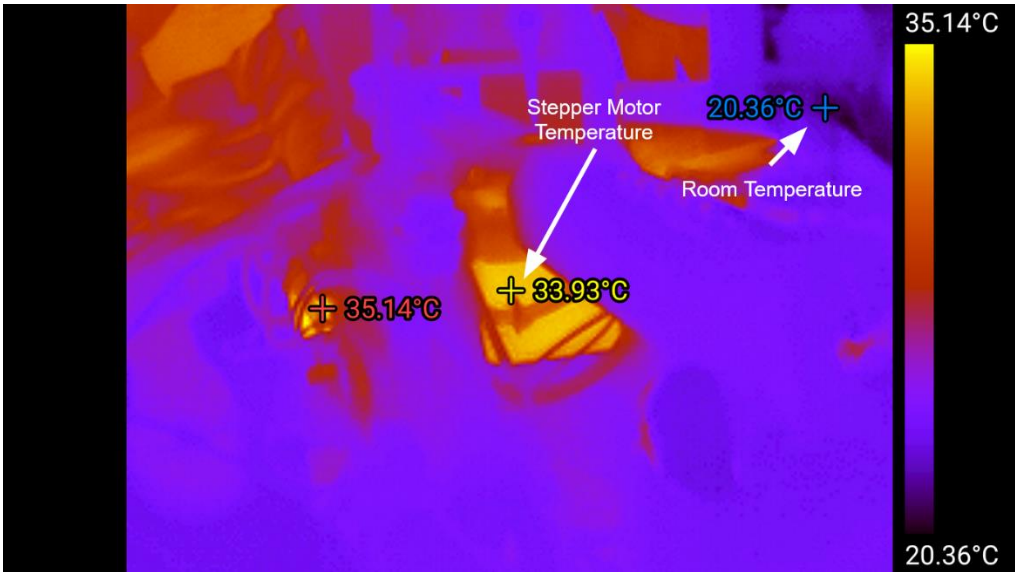
- Current effect on max acceleration
- Voltage effect on max Voltage
- Stepper motor temperature against voltage and current supplied
- Effect of carriage mass on max acceleration

For now additional brainstorming on my end is needed to see how to carry these out. Andrew has an IR camera that he personally owns for temperature measurements; this will make the process much easier.

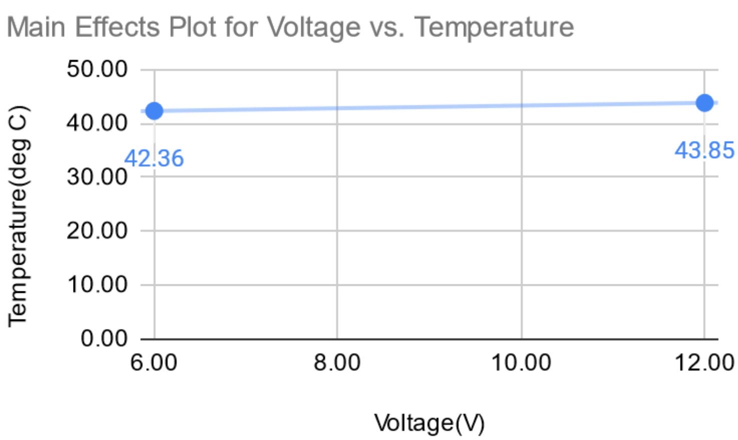
Date: 11/7/2022. Topic: Experimentation (Temperature)]

