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Automatic Trumpet Tuner

TUNG SAHUR

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Abstract

With the combination of many individual instruments composing the overall sound of an ensemble, each instrument's sound and the player's ability to play in tune is of extreme importance. Indoor ensembles enjoy the luxury of having time to warm-up and finely tune their instruments in a controlled climate before a performance; however, performers involved in marching band experience much greater sound dissonance due to ever-changing environmental conditions and irregular intervals between playing, causing instruments to commonly fall out of tune, despite initial warm-ups. With trumpets particularly being the most affected, as well as being the largest instrument group and often the loudest of the ensemble, an automatic tuning device to fix intonation issues was developed, utilizing an Arduino Nano and a piezoelectric sensor in prototype construction. With the use of Fast Fourier Transforms (FFTs), the vibrations of the piezoelectric sensor can be analyzed and used in a negative feedback loop to control a linear actuator, ultimately moving the slide of the trumpet to tune it continuously throughout outdoor performances, without much input from the player. While the tuning device prototype functions as intended and does tune the trumpet well in most cases, there are hardware limitations that limit the range of this functionality.

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I. Presentation and Justification of the Problem

I.1. Executive Summary

Background

Many artistic and technical components go into creating a musical performance; in addition to the performers, instrument physical factors are key: the material, shape, finishes, and other aspects of the instruments all define and affect intonation and timbre, influencing the overall sound of a performance. Shape affects how the sound vibrations travel throughout the instrument, and has the majority of the influence on the overall sound. Longer horns produce lower pitches[1], flaring bells amplify volume[2], and conical bores affect timbre[3], which is the defining characteristic of an instrument's unique sound, and is a result of the individual strengths of the frequencies produced by the harmonic series[4] (a series of frequencies at integer multiples that are produced alongside the base frequency being played). Timbre is thus how one can tell the difference between the same note being played on a piano or a saxophone, for example. Different materials are also a factor of timbre[5]. Finishes, such as metal platings or lacquer, can also influence how sound reflects or is absorbed into the material, which can slightly affect timbre[6].

When performing in dynamically changing environments, such as those encountered by marching bands, such aforementioned physical factors are influenced by environmental factors which in turn, affects the instruments' sound quality. As marching band players move between small, congested warm-up rooms to large game fields under a setting sun, many environmental and weather factors such as temperature (which affects the speed of sound and thus the perceived tune of an instrument[7]) and humidity (which can warp instruments and affect the resonance of reeds which in turn affects tune and timbre[8]) can negatively affect the ensemble sound due to the random and dynamic nature of the factors pushing the individual instruments' sounding characteristics into divergence from one another, resulting in a dissonant and uneven performance.

As the characteristics diverge, timbre is often perceived as "sluggish," describing an undesirable sound quality, while the actual pitch of the notes produced by the instruments can sound "sharp," or "flat" [9], which describe it as either at a lower or higher pitch than it is supposed to be, according to twelve equal temperament (the most widely used mathematical system used to calculate note frequencies so that they are evenly spread[10]). Such variations in sounding pitches can cause the music to sound different when the band is uniformly out-of-tune, or even worse (and more commonly), instruments having independently varying base pitches can cause the overall sound to be very dissonant and displeasing, due to the nature of dissonant frequencies and the brain's negative perception of them[11].

For this reason, instruments have the ability to be tuned through various methods such as changing the effective length of bore (tuning slide or mouthpiece placement), string tension, and reed length. This helps performers counteract the effects of changing environments and continue to play in tune. However, the tuning process often involves a device or a reference pitch, a free set of hands, and some time. This makes it often impossible for some types of performers, such as those in marching bands playing in dynamic conditions, to continuously adapt to the changing physical factors affecting their sound.

Problem Statement

For musicians playing in a marching band, dynamically changing environmental conditions and sporadic playing alter the pitch of their instruments[7], requiring all wind musicians to tune them constantly to maintain a good ensemble sound. Musicians often do not have the time to properly re-tune their instruments as conditions change, and thus results in an out-of-tune band, with 75% of musicians reporting intonation issues being at least moderately common in their ensembles.

I.2. Market Analysis with Problem Justification

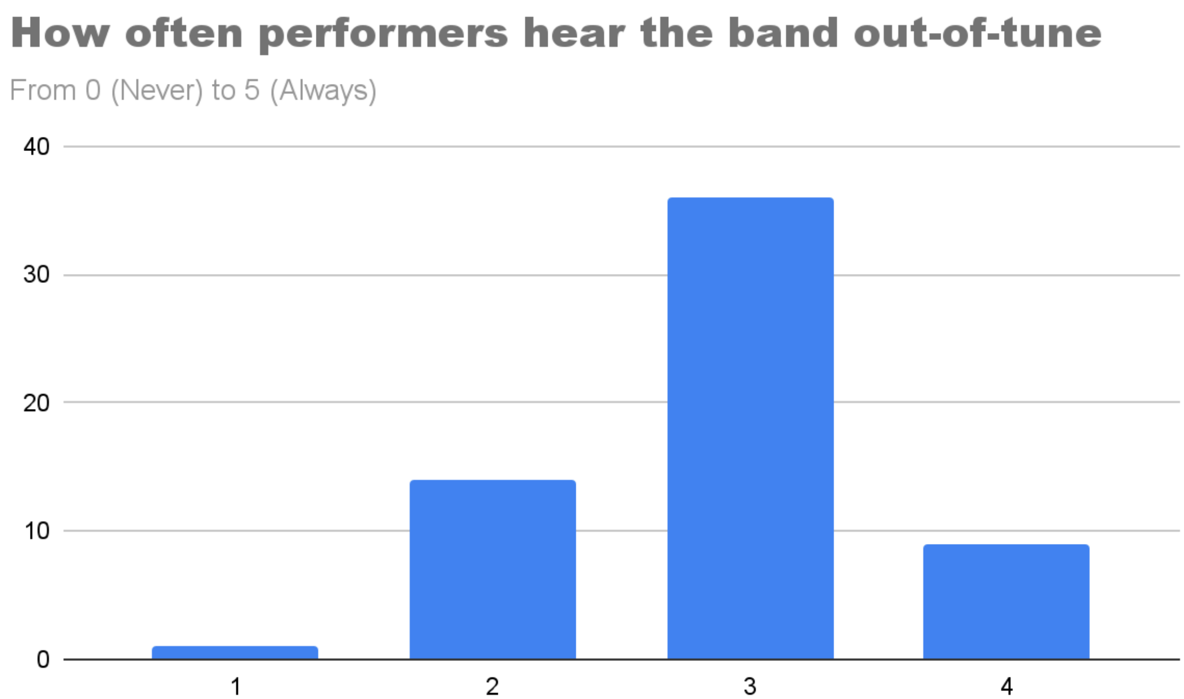
While the general audience is musicians, the target audience for this specific hypothetical product would be marching band members, as they are most likely to be exposed to the natural elements and experience slight fluctuations in pitch due to weather.

A survey was conducted among various populations of local high school band members, totaling 65 responses, to gauge the issue of tuning itself among demographics and estimate the general need and interest for a product solution.

It is important to note that of the 65 respondents, 61 selected that they performed in marching band, a yield of 95.3%. This is in accordance with our hypothetical target market, such that their tuning concerns will likely be affected by the dynamic environmental factors.

Figure 1

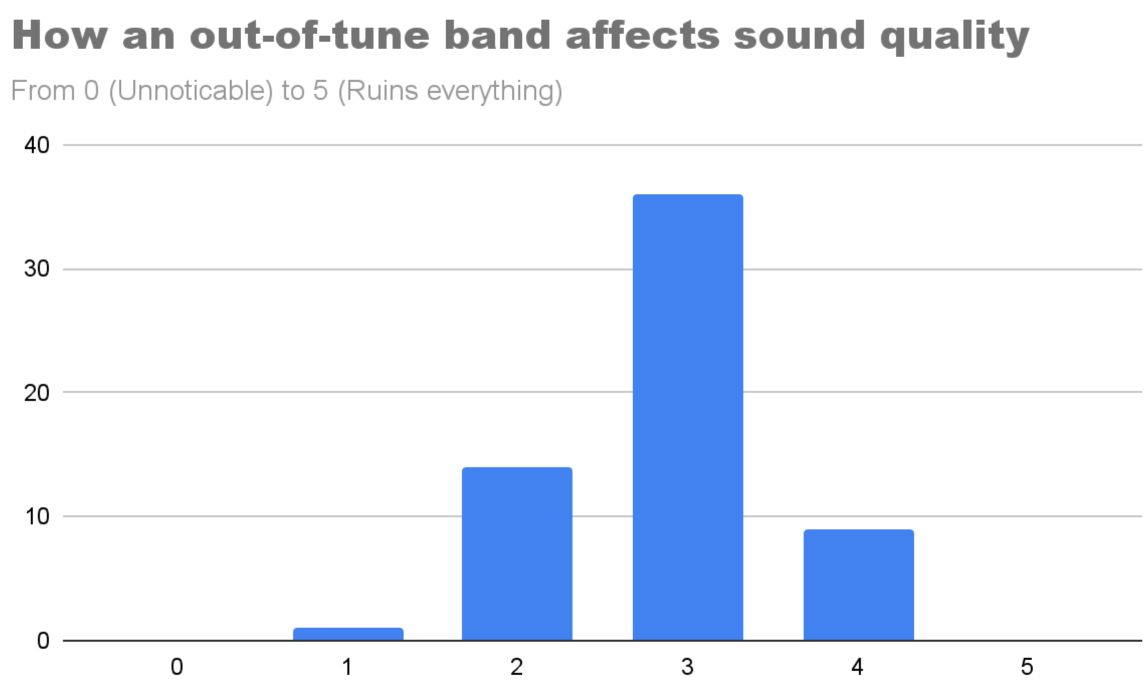
Combined summary of 60 responses to: "When you do judge, how often does the band sound in tune? (if you don't think about the tune, leave blank)"



The majority of performers perceive their band as out-of-tune about halfway between never and always, which could be interpreted as about 50% of the times that they judge the intonation. This is a considerable amount of judgment for an out-of-tune band with less than ideal conditions, emphasizing the presence of the issue.

Figure 2

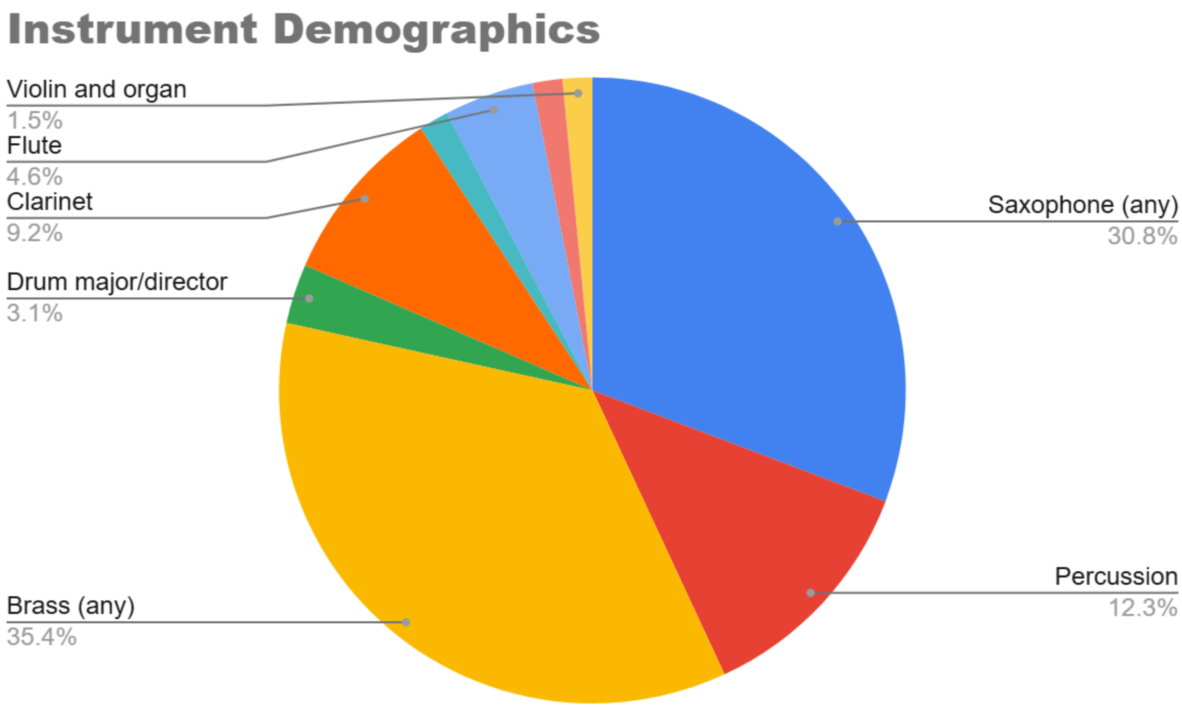
Combined summary of 60 responses to: "When the band does sound out-of-tune, how does it affect your overall listening experience? (if the band never sounds out-of-tune, leave blank)"



The most popular choice is 3, which indicates a moderate displease with an out-of-tune band. There is a general consensus with 53 of the 60 respondents selecting 2, 3, and 4 that are concerned with the overall band sound quality. This justifies the existence of the problem as something that is present and perceived among performers, while having a considerable impact on the listening experience.

Figure 3

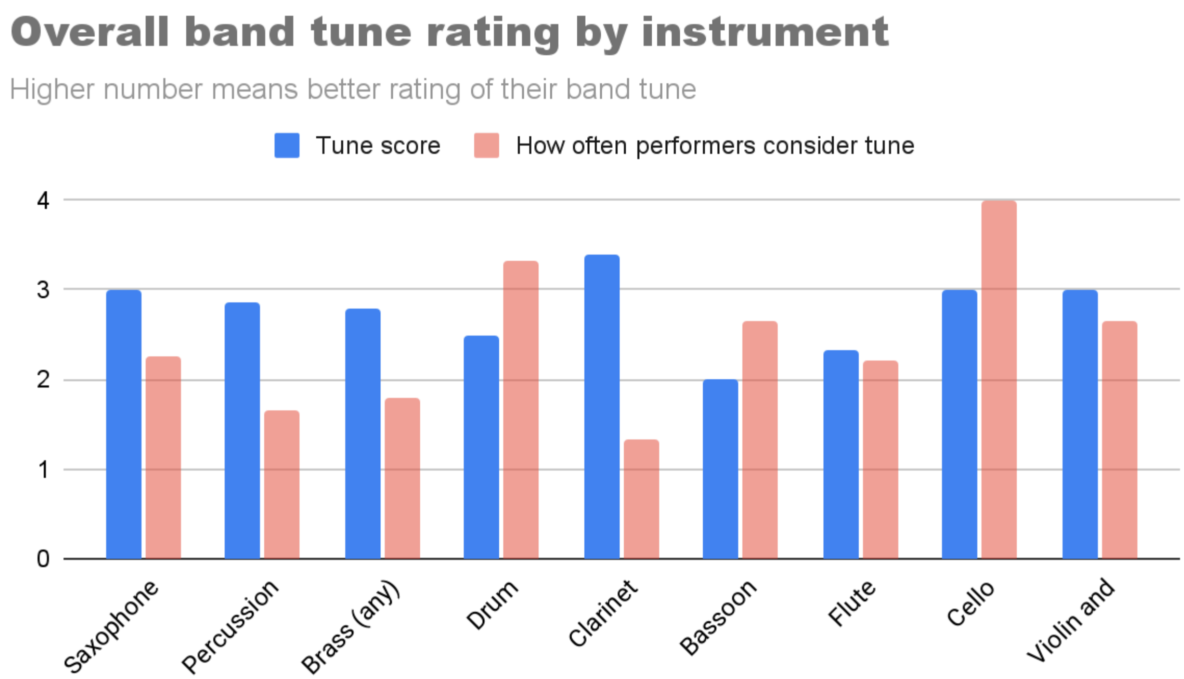
Summary of 65 responses to: "What instrument/role do you play most often?"



The largest instrument populations are brass at 35.4%, saxophones at 30.8%, followed by percussion at 12.3%. With the largest sections being brass and saxophone, constituting over half of the survey at 66.2%, a product to resolve the intonation issues of these instrument types specifically, would likely be the most ideal target market.

Figure 4

Combined summary of 65 responses to: "What instrument/role do you play most often?" "How often do you think about the overall tune of the band?" and 60 responses to "When you do judge, how often does the band sound in tune? (if you don't think about the tune, leave blank)"

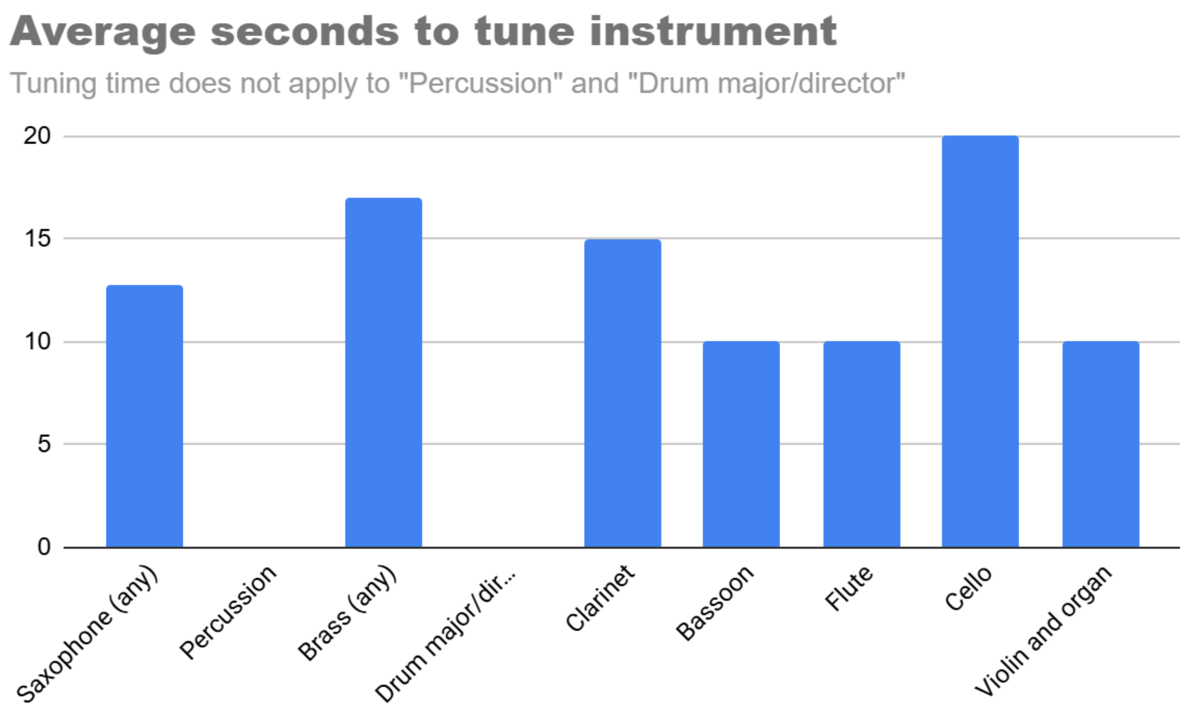


From the data, the way that different groups of instruments perceive the intonation of their band is apparent. Due to instruments being grouped together by section during performance, the overall perceived sound of the band for any particular player is in fact far more affected by the sounds of nearby instruments, of which mostly consists of their own section. Thus, a judgement of ensemble sound given by a particular performer is more closely a judgement of their own section's sound, as it makes up most of what can be heard during performance.

From the graph, it can be interpreted that bassoons have the lowest score for tune, followed by the score given by the directors and drum majors (of which are an exception to the aforementioned line of reasoning; they have a balanced perception of the ensemble), and then followed by brass with the third lowest score. As bassoons and directors/drum majors make up a very small minority of the demographics, they will likely not be the target audience for a solution. However, the brass, having the third lowest score for perceived tune, also makes up the largest population, which furthers the instrument group as being the most in need of a solution.

Figure 5

Combined summary of 65 responses to: "What instrument/role do you play most often?" and 55 responses to "How long does it typically take you to tune? (if you don't tune, leave blank)"



Although the Cello takes the longest time on average to tune, the instrument makes up one of the smallest groups in the demographic, with one respondent. Additionally, the problem has been previously narrowed down to strictly marching band instruments. Brass is then the next instrument that takes the second longest to tune, further supporting it as being the primary target for a solution.

I.3. Problem Identification

As identified by the survey, the problem of ensembles falling out of tune is present, noticeable, and causes displease among performers. Marching band is the largest performing group, with brass making up the largest instrument group. Further investigation reveals brass as being the most out of tune and taking the longest to tune. This suggests that, should the solution be specific to a single instrument type, brass instruments should be the primary target for a solution.

A solution to this problem would either prevent or negate any factors that cause the tune of the instrument to dynamically change throughout different environments or playing conditions, ensuring that it remains properly in tune with the ensemble temperament.

Such a solution would likely involve a device or augmentation to the subject instrument. Modern tuning devices, which detect pitch (and indicate the deviation from what it is supposed to be, to aid adjustments), do exist, and are commonplace in a performer's equipment case. The mechanical methods for adjusting pitch are also simple, and generally consist of moving a tubing slide. Thus, interfacing between these two concepts is realistic, and considering the common perception of this issue (Figure 1), justifies the effort for such a solution.

Since the solution is aimed at adjusting tune and pitch for performers, the question to define if the solution is successful is relatively straightforward: Does the product automatically tune the performer's instrument, particularly when exposed to the elements? Ideally, the device should be able to automatically adjust the tuning element of the instrument and adapt to a new environment, to increase the overall quality of the performance, especially for marching band players. Even if the individual adjusts the tuning themselves, the device should be able to readjust the instrument as necessary to the intended pitch. Performances can be recorded with and without the tuning device and the result can be audibly interpreted and judged as a working solution.

II. Evidence and Analysis of Prior Solution Attempts

II.1. Summary of Relevant Intellectual Property

The following patents discuss tuning products, applicable to piano and stringed instruments. Ideas from these patents can be utilized to formulate possible solutions to parts of our final design, highlighting various methods to achieve a proper tuning device.

Musical instrument tuning apparatus

Source

Google Patents[12]

Patent Number

US2958250A

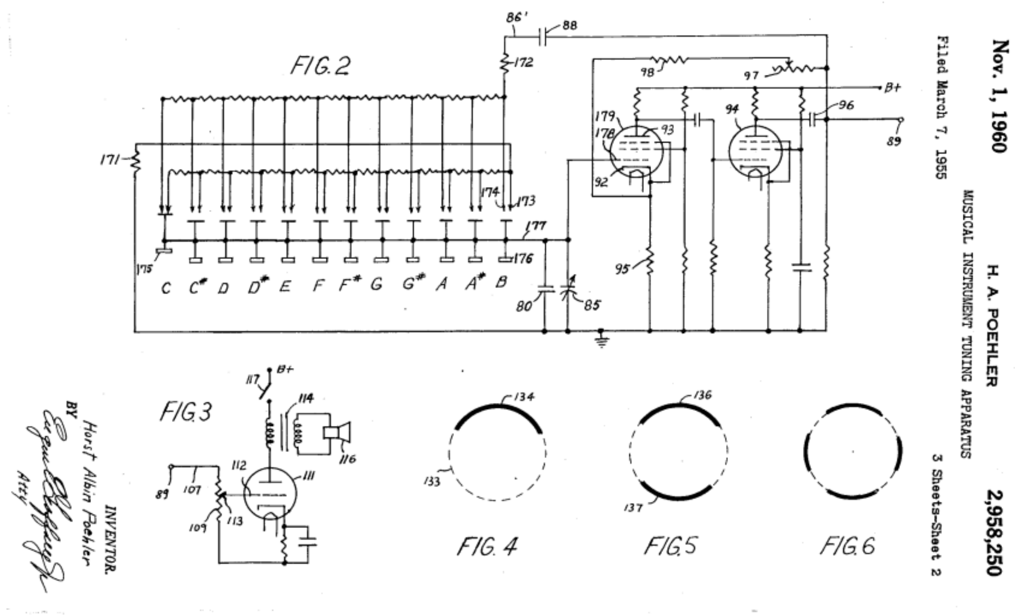
Patent Summary

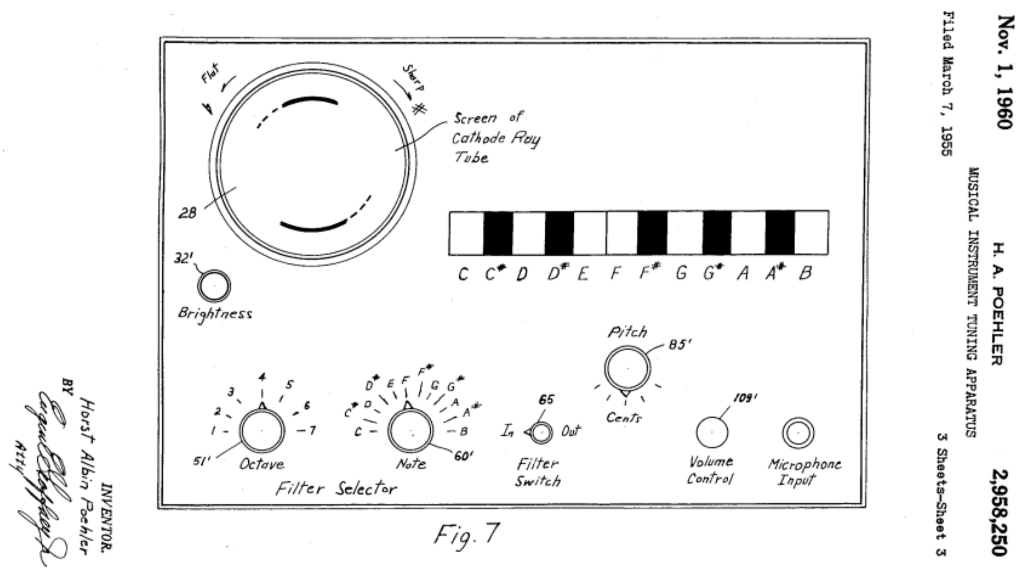
The invention improves upon a device and method for tuning musical instruments, as a device that visually indicates agreement or disagreement of an audible note with an audible standard of pitch. It is applicable to most instruments that emit an audible note with or without partials. This invention aims to: provide a visual indication of pitch, provide the relative magnitude and deviation of a pitch from a true harmonic series, and improve the method and apparatus for tuning pianos. It strives to aid in all aspects of detecting variations in a note with every intonation, including vibratos. This device excels at tuning pianos, a difficult and delicate art being able to differentiate between cycles of a note such as 59 or 61 cycles per minute. Twelve frequencies are spaced out in a ratio that matches the chromatic musical scale, but the frequency of them as a group can be adjusted up and down. Enabling the tuner to tune a given note will tune the others in the same ratio, whether it is pitched up or down.

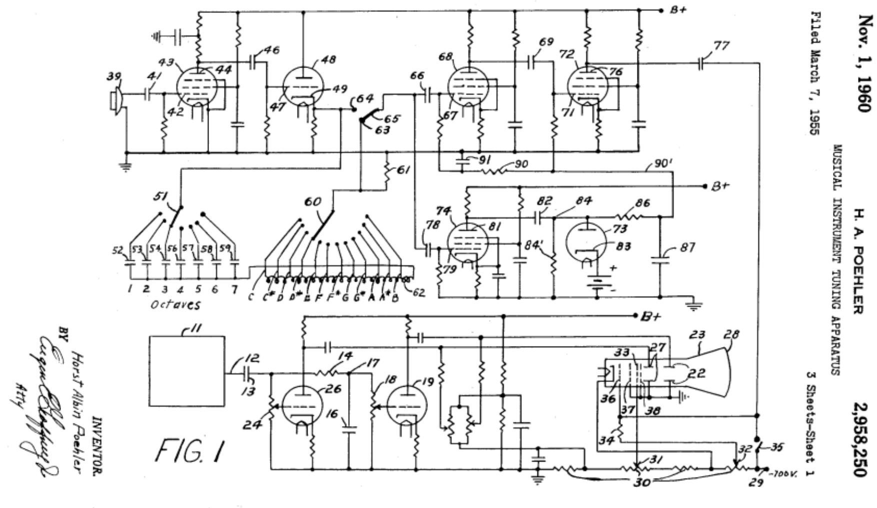
Patent Critique

This invention seems to be similar to the modern digital tuner (this patent is from 1960) but semi-automatic with its complexity. It is a standard for displaying the tone of the note visually. It aims to help tune pianos with its ability to differentiate from overtones and partials, as well as align with the pitched notes in an appropriate ratio for each note. While pianos are not our focus, this invention's ability to detect the ever so slight differences in pitch with deviations is an admirable feature, as this can be applied to fix pitch variation due to temperature. Ideally, we would be able to maximize the use of this tuner for brass instruments.

Images/Sketches







These figures are the datasheets for the musical tuning apparatus

Automatic string instrument tuner

Source

Google Patents[13]

Patent Number

US5824929A

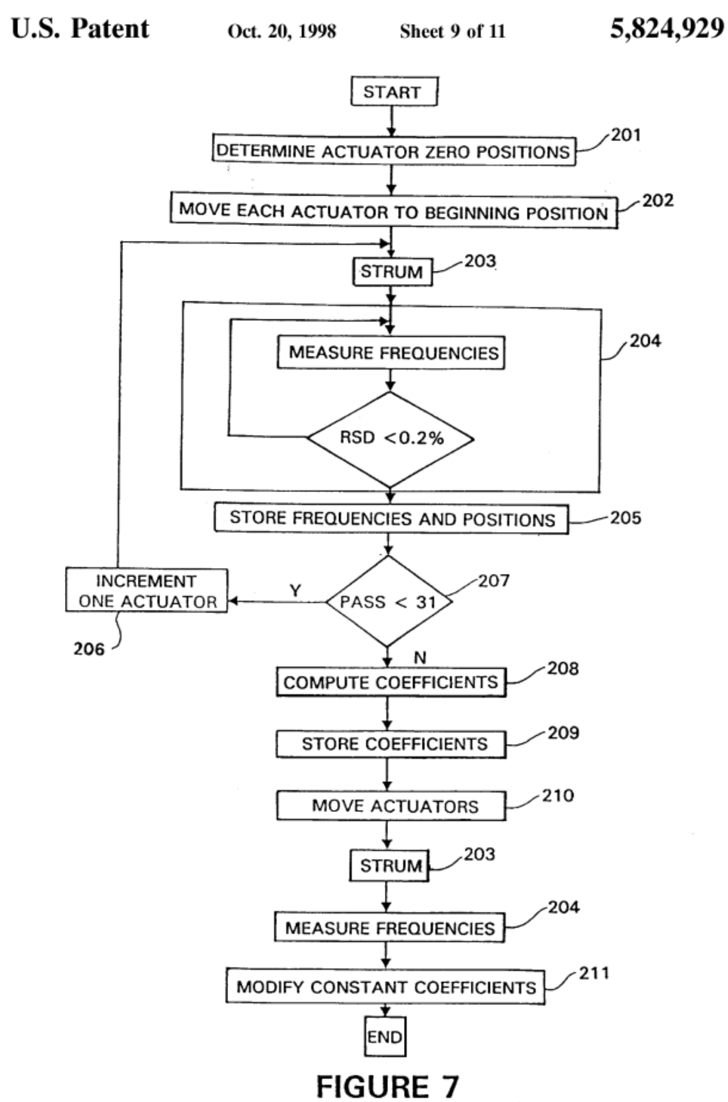
Patent Summary

This patent describes an invention in which a system of actuators, transducers, and processors are used to automatically change the base frequency of strings on a string instrument based on pre-calibrated functions generated in advance by the user, which are stored in a library based on environmental conditions, capos that are installed, and string materials. This allows for the instrument to remain in tune during changes in the aforementioned factors, as the user can switch through the calibrated presets quickly and make changes to the tune without requiring the instrument to make a sound for feedback. The user can also additionally re-calibrate the selected function by strumming the strings on the tuning notes.