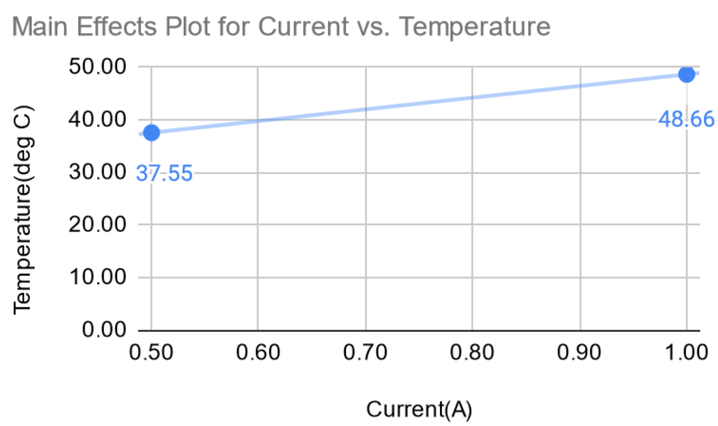
I helped carry out experiments, beginning with studying thermal effects.
Undoubtedly, there is a resistive element to a stepper motor as with all electronics. The following expression $P = I^2R$ suggests a correlation between power dissipation (which maps to temperature increases) and supplied current. However, complexities like heat transfer does not necessarily ensure a quadratic mapping.

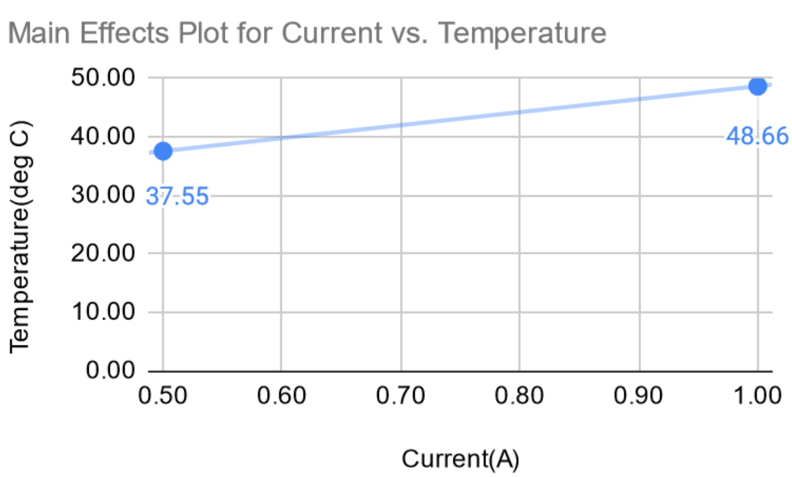
Here is an example of what the IR camera detects:



Using the IR camera, the following results were obtained and graphed. Voltage, current, and carriage mass (load) were varied:





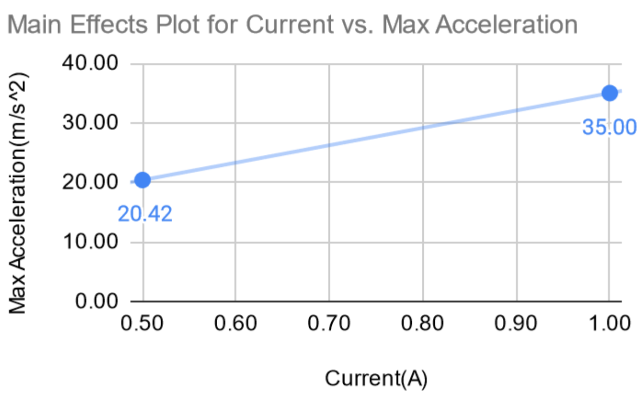


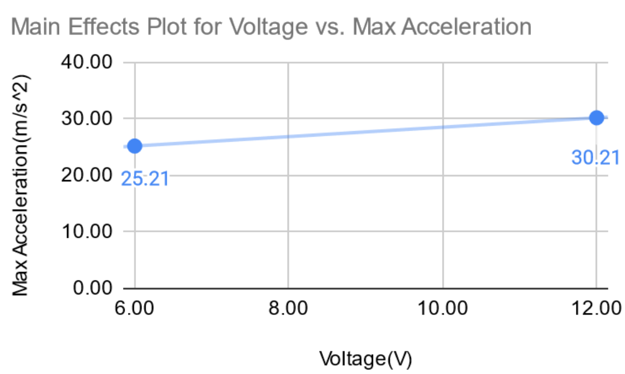
A quick qualitative analysis appears to show that current has the greatest slope and likely is the strongest correlation among the three independent variables.
While temperature is a great variable to assess, it is important to note that the stepper motor purchased is rated to operate at 100 degrees Celsius, with temperatures only nearing 50. As a result, the stepper is well within its rated temperatures for optimal performance, confirming that the stepper motor's temperature is not of great concern. It is warm at best.
In terms of surrounding material affected by the stepper motor, PLA's melting point temperature ranges between 170 and 180 °C, further showing that temperature isn't of great concern for control

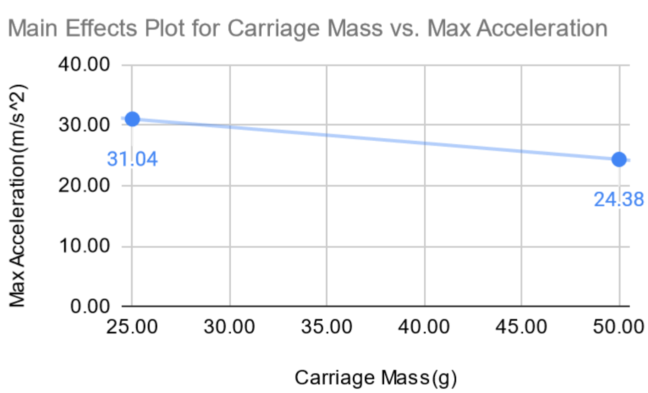
Date: 11/8/2022. Topic: Experimentation (Acceleration) & analysis

I then focused on working on max acceleration measurements. I varied the voltage and current with the DC power supply and then added blocks of known measured mass onto the carriage as the techniques in which the independent variables are configured. For the acceleration as a response, simply put, I placed a thin piece of colored tape near the homing bump switch, the max acceleration was set using the stepper script devised, and then I checked if steps were skipped. Skipping steps meant that the motor went past or behind the tape by a noticeable amount.

Some noise factors that would potentially hinder the accuracy of the experiments were any loss in tension from the belt or loss in teeth of the belt which could affect the motion profile and therefore the response variable, acceleration. To keep this consistent across all experiments, a visual inspection of the belt would be performed such that no teeth were stripped or damaged in any way. If the belt had suffered a loss of teeth, it would be immediately replaced with a new belt.
The following results were yielded:

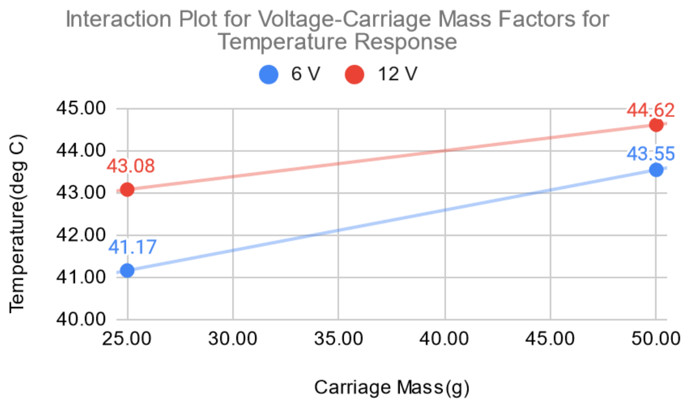


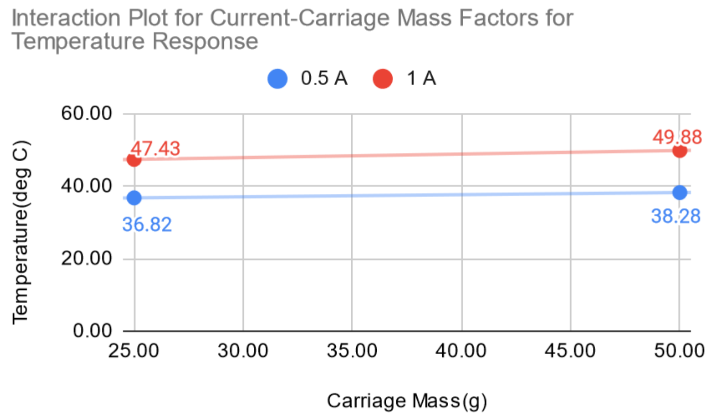




Further continuing with these results, I carried out the regression analysis to fully understand the correlations.