Patent Critique

This invention requires a possibly lengthy and time consuming process to generate the calibration functions, and it would be hard to calibrate for some conditions that are not easily replicable (some playing environments can not be predicted and thus replicated in advance). The system would also require many different calibrated functions to account for different combinations of tune factors, as it does not seemingly include a solution for relating different factors into a single function. Additionally, this range of calibrated functions would either require the user to be capable of accurately assessing the environment and then selecting the corresponding function, or include a variety of sensors or other inputs to determine which function to use automatically. Finally, the very recording, processing, storing, and recalling such functions would require a rather complex device.

Images/Sketches



Flow chart for the creation, storage, and recall of calibration functions.

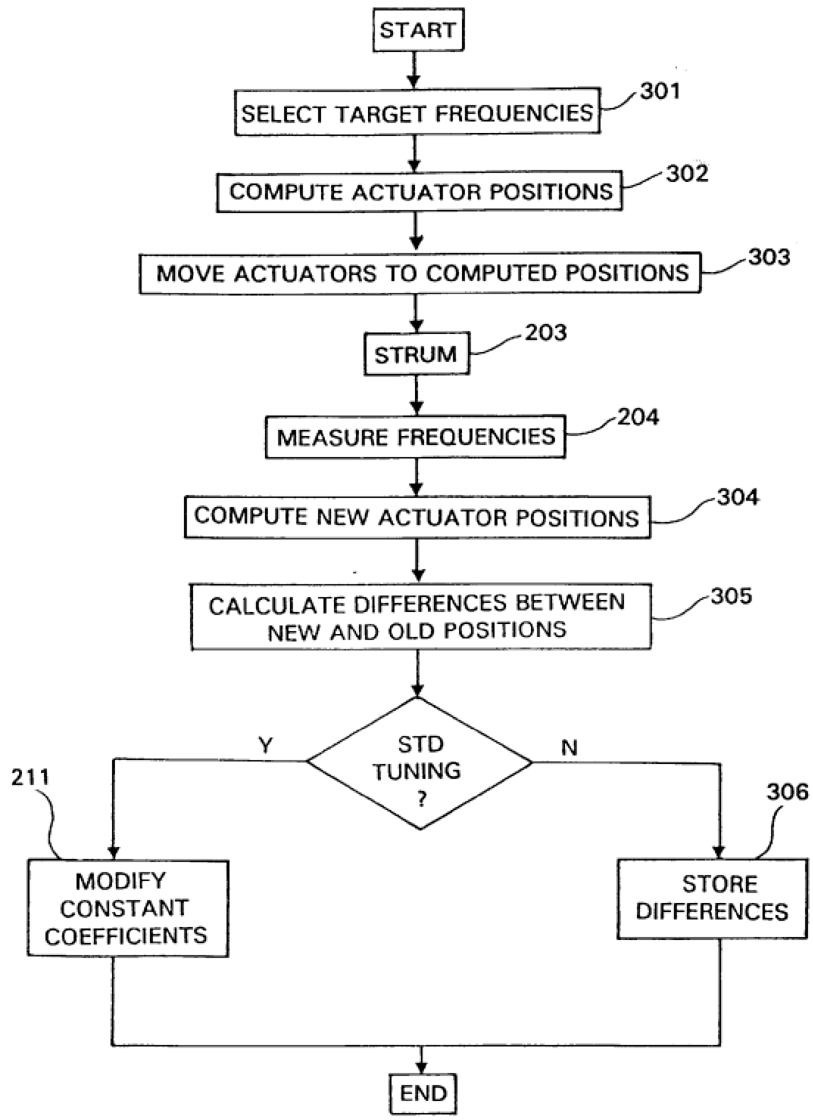

START
SELECT TARGET FREQUENCIES
301
COMPUTE ACTUATOR POSITIONS
302
MOVE ACTUATORS TO COMPUTED POSITIONS
303
STRUM
203
MEASURE FREQUENCIES
204
COMPUTE NEW ACTUATOR POSITIONS
304
CALCULATE DIFFERENCES BETWEEN NEW AND OLD POSITIONS
305
STD TUNING ?
Y
N
211
MODIFY CONSTANT COEFFICIENTS
306
STORE DIFFERENCES
END

FIGURE 8

Flow chart for the re-calibration of the selected function.

Gearless tuner

Source

Google Patents[14]

Patent Number

US005103708A

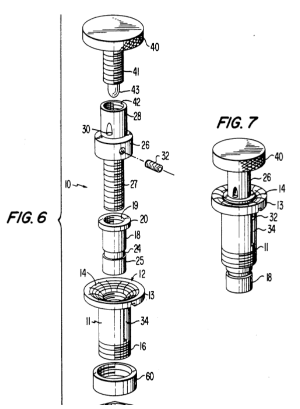
Patent Summary

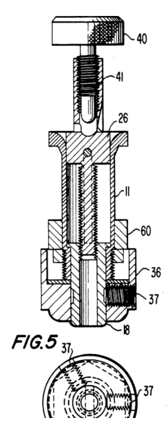
This patent describes a product that inserts into the headstock of a stringed instrument, then using worm gears and screws a knob can be turned to individually tune the strings on a stringed instrument. The turning of the knob can tighten or loosen a string however the design is not automated and requires manual turning of each knob.

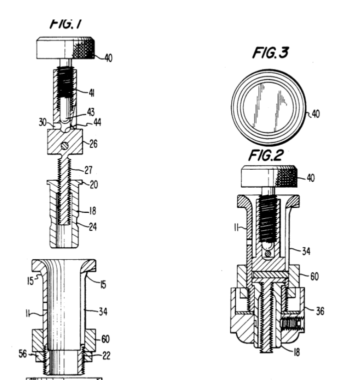
Patent Critique

While the patent is very similar to the tuning pegs on modern stringed instruments, it is too similar to be more effective than the standard stringed instrument tuning pegs. The patent is also lacking in that it can only be used for stringed instruments and will not help in the tuning of wind instruments. The product is also not automated and requires manual adjustment and tuning of the instrument.

Images/Sketches







II.2. Benchmarking of Competitive Products

Roadie 3

Source

Roadie Music[15]

Product Summary

The Roadie 3 is an automatic tuner with compatibility to most string instruments, except for bass guitar. It clasps on the pegs of the string instrument up to a gauge of 75. The tuner can save up to 150 custom tunings and pitches, has a built-in metronome, and dynamic frequency display, all while being pocket-sized. Its peg connector allows it to move more instruments than its predecessors, and can rotate faster with more torque for the appropriate tension to tune.

Product Critique

Again, this device is primarily useful for string instruments and would not be compatible with wind or brass instruments. Its automatic feature of displaying the frequency over a large range and ability to change the pitch informatively is an attribute that may be considered to be replicated. The instant response to an out-of-pitch frequency, relative to tones already embedded in the device is useful, very apparently so, combined with its motor to automate the pitch adjustment is appealing. Although the peg connection to tune string instruments cannot be utilized, other features of this product such as its automatic detection of the device being pitched slightly upward or downward may be replicated in our final product.

Images

Fender FCT-2 Clip-On Tuner

Source

Austin Bazaar[16]

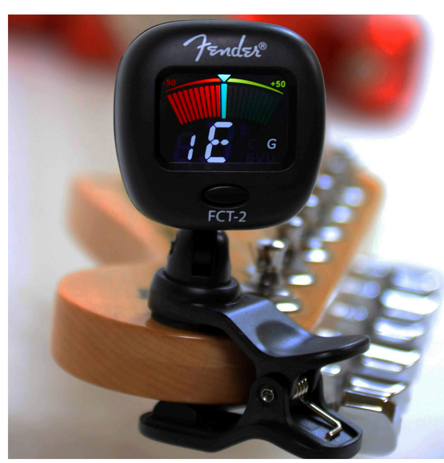
Product Summary

The Fender FCT 2 Clip on tuner is a device that is designed to clip on to any instrument, typically the end of the neck or bell, and displays the current pitch being played by the instrument and how much it deviates from the standard tuning pitch. It does this by using a “vibration sensor” to detect the frequency at which the clip resonates to determine the note being played, and then the deviation from the standard tuning pitch is likely compared using a look up table. This allows players to get instant feedback on the adjustments they make as they tune. It is also small and portable, and can fit into most instrument cases as an accessory.

Product Critique

This product, however, still requires the user to tune the instrument manually, which does not solve the issue of the user being incapable of adjusting the tune of the instrument during performances. Its frequency reading also could possibly be affected by the noisy vibrations of surrounding instruments, which might make the feedback inaccurate. This particular clip configuration also does not seem particularly suitable to some instruments such as brass, in which the clip might not hold on to the bell well, or the saxophone, in which the bell is too low for the user to see anything that is clipped on to it.

Images



Korg CA-2 Chromatic Tuner

Source

Meridian Winds[17]

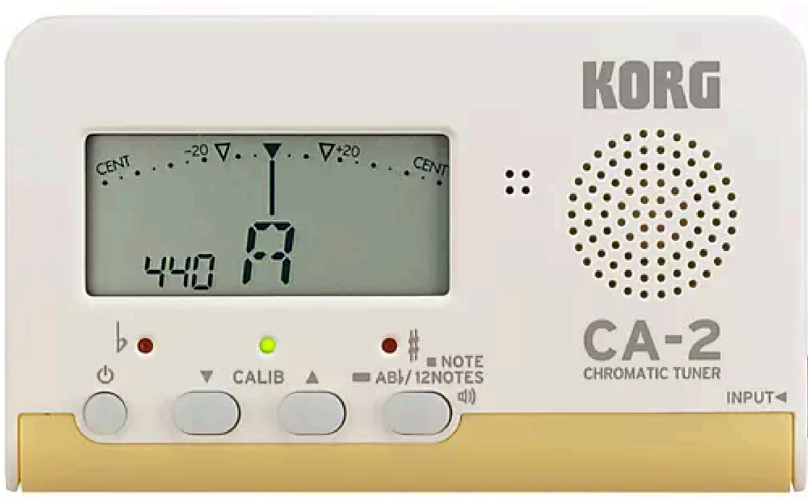
Product Summary

The Korg CA-2 Chromatic Tuner is a simple, affordable device that displays the tone and pitch of the audible note being played. It can help indicate if the note played is too sharp or too flat with a needle-style meter that is suitable for all types of instruments. It has an adjustable calibration to adjust the reference pitch from 410-480 Hz and is an ideal compact, handheld, and lightweight chromatic tuner that is easy to use for any instrument.

Product Critique

This product seems to be very good and ideal for all musicians in any instrument for its simplicity and affordability, however it also appears to be very rudimentary for our needs. We would like to incorporate its basic features of detecting the precision of a note whether it is sharp or flat into our own product but would like the tuning process to be automatic and specialized towards brass instruments rather than a simple indicator.

Images



II.3. Key Findings

After searching through old patents and products relating to tuning, we discovered a plethora of inventions and devices that have assisted and improved upon the process of tuning for modern-day instruments. Variations of these devices are still found today, despite some of the patents being established over 50 years ago. The tuning devices that display a visual of the pitch audibly played are still frequently used by musicians to manually tune and adjust all types of instruments. These designs helped support our understanding of the current market and products associated with the issue we'd like to investigate, gauging our product's capabilities and further supporting our intended audience.

Much of the patents and products reviewed were specialized for string instruments with pegs, or were generalized to all instruments. Many of the products reviewed were very simple and rudimentary, merely displaying the tone of the note being played and its discrepancy or deviation. While this indication is an important feature we would like to include in our product, we would also want a more advanced and specialized method to automatically tune for a specific type of instrument, namely brass. There was one product we reviewed that had an automatic tuning feature, the Roadie 3, with its motor that can utilize torque on a peg and adjust it with minute steps, but again, this device is specifically designed for string instruments with pegs. The "musical instrument tuning apparatus" patent had a semi-automatic design for tuning, by breaking up the notes into a predetermined yet adjustable ratio of notes, that can all be modified from the reference note. However, once again, this design excels for pianos, a different type of instrument much different from brass instruments.

After investigating the current market and state-of-the-art intellectual property available, we discovered a small variety of automatic tuning devices, none of which were associated specifically with brass or wind instruments. The devices are primarily simple indicators of the tone, informative for pitching the note up or down with little to no designs that automate the tuning process. There appears to be a limited selection of devices that are specialized to tune brass or wind instruments, and an even more limited selection of devices that would be able to automate that process, leaving us with plenty of research and innovative practice to uncover and resolve our issue.

III. Generating and Defending an Original Solution

III.1. Design Brief

Client

Electronics manufacturers

Target consumer

Online stores and music stores

End user

Brass musicians in marching bands

Problem Statement

For musicians playing in a marching band, dynamically changing environmental conditions and sporadic playing alter the pitch of their instruments[7], requiring all wind musicians to tune them constantly to maintain a good ensemble sound. Musicians often do not have the time to properly re-tune their instruments as conditions change, and thus results in an out-of-tune band, with 75% of the 65 surveyed musicians reporting intonation issues being at least moderately common in their ensembles, and brass musicians reporting the most trouble with tuning.

Design Statement

Design and construct a device that allows brass musicians to remain in tune throughout dynamic playing environments and changing factors, while being inexpensive enough to be accessible and easy to install, remove, and operate.