Before doing so, Andrew checked the interaction plots of Temperature vs. carriage mass with voltage and current varied each time but it seemed the plots were parallel (2 figures attached here). This indicates that carriage mass variations have very little effect or correlation with the stepper temperature. It is possible that the higher carriage mass adds more physical load which increases mechanically dissipative effects, but the correlations had to be examined





Regression Statistics								
Multiple R	0.985405025							
R Square	0.971023063							
Adjusted R Square	0.960795909							
Standard Error	1.7327582							
Observations	24							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	6	1710.416667	285.0694444	94.94557823	4.0042E-12			
Residual	17	51.04166667	3.00245098					
Total	23	1761.458333						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	27.70833333	0.353697787	78.33900689	3.40288E-23	26.96209623	28.45457043	26.96209623	28.45457043
X1 -- A (Current)	7.291666667	0.353697787	20.61552813	1.82249E-13	6.545429567	8.037903766	6.545429567	8.037903766
x2 -- B (Voltage)	2.5	0.353697787	7.068181072	1.88743E-06	1.7537629	3.2462371	1.7537629	3.2462371
x3 -- C (Carriage Mass)	-3.333333333	0.353697787	-9.42424143	3.66606E-08	-4.079570433	-2.587096234	-4.079570433	-2.587096234
x1-x2	0.416666667	0.353697787	1.178030179	0.255012816	-0.329570433	1.162903766	-0.329570433	1.162903766
x2-x3	-0.625	0.353697787	-1.767045268	0.095166645	-1.3712371	0.1212371	-1.3712371	0.1212371
x1-x3	-0.416666667	0.353697787	-1.178030179	0.255012816	-1.162903766	0.329570433	-1.162903766	0.329570433

Figure : Acc response

ANOVA was carried out with max acceleration as the response variable, and the final multilinear regressor is obtained. The other term combinations has rather small slopes so I discarded them.

$$\mathbf{y_1=27.71+7.29x_1+2.50x_2-3.33x_3}$$

Andrew's temperature response analysis:

Regression Statistics	
Multiple R	0.998267459
R Square	0.99653792
Adjusted R Square	0.995316009
Standard Error	0.399540177
Observations	24

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	6	781.1358333	130.1893056	815.5571421	6.01941E-20
Residual	17	2.71375	0.159632353		
Total	23	783.8495833			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	43.10416667	0.081555797	528.5236391	2.79795E-37	42.93209898	43.27623436	42.93209898	43.27623436
X1 -- A (Current)	5.554166667	0.081555797	68.10265934	3.65228E-22	5.382098976	5.726234358	5.382098976	5.726234358
x2 -- B (Voltage)	0.745833333	0.081555797	9.145068284	5.64316E-08	0.573765642	0.917901024	0.573765642	0.917901024
x3 -- C (Carriage Mass)	0.979166667	0.081555797	12.00609523	9.98444E-10	0.807098976	1.151234358	0.807098976	1.151234358
x1-x2	0.279166667	0.081555797	3.423014386	0.003242162	0.107098976	0.451234358	0.107098976	0.451234358
x2-x3	-0.2125	0.081555797	-2.605578114	0.01846573	-0.384567691	-0.040432309	-0.384567691	-0.040432309
x1-x3	0.245833333	0.081555797	3.01429625	0.007812803	0.073765642	0.417901024	0.073765642	0.417901024

Figure : Temp response

$$\mathbf{y_2=43.10+5.55x_1+0.75x_2+0.98x_3+0.28x_1x_2-0.21x_2x_3+0.25x_1x_3}$$

Given a constant torque output, it makes sense that carriage mass and max acceleration are negatively correlated as seen by the negative term (-3.33). While I expected voltage and current to have positively correlated effects with max acceleration by increasing power output, I didn't which would have the greater slope effect.
7.29 > 2.50, so current effect more substantial.