Criteria and Constraints

1. Inexpensive and widely accessible (the more brass players that have this solution, the best overall impact, as even only a few individual out-of-tune instruments could diminish the impact of these tuners)
2. Can be installed onto many varieties of brass instruments (not immediately necessary for the prototype)
3. Quick to install and remove
4. Small enough to fit into a a typical instrument travel case

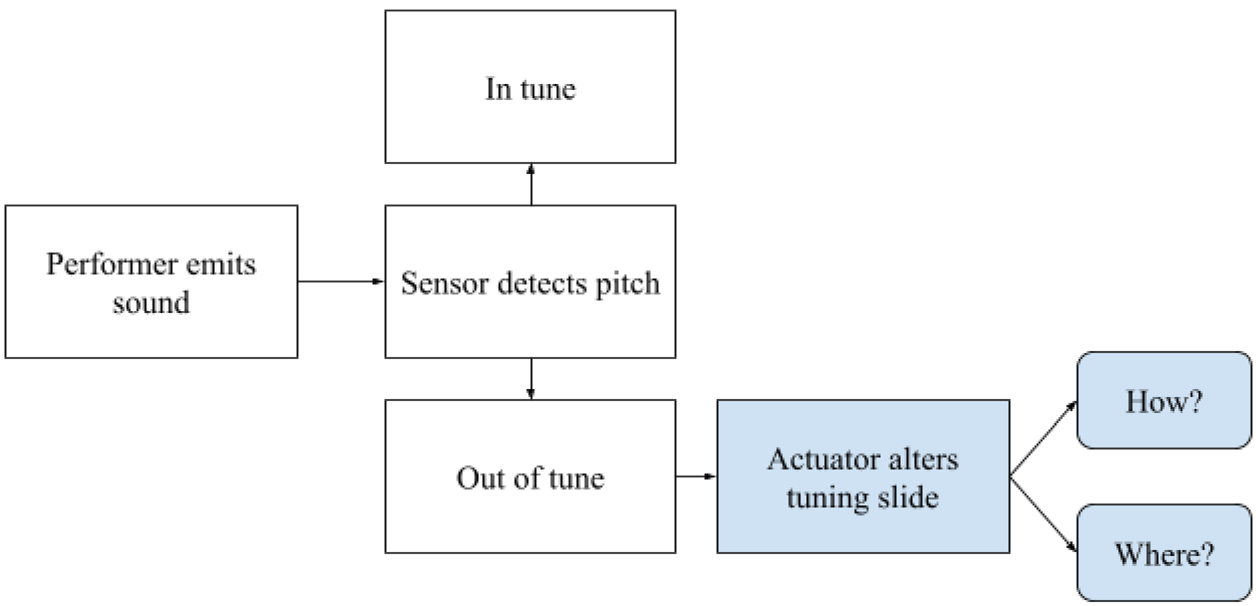
5. Must function well and throughout entire performing events (at least 3 hours of battery life)

6. Lightweight enough not to significantly affect playing ergonomics or performance

7. Functions under extreme weather conditions

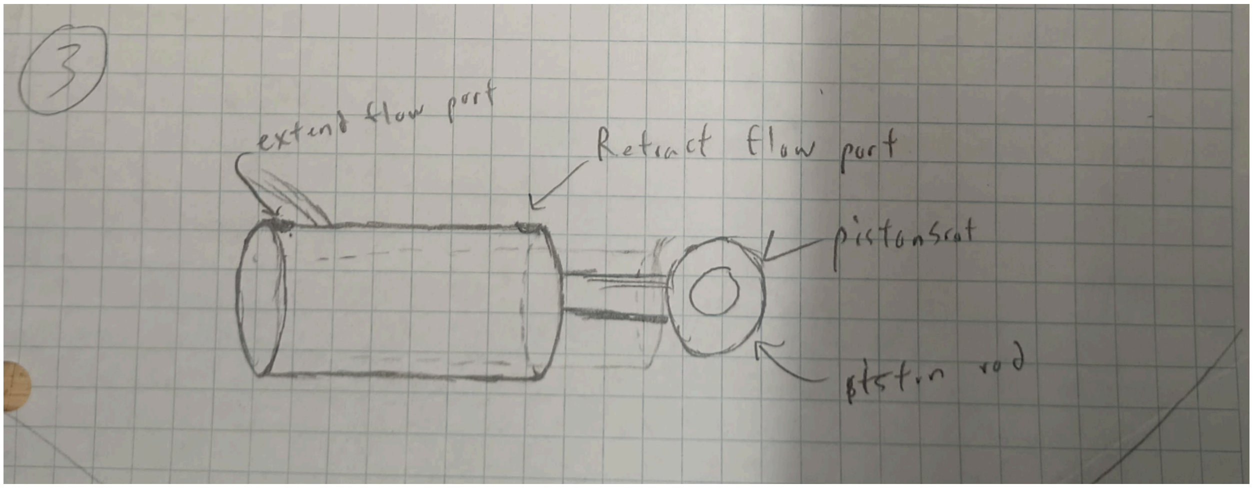
III.2. Design Concept Generation

To clarify, below is a diagram to illustrate and justify our upcoming concepts and designs. Although we identified and justified our solution to cater toward brass instruments, we collectively decided that we would like to focus specifically on a trumpet, and the design can be altered and dimensioned as necessary for other instruments. There are several parts to designing this device from the actuator component (how?) to the location on the instrument that it can be attached optimally (where?), different enough to justify completely concept sketches and decision matrices that must be considered separately.



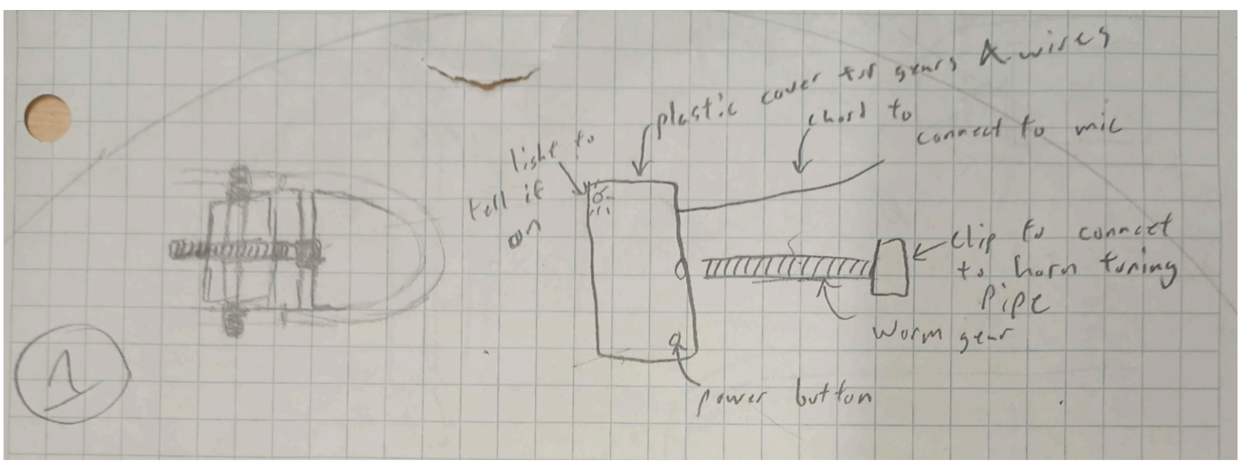
Actuator Designs

"Hydraulic actuator" by Logan



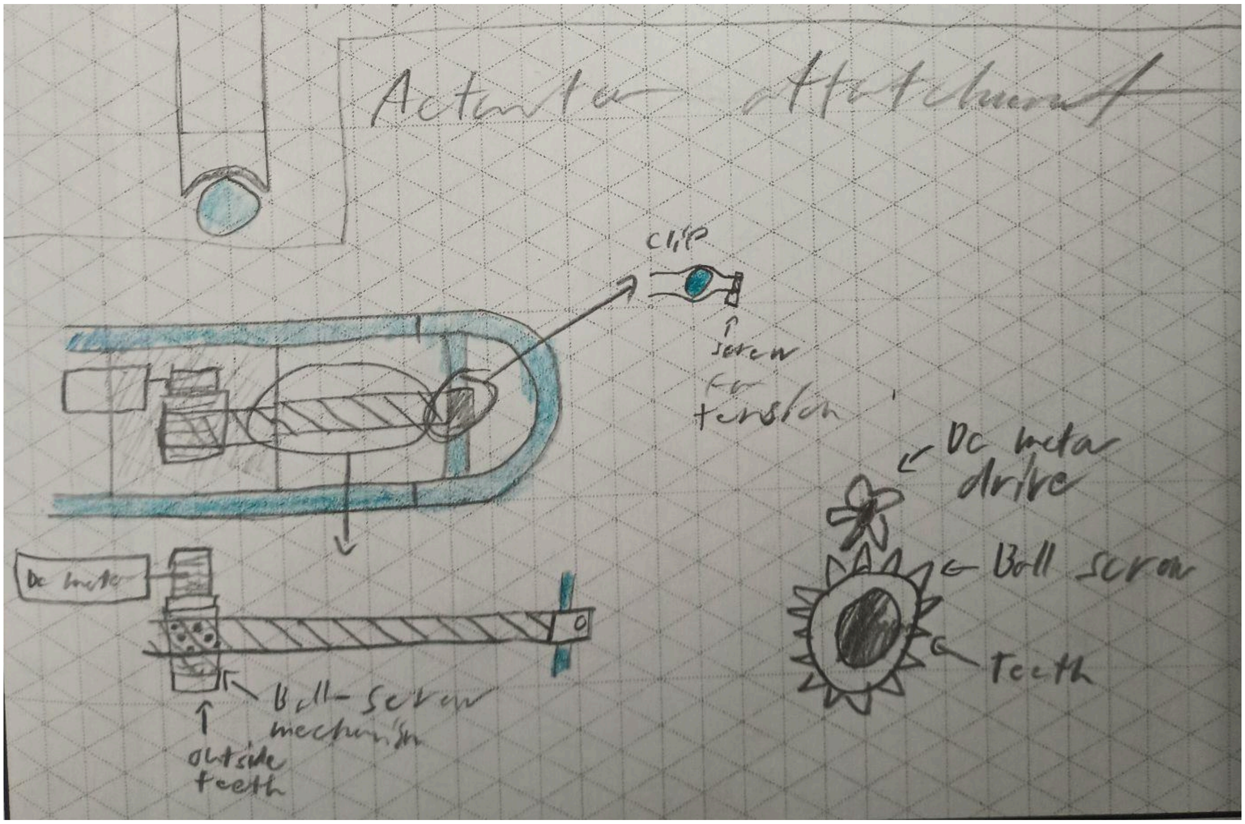
Design 3 is of an alternate tuning slide adjustment arm, which will use a hydraulic actuator instead of gears to move the tuning slide while taking up less space than a gearbox would and applying more force.

"Screw actuator" by Logan



Design 1 is of a tuning slide extender that will mechanically move the tuning slide using worm gears on the tuning slide and gears inside the containment/ attachment unit that will go between the bars of the trumpet. There will be a bar with the worm gear around it on one side and a clip to allow it to grab onto the tuning slide.

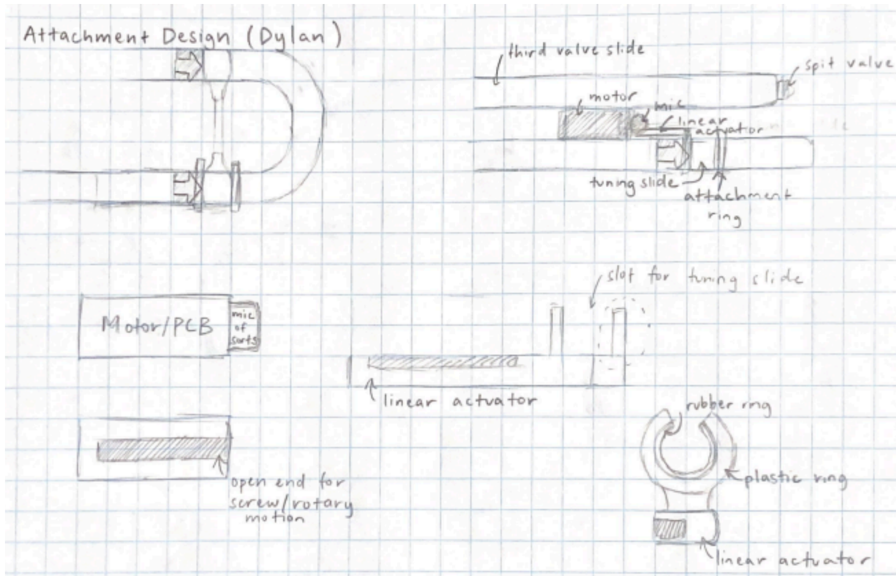
“Ball-screw actuator” by Nehuel



A DC Motor powers a helical pinion gear which drives a ball-screw nut with helical teeth on the outside, driving it to rotate and drive a screw. The end of the screw is attached to the tuning slide pillar using a plastic clip that clamps with a small screw.

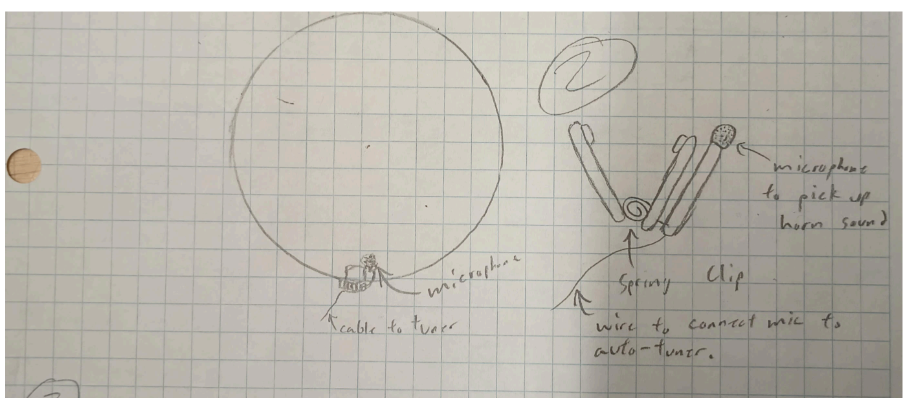
Attachment Designs

“Ringed design” by Dylan



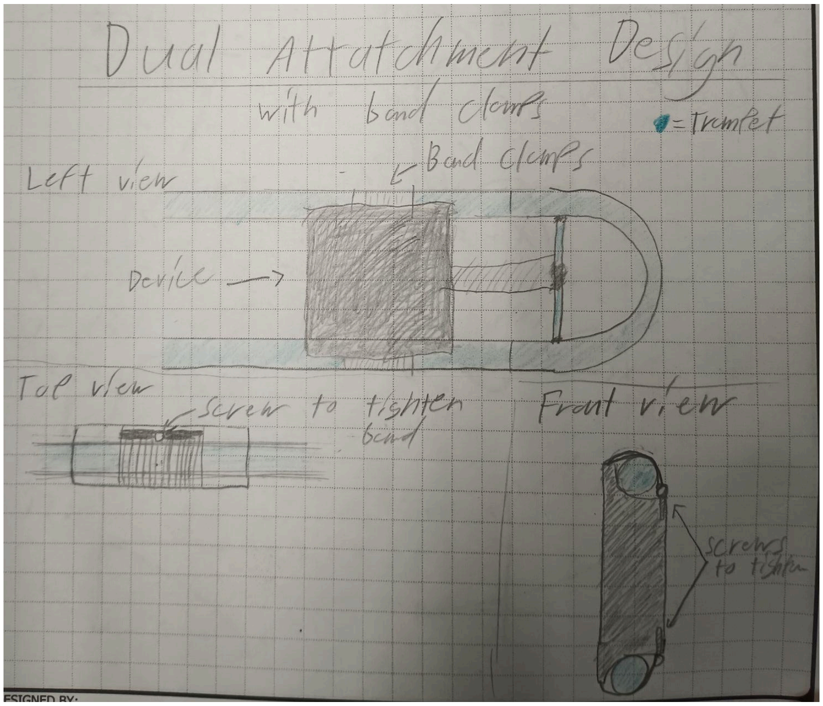
A small linear actuator could be situated between the third valve slide and the main body. It would be nested and mostly concealed in the central area, while also having a close vicinity to the actual tuning slide that would be adjusted. The linear actuator would connect to the bottom of the handheld part of the slide, ideally in between two rubber rings to secure the device and ensure enough frictional force to move the slide.

“Microphone mount” by Logan



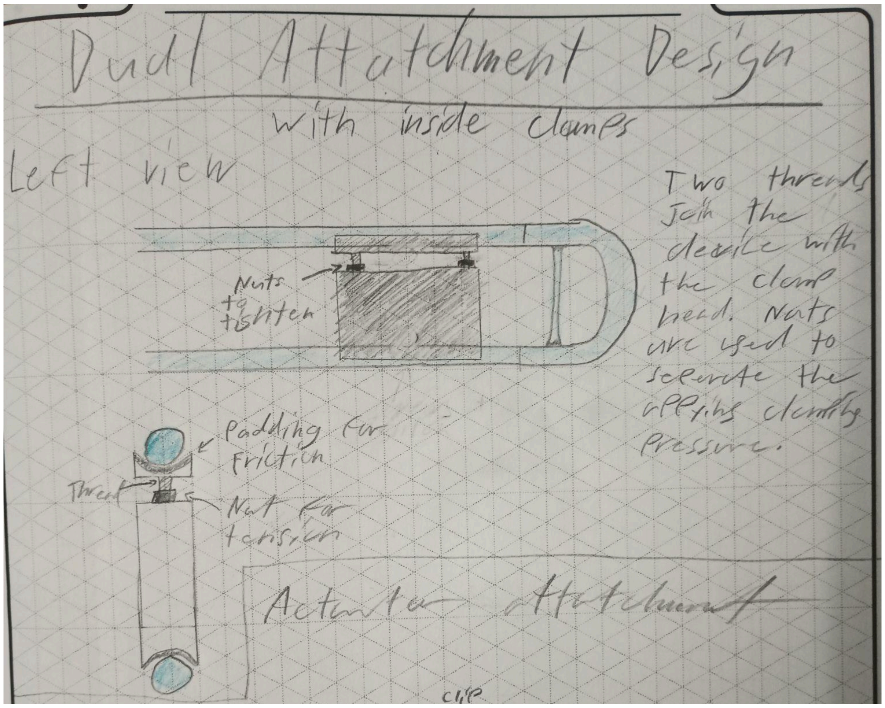
Design 2 is of a microphone that can pick up the sound of the trumpet by attaching to the bell of the instrument and using a sensitive mic to hear the pitch and notes played by the instrument. It will use a clip with a spring to allow for attaching/detaching of the tuning microphone and a wire will connect the input mic to the tuner

“Band clamp” by Nehuel



The device casing has curves indented in the top and bottom facing into the trumpet. Bands made of a flexible material protrude out of the higher end and wrap around the trumpet tubing. The end of the band is looped around a metal bar, which contains a threaded bore in the middle to screw into the other side of the curve to create tension.