The Multiple R^2 values are 0.985 and 0.998 for maximum acceleration and temperature respectively. This indicate strong correlations between response and independent variables.

Overall, the low slopes shown in temperature response indicate that thermal controls shouldn't be a focus, setting the device to 12V running at 1A seems best for max acceleration. Mechanical redesigns would not be needed.

Date: 11/15/2022. Topic: Milestone review 3

The team got all subsystems working. There are primary pieces of feedback to look out. Firstly, implementing a guitar tuning peg can help the user tension the string and scale as they please. This also ensures that the string stays suspended with minimum sound damping. Overall, a tuning peg helps minimize setup time for the user and can boost performance by having better sounding songs. This was then ordered. Secondly, to ensure educational value, Dr. Seepersad suggested that the GUI for song input be displayed on the position-time plots, then differentiated twice to display velocity and acceleration plots.

I find that this is the key to user engagement, educational value, and a highly unique aspect to this product. The team collectively agreed, so I had to setup the GUI to accept to convert user input into these serial commands.

The simplest way to get this working is for Elliott and I to use tkinter, a rudimentary package for GUI creation by creating a canvas.
Ensuring successful implementation will guarantee that audience engagement and educational value are achieved in terms of customer needs.

Date: 11/25/2022. Topic: GUI implementation

Tkinter was rather hard to work with, and much of the code was rather very ‘Spaghetti’ and hard coded. I definitely feel that for a long-term implementation, the code needs to be polished. Moreover, labeling the axes seemed to be tough and often times spikes on the velocity graph can clip into the displacement-time graphs.

Two files were created. GUI.py and demo.py. I primarily focused on demo.py to work with the inputs and kinematic quantities. By using simple kinematics, the trapezoidal trajectory from point to point can be completed, ensuring that the stepper motor can avoid slip issues as noted several entries earlier.
The following two images show demo.py

temp.py × demo.py ×

```python
import tkinter as tk

top = tk.Tk()
P = tk.Canvas(top, bg="#EEEEEE", height=250, width=1000)
V = tk.Canvas(top, bg="#EEEEEE", height=250, width=1000)
A = tk.Canvas(top, bg="#EEEEEE", height=250, width=1000)

ps = []

def clear():
    for x in [P,V,A]: x.delete("all")

clear_button = tk.Button(top, command=clear)

max_accel = 100
max_vel = 100

last_time = 0.0
last_position = 0.0
last_velocity = 0.0
last_acceleration = 0.0
time = 0.0
position = 0.0
velocity = 0.0
acceleration = 0.0

def add_point(p1, p2):
    global last_time, time, last_position, last_velocity, last_acceleration, position, velocity, acceleration
    time = last_time + 1
    P.create_line(last_time, last_position+125, time, position+125, fill="blue", width=2)
    V.create_line(last_time, last_velocity*50+125, time, velocity*50+125, fill="purple", width=2)
    A.create_line(last_time, last_acceleration*500+125, time, acceleration*500+125, fill="red", width=2)
    last_time = time
    last_position = position
    last_velocity = velocity
    last_acceleration = acceleration

def callback(event):
```

temp.py × demo.py ×

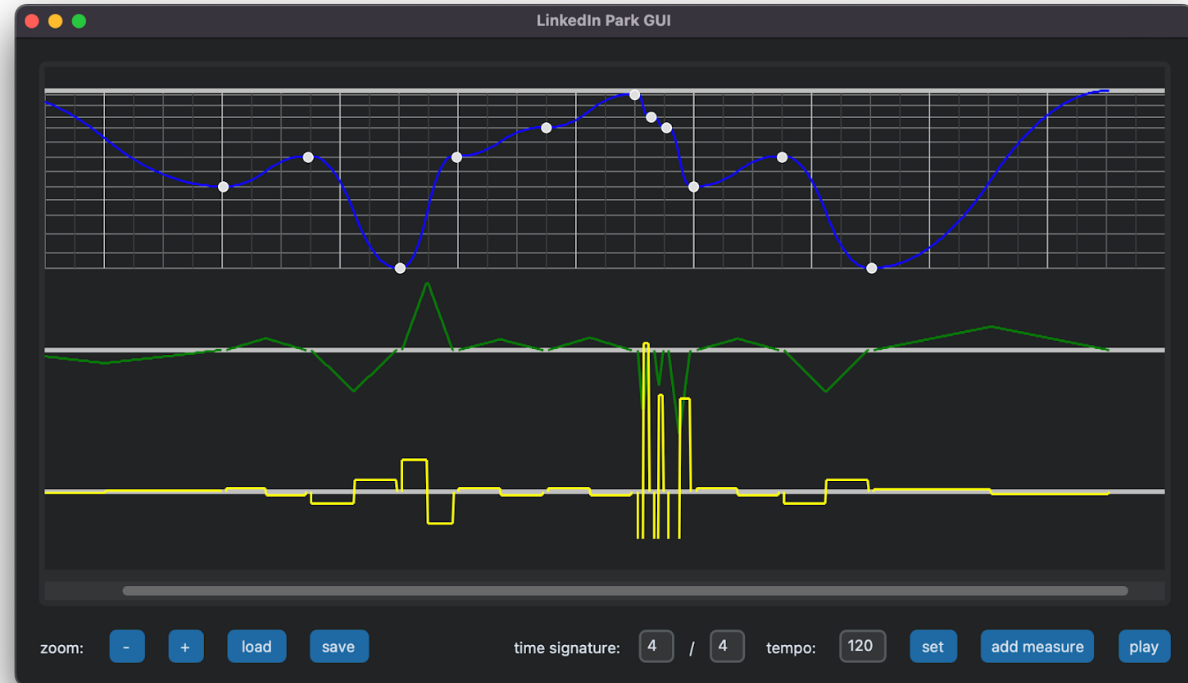

```python
    global last_time, time, last_position, last_velocity, last_acceleration, position, velocity, acceleration
    time = last_time + 1
    P.create_line(last_time, last_position+125, time, position+125, fill="blue", width=2)
    V.create_line(last_time, last_velocity*50+125, time, velocity*50+125, fill="purple", width=2)
    A.create_line(last_time, last_acceleration*500+125, time, acceleration*500+125, fill="red", width=2)
    last_time = time
    last_position = position
    last_velocity = velocity
    last_acceleration = acceleration

def callback(event):
```


```python
    global last_time, time, last_position, last_velocity, last_acceleration, position, velocity, acceleration
    clear()
    ps.append([event.x, event.y-125])
    ps.sort(key=lambda p: p[0])
    if len(ps) >= 1:
        p2 = ps[0]
        P.create_oval(p2[0]-4, p2[1]+125-4, p2[0]+4, p2[1]+125+4, fill="black")
    if len(ps) >= 2:
        for p1, p2 in zip(ps[:-1], ps[1:]):
            move_distance = p2[1] - p1[1]
            move_time = p2[0] - p1[0]
            coast_time = 0.4 * move_time
            accel_time = 0.3 * move_time
            accel = 100.0*move_distance/21.0/(move_time*move_time)
            coast_velocity = 10.0*move_distance/7.0/move_time
            last_time = p1[0]
            last_position = float(p1[1])
            last_velocity = 0.0
            last_acceleration = 0.0
            position = 0.0
            velocity = 0.0
            acceleration = 0.0
            for t in range(int(accel_time)):
                acceleration = accel
                velocity = last_velocity + acceleration
                position = last_position + velocity
                add_point(p1, p2)
            for t in range(int(accel_time), int(accel_time + coast_time)):
                acceleration = 0
                velocity = coast_velocity
                position = last_position + velocity
                add_point(p1, p2)
            for t in range(int(accel_time + coast_time), int(move_time)+1):
                acceleration = -accel
                velocity = last_velocity + acceleration
                position = last_position + velocity
                add_point(p1, p2)
            P.create_oval(p2[0]-4, p2[1]+125-4, p2[0]+4, p2[1]+125+4, fill="black")

P.bind("<Button-1>", callback)

P.pack()
V.pack()
A.pack()

top.mainloop()
```