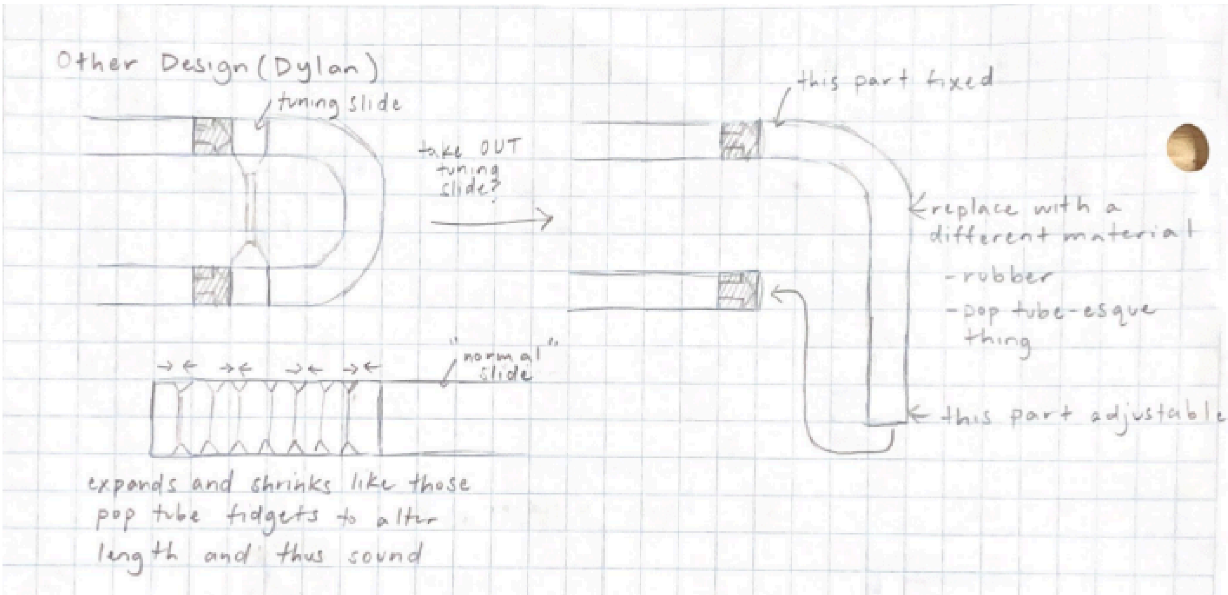
“Interior clamp” by Nehuel



The top portion of the casing has circular bores on both ends, and the bottom has a rubber-padded curve. A clamp has a curved top with rubber padding for gripping onto the trumpet tubing, and has two threads protruding from the bottom on both ends. Nuts are inserted onto the threads and tightened down into the top of the casing, putting pressure on both the clamp and casing.

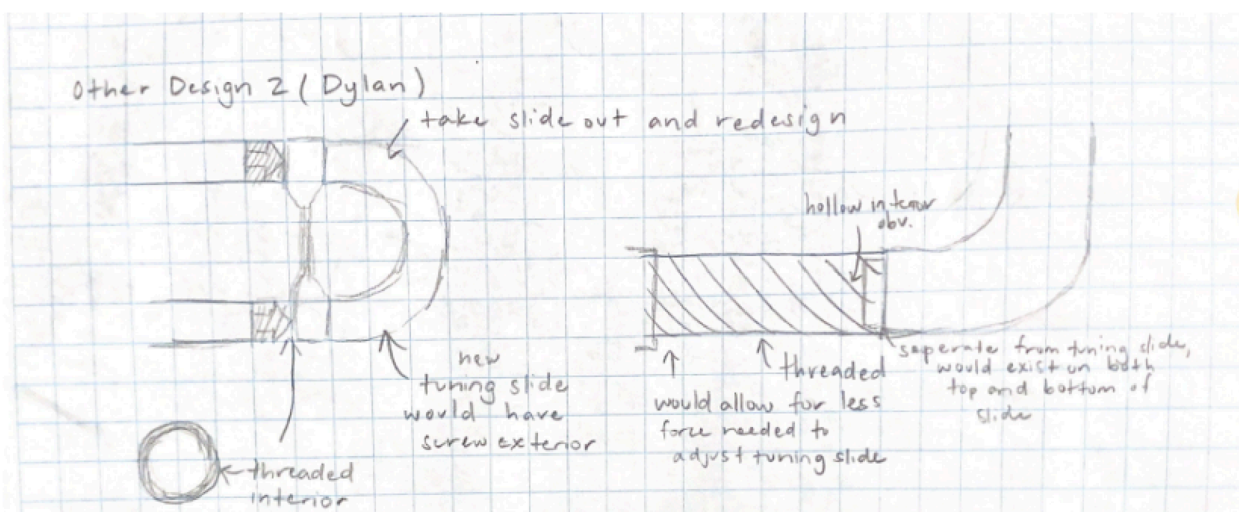
Other Designs

“New material?” by Dylan



We could also consider removing the entire tuning slide as well, and recreating it for our needs. We could replace it with a different material that would be more easily adjusted such as a rubber or a plastic. Changing the structure of the tuning slide to allow a motorized device to be able to move the slide may be beneficial, but also may compromise the sound. A structure that mimics the pop-tube kid’s toy could allow for easier maneuvering of the tuning slide for the motorized device.

“Tube screw” by Dylan



In order to reduce the amount of force the linear actuator must use, a new mechanism for the tuning slide that would be threaded on the interior of the trumpet and the exterior of the tuning slide would allow for readjustments while concealing nearly the entire mechanism. There would be difficulty in accurately constructing the parts with appropriate tolerance, but would also reduce the total force of the linear actuator required, possibly reducing the size of the mechanism as a whole.

III.3. Decision Selection with Matrices

For the linear actuator:

The linear actuator is a key feature of the device, allowing for the movement of the tuner. Within it, the actuator needs the appropriate force with the appropriate precision while being small, strict requirements considering the small budget. Another constraint of consideration is time, noted in the ease of construction criteria. Replacing the slide is an added design idea that would require additional concept generation and consideration, but is feasible depending on the logistics of the device so thus, added to the matrix but very vague. A store-bought linear actuator was also added to the design list for its versatility and time-constraint, although it encompasses a wide range of devices.

Each idea is considered on a scale from 0-4, where zero is rated as inadequate and four is rated as ideal. The scale begins at zero to compensate for very inadequate designs having inflated scores.

	Reliability	Precision	Force	Maintenance	Effect on timbre	Affordability	Energy consumption	Ease of construction	Total
Hydraulic	2	4	4	0	4	0	1	0	15
Screw	4	4	1	4	4	4	1	4	26
Ball-screw	3	4	4	1	4	1	3	2	22
Replace slide	1	1	4	3	0	3	4	1	17
Off-the-shelf	3	2	2	0	4	3	2	4	20

At 26 total points out of a possible 40, the screw linear actuator received the most points out of any design, followed by ball-screw and an off-the-shelf actuator. While a unique screw linear actuator could be created, as it is seemingly the best option, this would take a considerable amount of time, not even including the other logistical parts of the mechanism. With such variety in the market, an off-the-shelf linear actuator is like the best option as these would have varying options and score differently, even considerably higher than the initial screw rating. As such, an executive decision to choose an off-the-shelf actuator will be taken, but it will be in consideration with a screw actuator to maximize time and efforts for other logistical parts of the device.

For the attachment:

Each idea is considered on a scale from 0-4, where zero is rated as inadequate and four is rated as ideal. The scale begins at zero to compensate for very inadequate designs having inflated scores.

	Sturdiness	Ease of install	Durability	Total
Ringed design	2	4	2	8
Microphone mount	3	4	2	9
Band clamp	4	3	4	11
Interior clamp	4	1	4	9

At 11 points out of a possible 12, the band clamp is considered the best attachment design for the device. It would have the best sturdiness and durability out of all the designs, with its one downside in ease of installation, but in terms of quality of the device as a whole, this piece of criteria is least significant.

III.4. Consideration of Design Viability

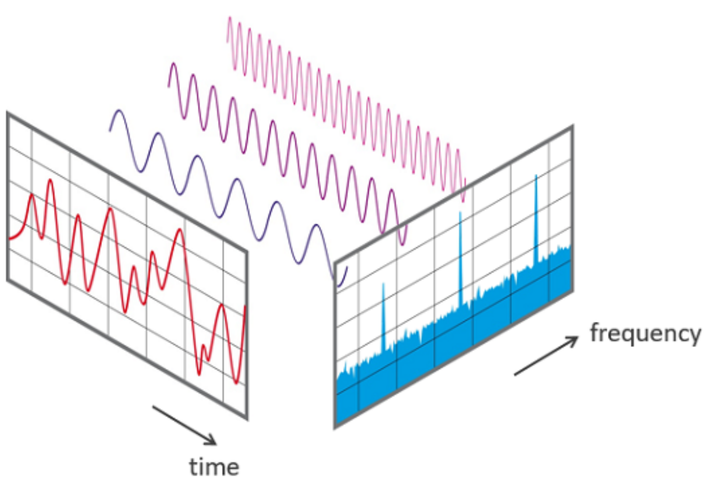
The device will be composed of an actuator that moves the trumpet main tuning slide, a body/frame that clamps to the inside of the two tubes, and a sensor that clips onto the bell to detect vibrations.

Electronic system

A piezoelectric transducer has been chosen to be the sensor, as clipping it onto the bell of the trumpet will provide an analog signal of the vibrations produced by the trumpet while being less susceptible to the interference of other sounds or instruments. This signal will then be wired to an Arduino Nano Every microprocessor, which processes the signal using filters and a Fast Fourier Transform to isolate the base pitch and find the closest 12-equal-temperament pitch, sending a PWM signal to the motor controller. The system will be powered by a 12V battery with a 2.6A capacity and a maximum draw of 5A.

Fast Fourier Transform

The Fast Fourier Transform (FFT) is an optimized algorithm of the Discrete Fourier Transform (DFT), which takes an analog signal sampled over multiple points of time (magnitude to time) and transforms it into a frequency domain of magnitude to hertz. DFT has a complexity of about O(N^2) while FFT has a complexity of O(N log N), which is a great improvement over the original algorithm. For these algorithms to accurately extract the individual frequencies, their sample rate must be at least double that of the maximum expected frequency that should be detected.



[18]

The Fast Fourier Transform would allow us to take the analog signal from the piezoelectric sensor attached to the bell of the trumpet, sample it with our Arduino Nano Every, and then use the FFT to get a list of frequencies and their magnitudes. Then it would filter out all other frequencies created by noise, as well as all of the additional frequencies produced by the harmonic series of the trumpet, and obtain the pure fundamental frequency of the note being played. However, we have to ensure that our analog signal remains as intact as possible, which would require shielding to prevent EMF interference. This project will use the open-source *arduinoFFT* library created by Enrique Condes.[19]

Actuator

Having previously determined that a screw mechanism would be the best choice, the AWINLI 2 Mini Linear Actuator, a pre-assembled form of the mechanism, would be a significant timesaver in prototyping. It is capable of providing up to a rated 60N of force, which is more than a sufficient force according to a quick survey that was performed measuring the force required to overcome the static friction of the main tuning slide.

Trumpet	Gavin	Wyatt	Patric
Force (N)	11.05	46.87	71.47

It was determined that designing this device to function for more than 60N of force is in vain without first cleaning and sanding the slide to reduce the frictional force required to move it. Also, with Gavin's trumpet requiring the least amount of force and a valuable friend who's trumpet we would have access to easily, all future dimensioning, prototyping, and testing is with his same trumpet.

The actuator should provide sufficient force to move most well-cared-for trumpet slides while drawing a peak 2.6A at 12V, which is within the capacity of the battery. However, there are uncertain effects of the exact noise levels generated by this actuator, and thus only future testing will reveal whether it is reasonable to degrade the overall sound.

Body

The body of the device will be 3D printed using a currently undetermined material. The components have been ensured to fit within the form factor of the trumpet tubings, however there is a chance that the cumulative assembly will have to protrude outside of the domain slightly. There is likely no other effect of the product other than degraded aesthetics and a slightly increased mass.

IV. Constructing and Testing a Prototype

IV.1. Product Design and Planning

As previously discussed, a solution was hypothesized from the decision matrices. Parts were ordered and the configuration of how to put each component was discussed. A document was produced to organize the dimensions of each component and subsequently, could be modeled and an isometric sketch could be produced to depict all the parts in the trumpet itself. Visualizing the product and components is vital to ensure that the product could conceptually work, for continuation of modeling and commencing prototype processes.