After merging with Elliott and receving some additional assistance because of his coding experience, a sample gui was created as seen below.

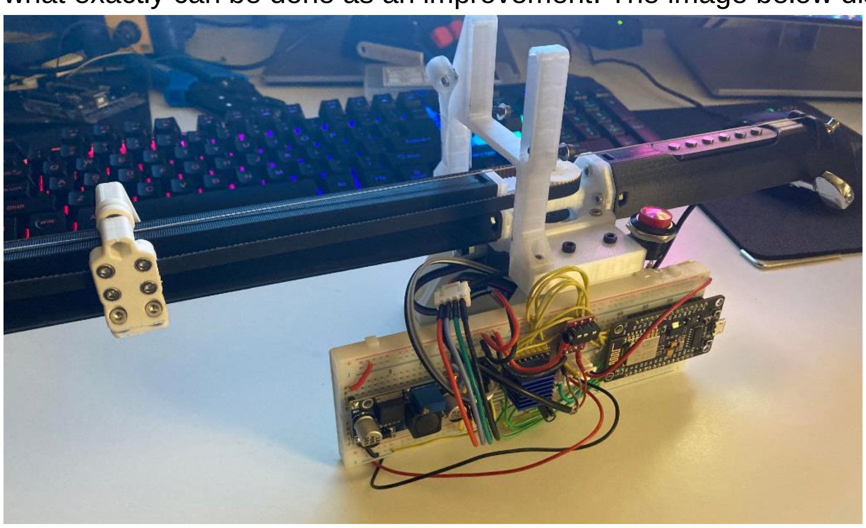
A key insight is that not labeling the graphs can really throw off some people, so users will have to be guided through the process as labels seem to clip and glitch the program.

Perhaps later on, a GUI overhaul is warranted. Maybe interfacing with desmos or matplotlib may be more beneficial for future iterations. A visual inspection and musical sound test shows that the GUI matches output!



Date: 12/3/2022. Topic: Demo, Evaluation, Recommendations:

The final demo went well and everyone was impressed luckily. Knowing that a report should include possible improvements, I am documenting what I believe can be improved upon. I will discuss this with my team to see what exactly can be done as an improvement. The image below displays the showcased final product.



While the instrument operated well, the electronics are left exposed. This made carrying the final assembly rather awkward and cumbersome. Wires can get knocked off, and components can fall out. This hinders device reliability and can add to setup time, which are crucial customer needs.

As a solution, I suggest placing an enclosure. Not only with help with the aesthetic, but carrying the device is easier, and the user, especially younger members of K-12 will be prevented from dangerous meddling of electronics.

Also, Because the instrument can only play note at a time because of the servo operation and roller movement, we had to keep the overall string length interval short to avoid unnecessarily long traversal times. As a result, bandwidth is reduces far below the frequency bandwidth expectation and is effectively about 470Hz when checked with the tuner. By switching back to the DC motor and trying to carry out closed loop control, a faster roller can be achieved, allowing notes of different frequencies to be played much faster. The faster traversal overall can mean we can afford to perhaps work with a longer neck, which can extend bandwidth, but then again contradicts compactness.

The project has been fun and I enjoyed working with my colleagues! Overall the instrument was a great success.