List of items to be purchased

#	Part	Cost	Function
1	Arduino Nano Every	$17.90	Microcontroller
2	L298N Motor DC Dual H-Bridge Motor Controller	$9.99	Motor controller for linear actuator
3	Li-ion battery, 12V 5A 2.6Ah	$20.99	Rechargeable battery for QoL
4	AWINLI 2 Mini Linear Actuator	$32.99	To move the slide
5	1/2 inch cable clamp	$8.99	To affix the device to the trumpet
6	20PCS 20mm Piezo Disc Transducer	$7.99	Sensor
7	Bridge rectifier	$5.99	Converts AC to DC
8	5pcs DC 5-30V to 5V Buck	$9.59	Voltage regulator

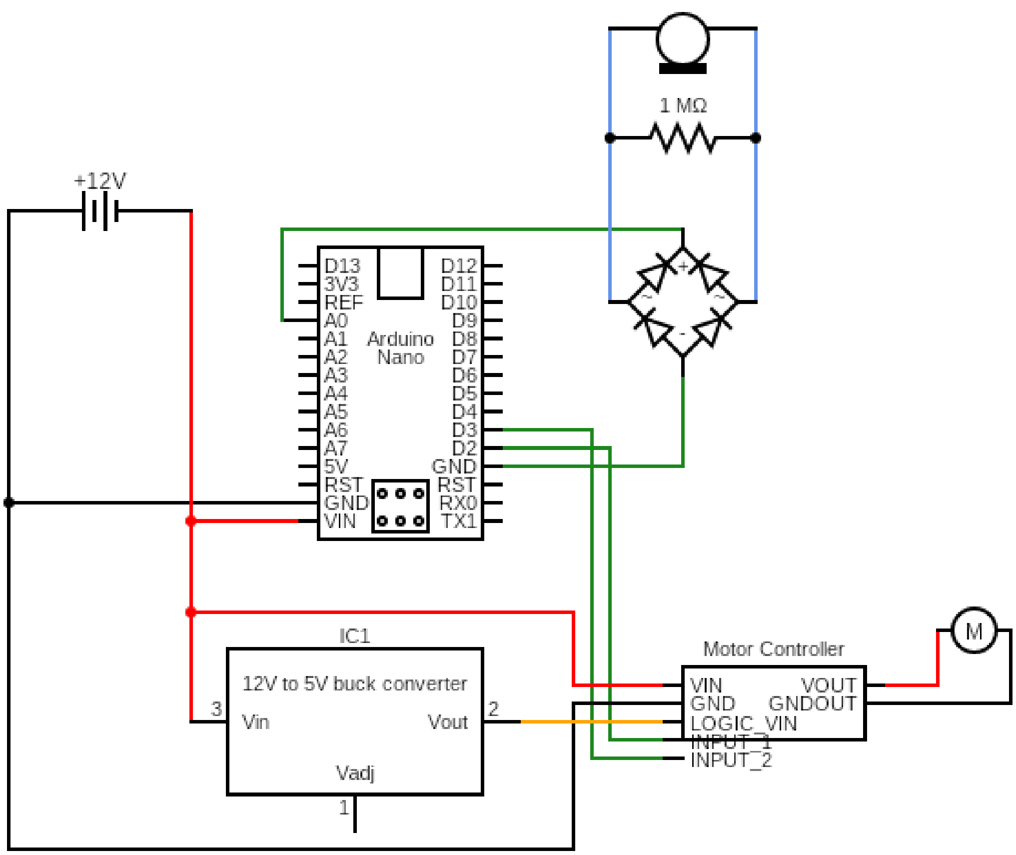
Total Cost: $114.43

List of items to be manufactured

#	Part	Function
1	Slide clip	Affix the linear actuator to the tuning slide
2	Case	Hold all the major components
3	Piezo attachment	Affix the piezoelectric sensor to the bell
4	Circuit	Control the linear actuator to move based on inputs

Initial circuit

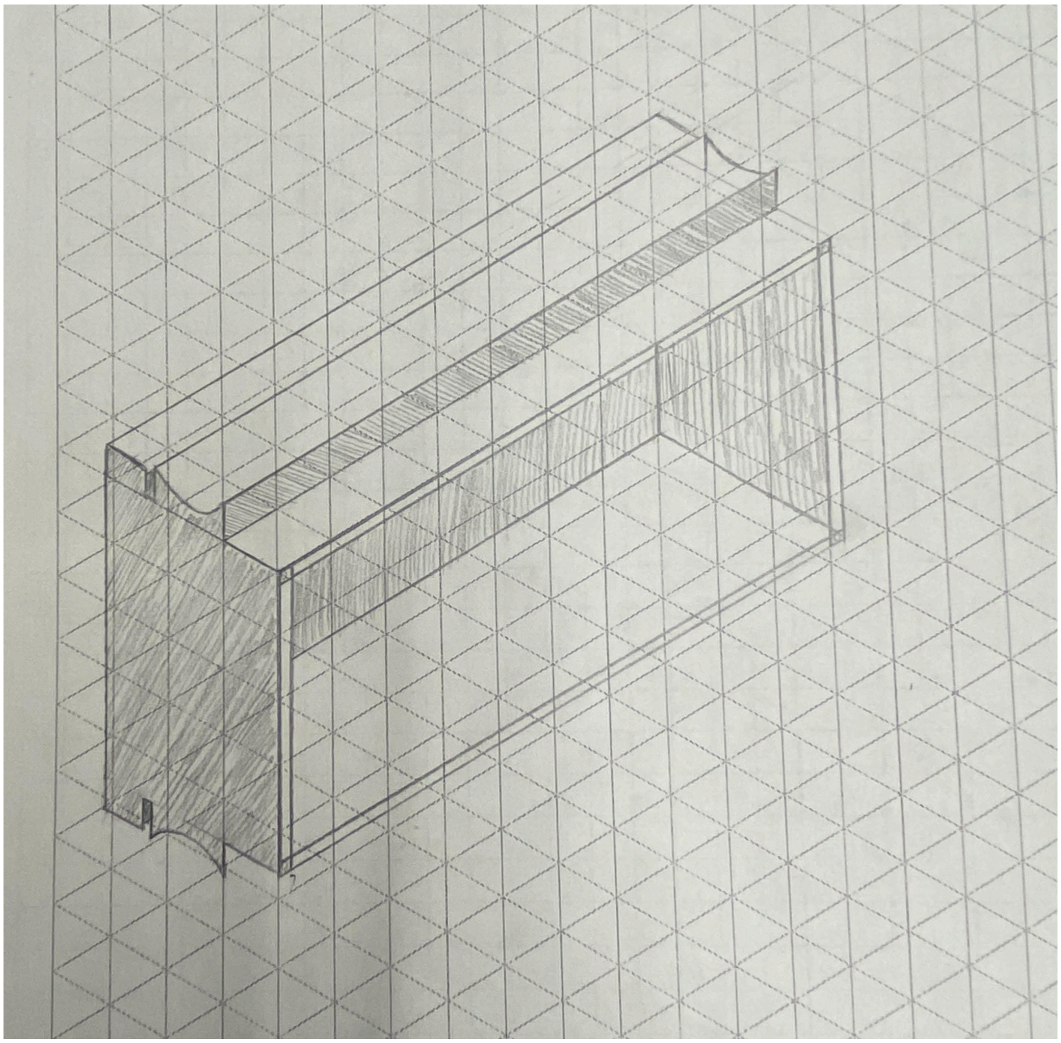
Below is the initial circuit drawing featuring the Arduino Nano as the microprocessor; an outline for the wiring inside the physical construction of the product.



This design does not include user interface components or the piezoelectric signal processing which was further developed later.

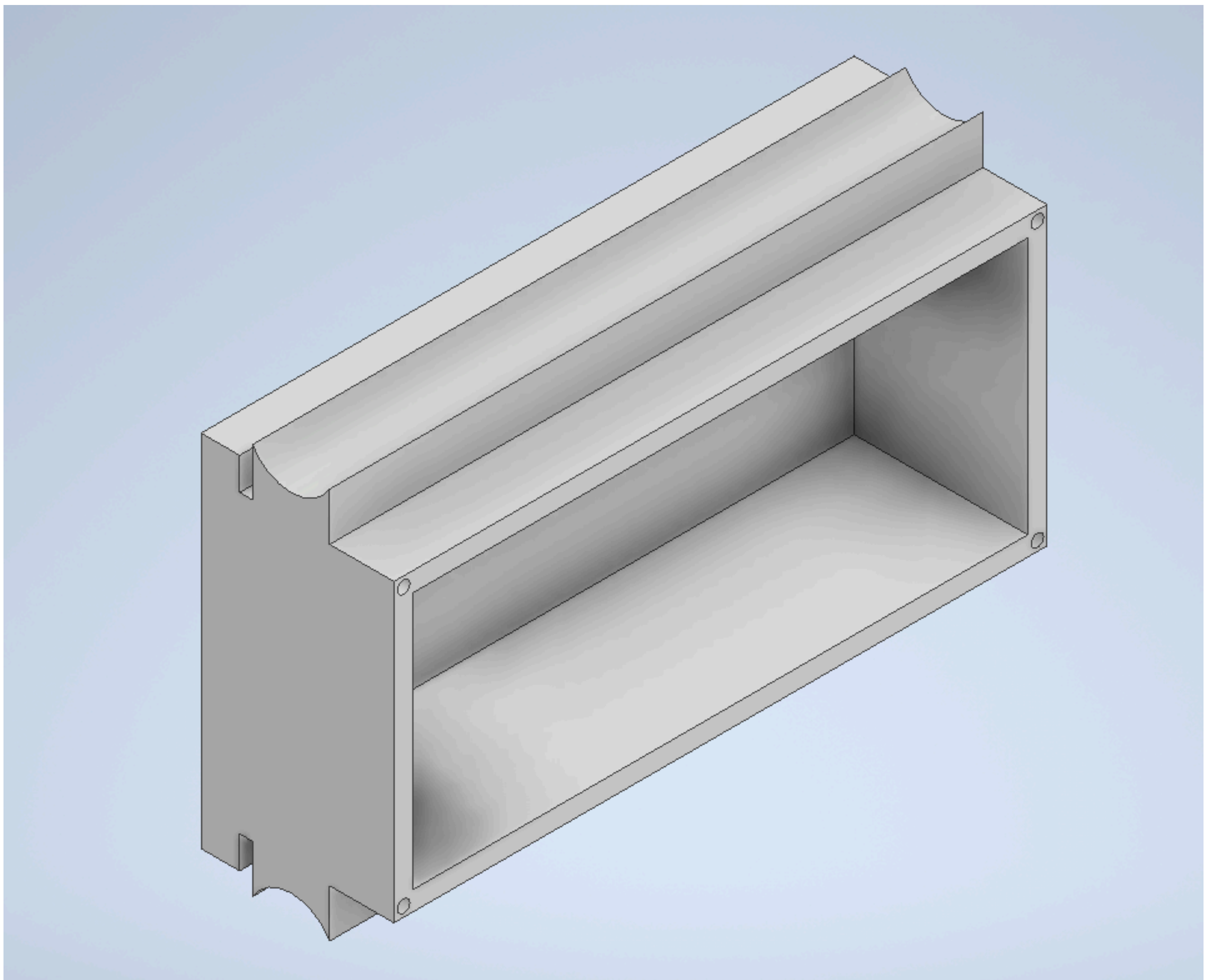
Isometric Sketch

Below is the isometric sketch of the product, nested in the trumpet, on its tuning slide.

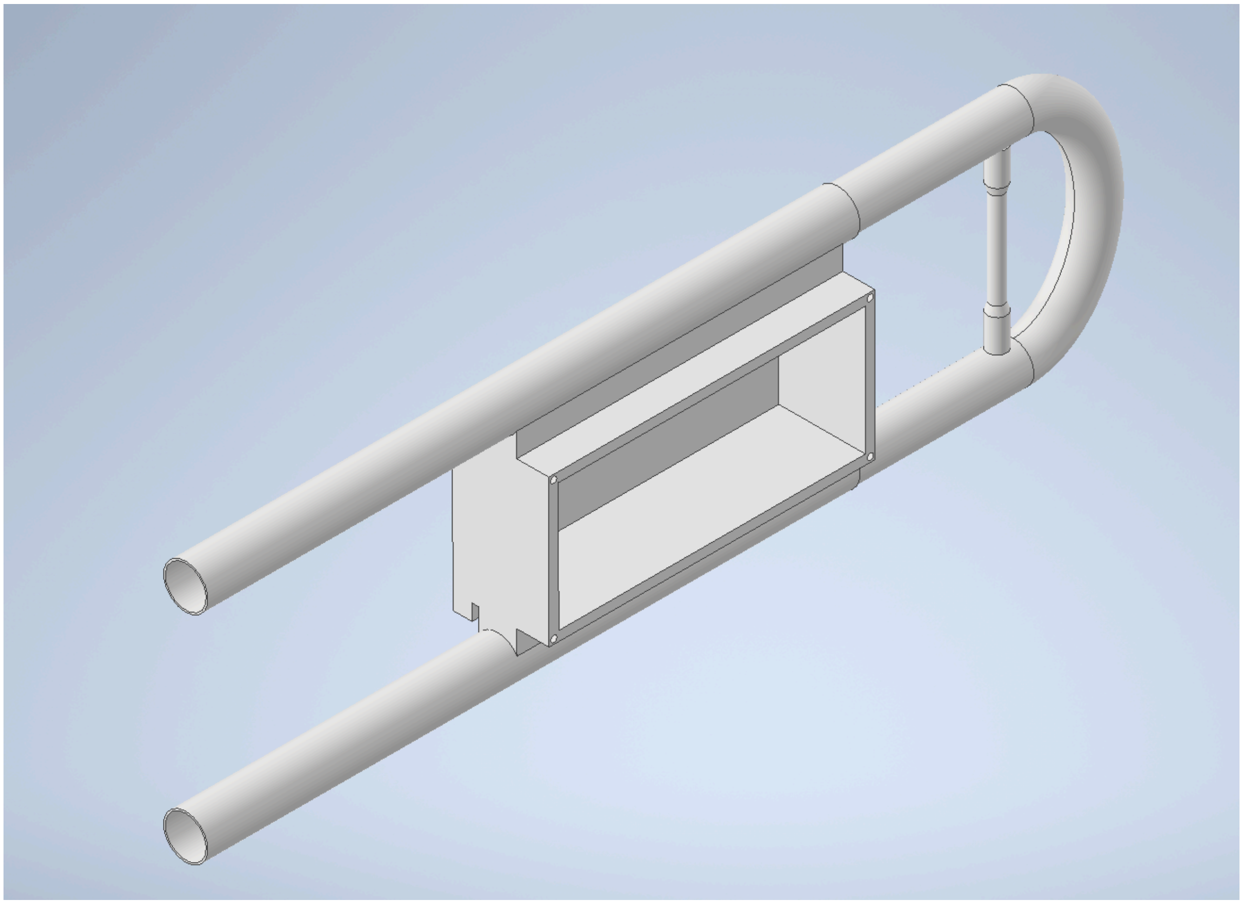


CAD Model

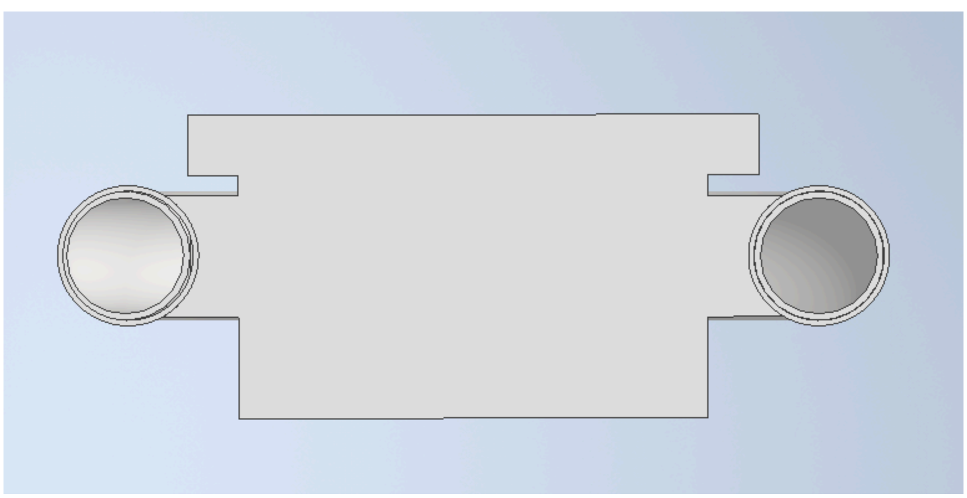
Below is the initial CAD model of the main casing of the device. It has a slot on the left to insert the straight end of the clamp, followed by a “cupping” for the trumpet tubes. Holes will be drilled at an angle to insert screws to tighten the clamps. Bores are provided in the corners to install the casing lid. This design will be modified as we receive the parts and are able to accurately measure mounting holes, in which we can then design seatings for the individual parts within the case and adjust dimensions if needed.



Below the casing is depicted sitting in between the trumpet tubes, in its installed position.



Below is the side view of the casing.



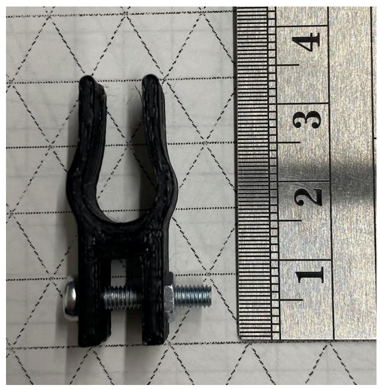
IV.2. Construction of a Testable Prototype

Mechanical design

Slide clip

The slide clip attaches the device from the linear actuator to the tuning slide. Its shape is quite precise and is vital to ensuring that the case with the device does not slide only the device and secures to the slide.

Slide clip print 1



This is the first model and print of the slide clip. The rounded center is intended to wrap around the tuning slide securely with the bottom screw and nut intended to secure around the linear actuator's end. The model was printed with 100% infill as well as all of its succeeding prints since the piece would be undergoing plenty of stress and needed to be strengthened. The radius of the center was doubled and incorrect and the space for the linear actuator could be given more tolerance. An extra location for a nut and screw around the tuning slide on the other side of the clip would be beneficial to secure the device. For a slightly nicer design, the nut of the screw could be embedded into the print.

<u>Slide clip print 2</u>

The second iteration was printed with the additional hole for a nut and screw, the correct radius, and seated nuts. While the clip could go around the tuning slide, it was extremely difficult to put on and remove, likely due to the walls of the clip being too thick. The seated nut for the linear actuator did not have enough clearance for it to fit nicely either.

<u>Slide clip print 3</u>

The third iteration introduced slightly thinner walls and seated nut adjustments. However, the last print also had issues with the skirt and due to a time constraint, Print 3 was printed without the skirt. While the thinner walls proved to be the best clip securing onto the trumpet, the filament at the bottom surrounding the linear actuator flattened and did not fit nicely.

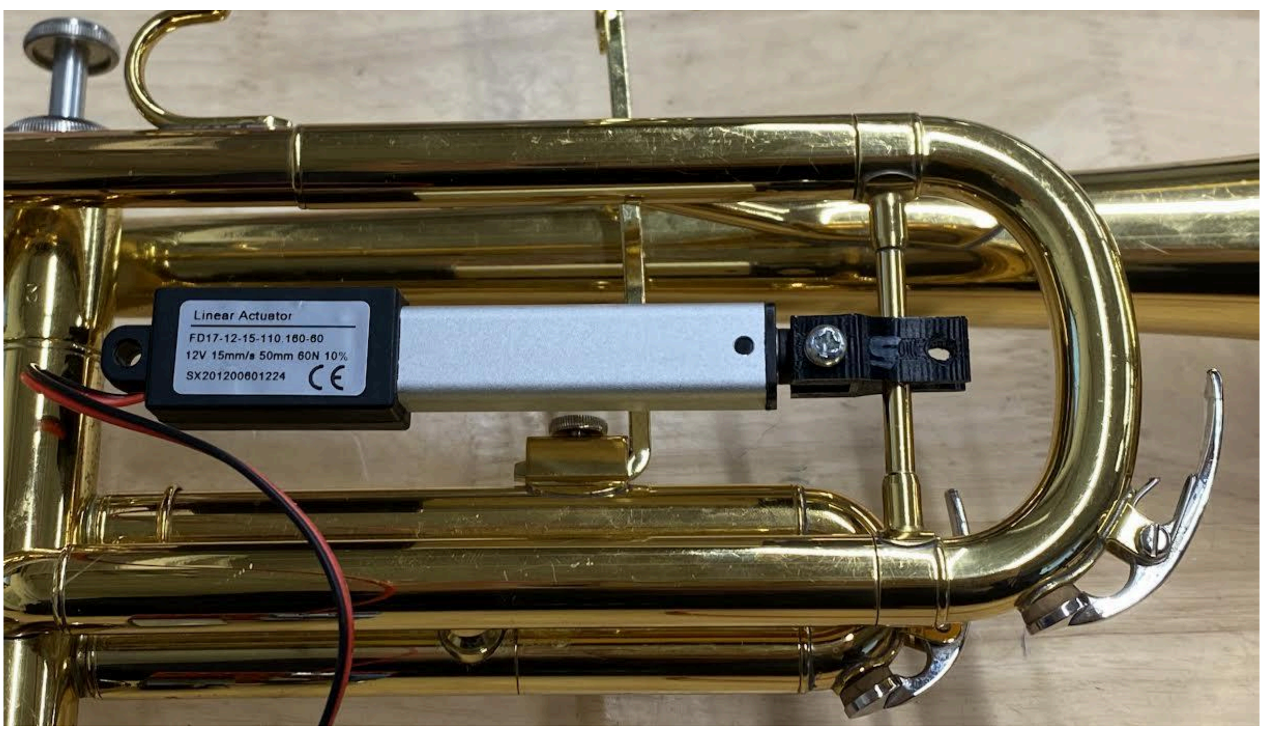
<u>Slide clip print 4</u>

The fourth iteration had fixed upon all of the previous issues and fit around the trumpet nicely. The rectangular hole for the linear actuator was given a sloped top to fit around the linear actuator more snugly and this clip was used pretty frequently while other parts were worked on. While the clip functioned very well, this resulted in cracks along the sides of the clip that introduced a new design to increase its longevity.

<u>Slide clip print 5</u>

The final print is the fifth iteration of the clip, utilizing thin yet sturdy walls to stay firm to the tuning slide. It also holds seated nuts to fit nicely around the trumpet and the linear actuator.

Below is the slide clip affixed to the tuning slide and the linear actuator.

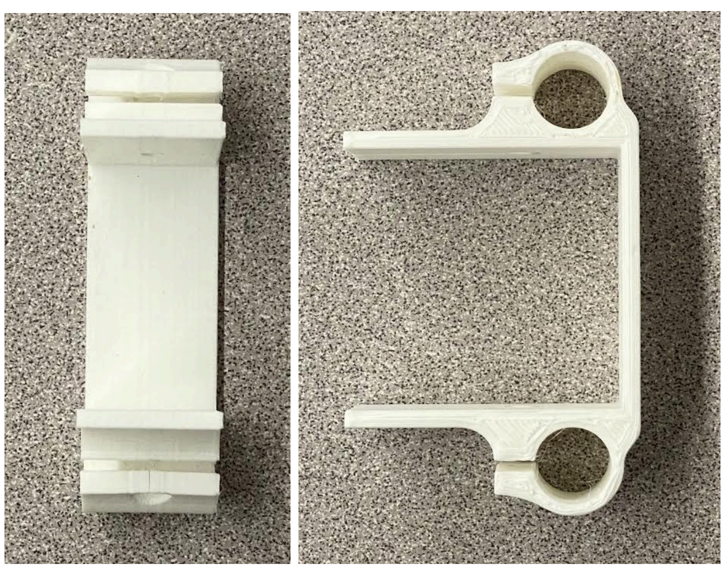


Below are all five prints of the slide clip in chronological order from left to right, with the final rendition being the last.

Case print tests

The case is intended to wrap around the trumpet tubes that are connected to the slide and then hold a rectangular shape that nests all the external pieces. A test print was initially done to ensure that the holes were of the right tolerance and to check the clearance with the other tubes and the wire.

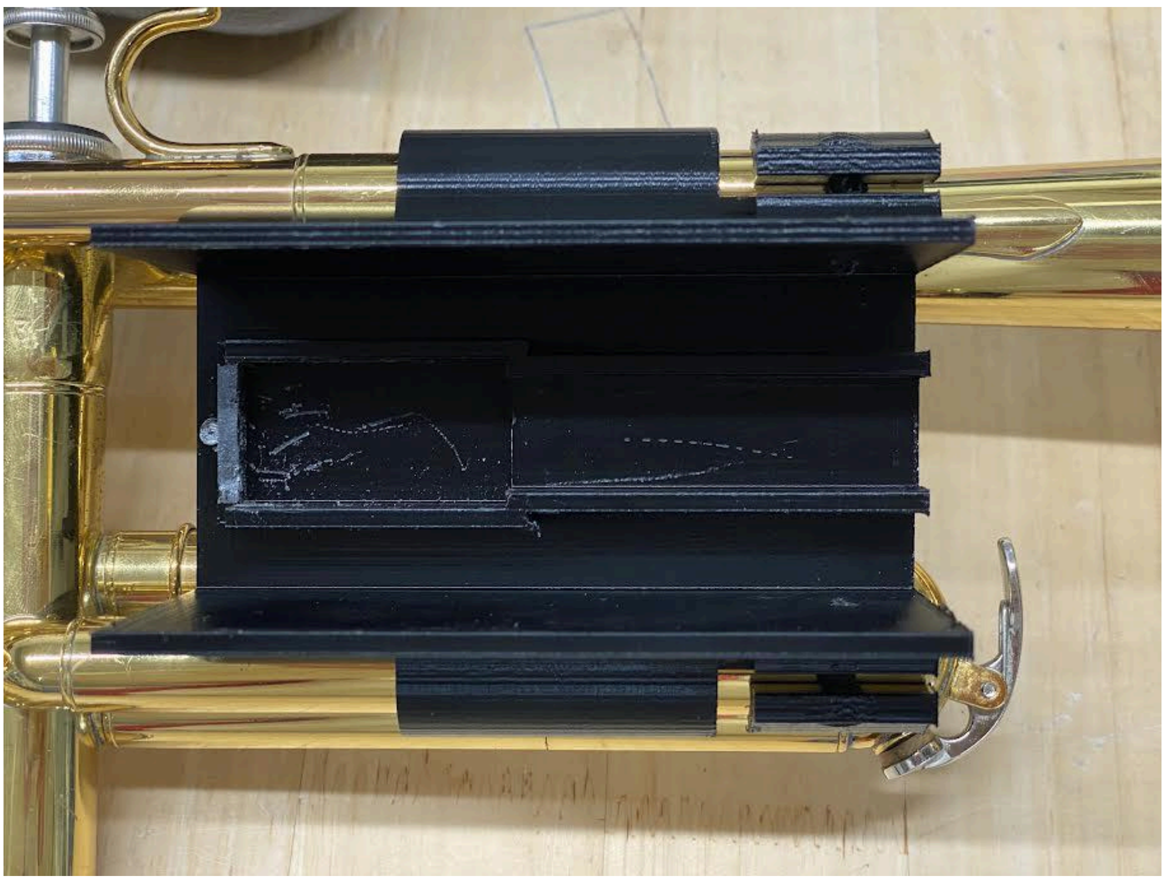
<u>Tubing test print</u>



The tolerance on the tubes was perfect, and a mechanism was added to ensure that the case would clamp onto the tubes securely as to not move the case when the linear actuator activated. The depth of the rectangular connection also allowed a visualization for possible configurations of the physical components. This print had the axis of the holes perpendicular to the 3D printing plane to ensure the holes would have no supports interfering on their interiors to affect the tolerance.

Case print test

The case is intended to hold all of the physical components namely: the Arduino Nano, the linear actuator, and the motor controller, and the battery as well as most of the wires connecting them. A rudimentary version of the case was modeled in planning that has been further developed. It yields a cut out and a dowel to nest the linear actuator, and rings outside to fit the trumpet tubes. The rings have a cut out for extra attachments on the trumpet and a gap with a hole for a screw as a clamping mechanism to secure the case firmly to the trumpet as to ensure it will not move with the linear actuator. This case is also considered rudimentary in order to figure out an effective configuration for each of the parts.



This prototype was printed vertically with the holes of the tube facing upward, as they are the critical dimension and must be printed accurately without any support. The inner nest dimensions for the linear actuator fit it very well, however the larger rectangular portion in the back was nested too tall to sit flat all the way; the dowel was also slightly misaligned, causing the linear actuator to not sit nicely as well.

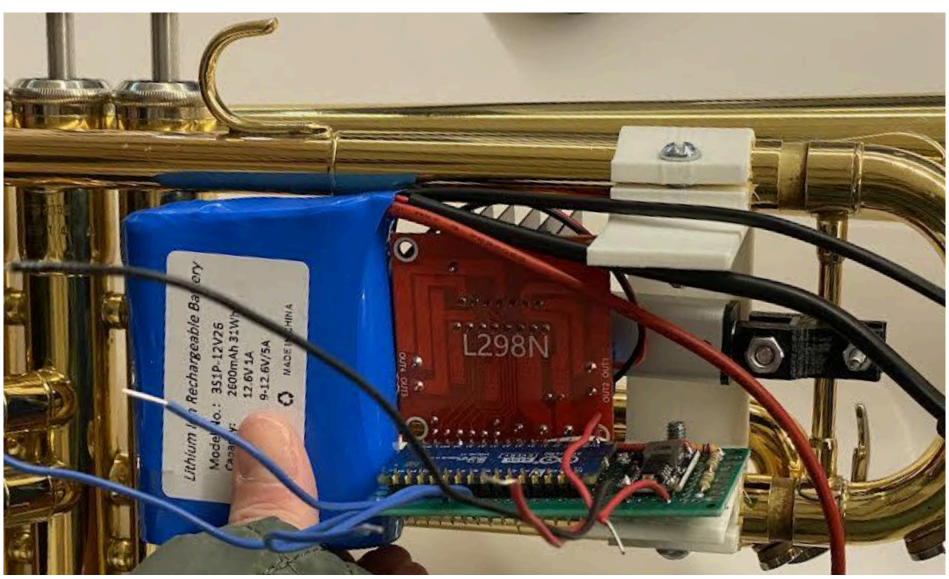
After jamming the various components into these rudimentary cases in various ways, we found a few possible configurations.

Configuration considerations

The linear actuator's location is fixed to be centered on the slide to allow the maximum efficiency of the force applied. The motor controller and the Arduino's location only need to be considered relative to one another for ease and practicality of wire connections. The battery's size is too large to fit the clearance in between the tubes in any configuration and the battery cannot interfere in the center of the trumpet. The battery cannot lay flat, centered on the trumpet due to the lyre (a piece to hold marching band sheet music) and cannot be significantly off-centered as to change the center of mass of the trumpet, providing a different handling experience for the trumpet player. Since the battery must be laid vertically, an extension of the rectangular case must be created to seat the battery.

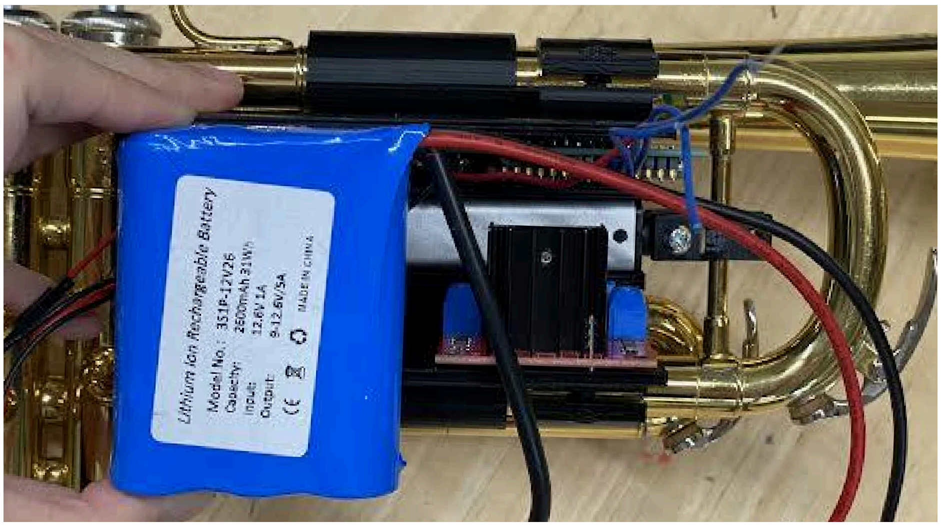
<u>Configuration 1</u>

Configuration 1 features the motor controller's heatsink sitting flush with the linear actuator and the top of the case. There is enough clearance to fit the Arduino underneath it with the soldered joints and wires; however, there is no configuration for the battery that allows it to fit within the trumpet tubes. This configuration also nests the battery lower on the trumpet, with its top in line with the other components. The battery cannot be much higher than this constraint due to encroaching on the finger hook, significantly affecting the player's comfort and performance.



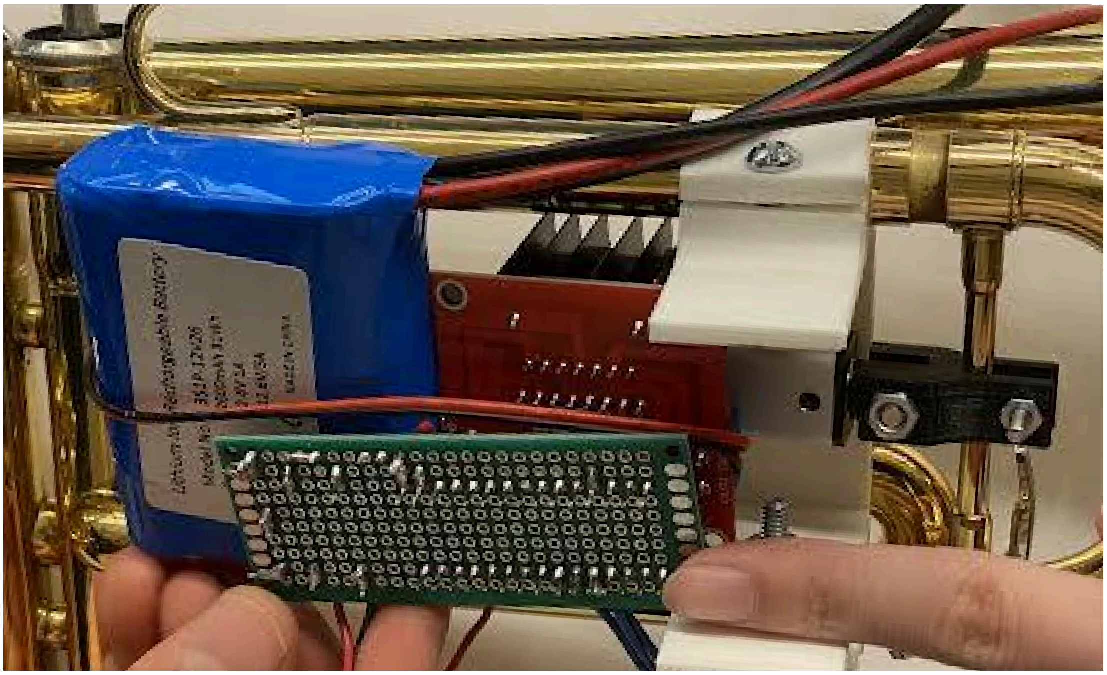
Configuration 2

Configuration 2 utilizes the same location of the battery as Configuration 1 but with swapped locations of the Arduino and the motor controller to fit the heatsink more effectively. The heatsink has more clearance to move around the linear actuator and the Arduino oriented in this manner allows much more of the wires to be exposed. Since there is more clearance on the components, a tighter case or additional stand offs for the pieces must be added to ensure they are secured so as to not damage one another.

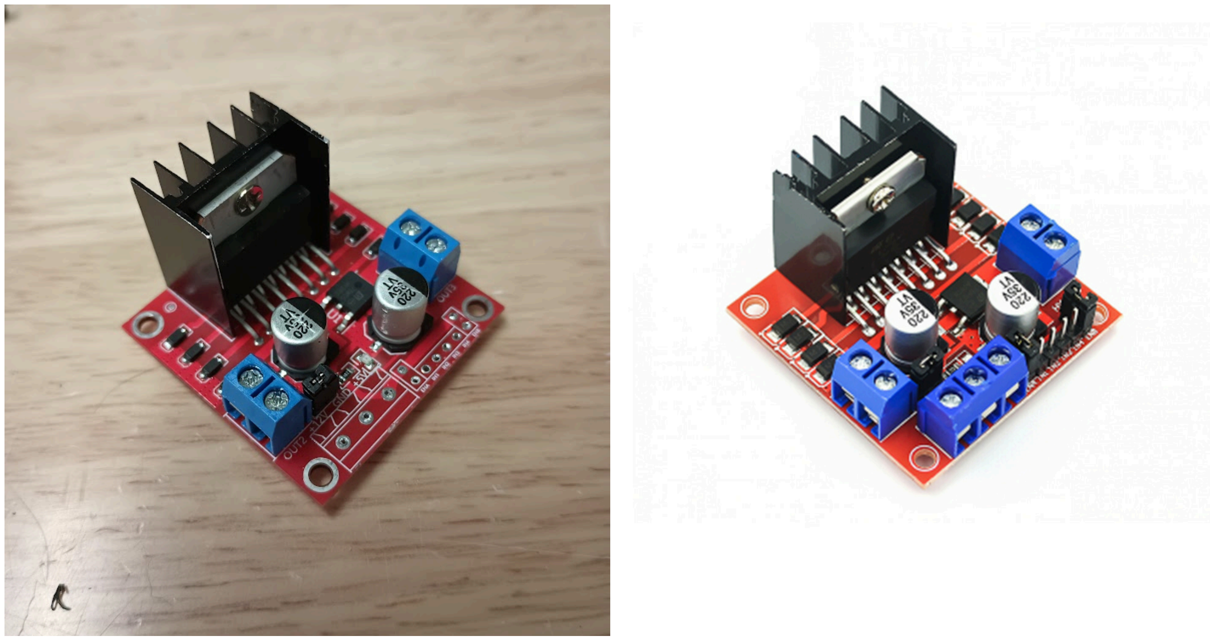


<u>Configuration 3</u>

Configuration 3 utilizes similar orientations of the battery and motor controller as Configuration 1, but the Arduino is laid with its bottom outward. This configuration minimizes the length of the case components, utilizing the full length of the motor controller's wires attached to the Arduino, wrapping tightly around the battery.



Configuration 1 was deemed the best configuration due to the heatsink's flush arrangement to the top of the case height limit while also fitting the Arduino in the same space. However, achieving this did require some modifications to the motor controller to be made removing terminals and pins, opting for more compact soldering instead**:**

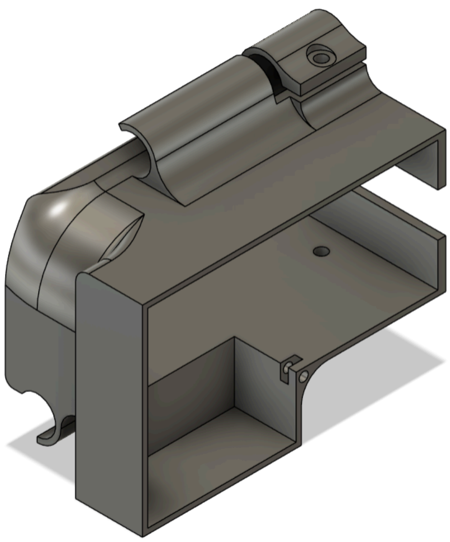
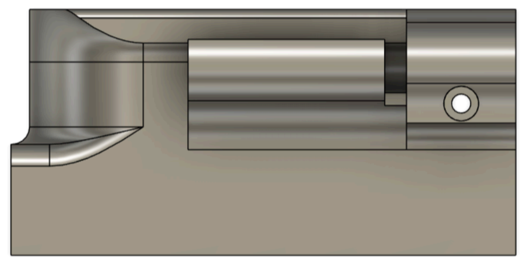
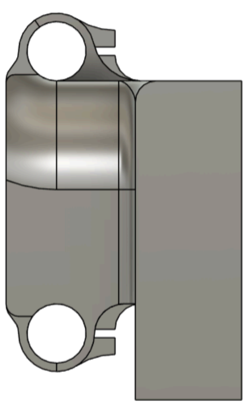
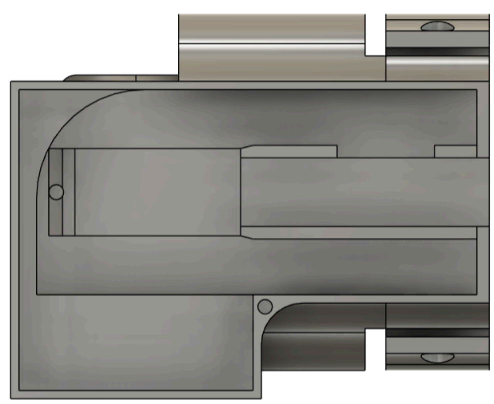


With our modifications (left), original form (right)

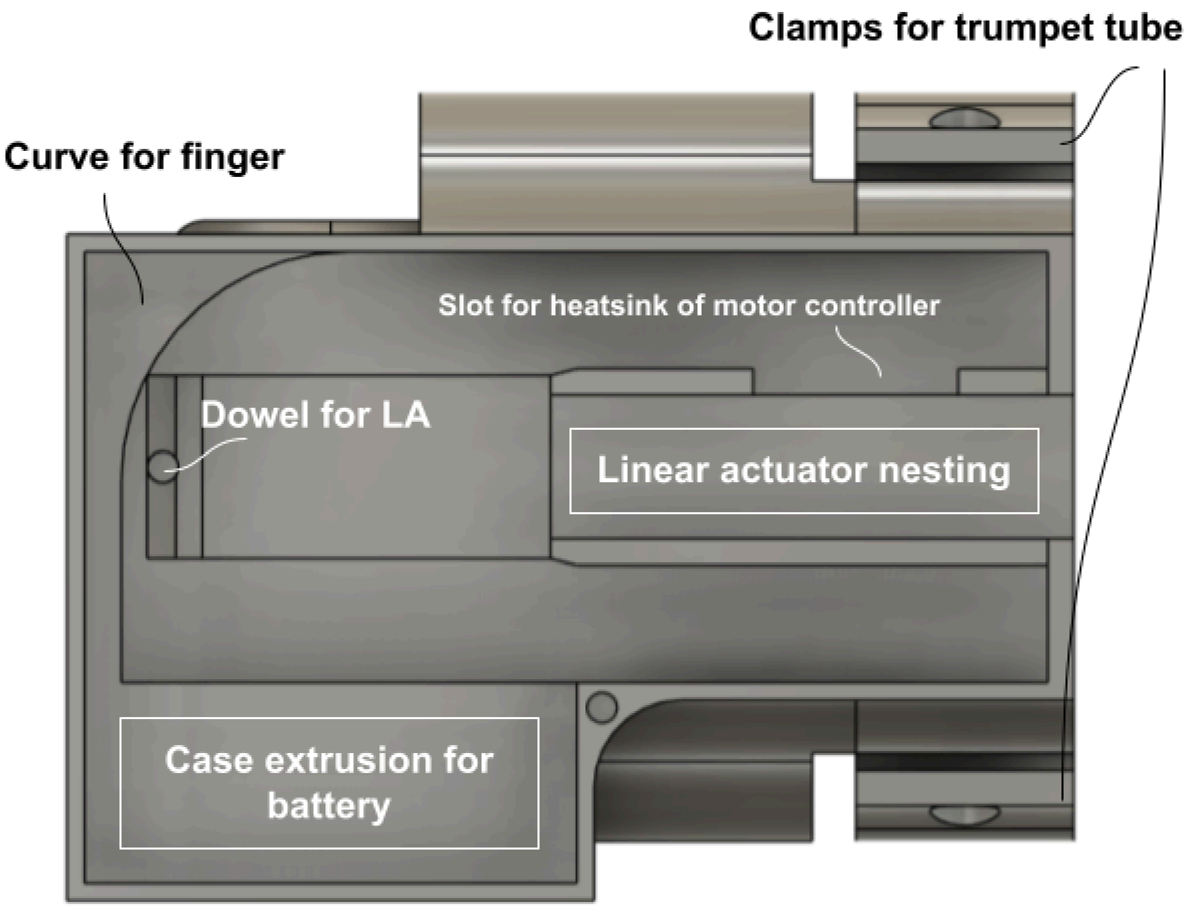
The configuration allows us to maximize the space we have vertically and in depth, rather than horizontally. The horizontal configurement is maximized by the linear actuator and a flush fit for the parts combined with design simplicity allows for less movement among the pieces, which could lead to damage. The only addition that would need to be made for the battery would be an extended seating.

Final Tuning Case

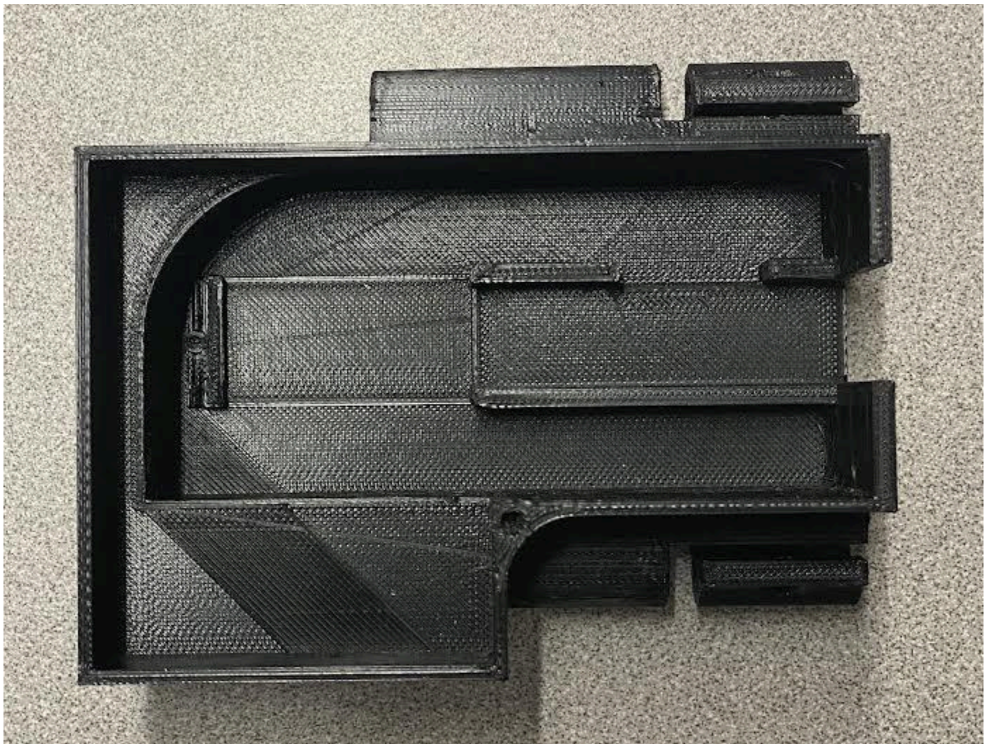
<u>Orthographic View (Left)</u>

Isometric 	Top 
Left 	Front 

Isolated Front View with Labels

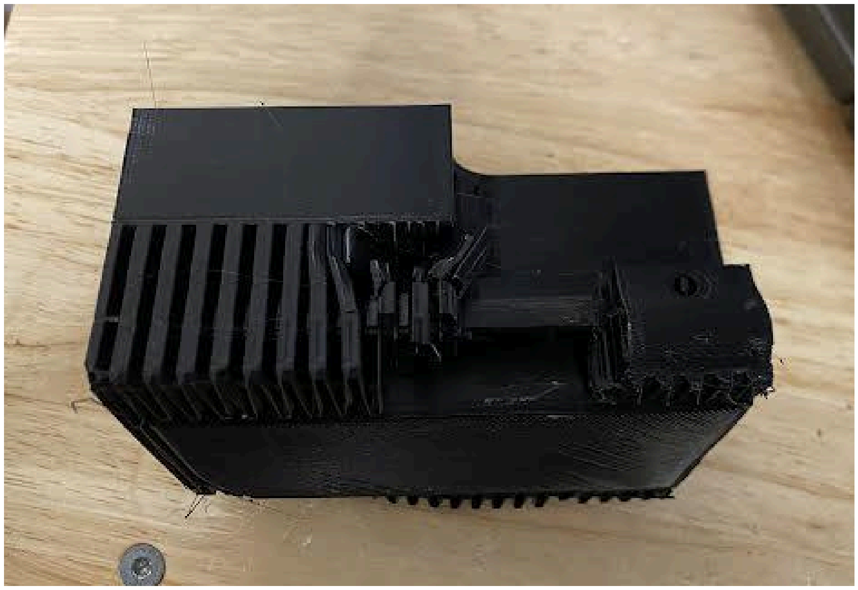


<u>Case 3D Print 1</u>



The first print of the case was decided to be printed with the axis of the holes parallel with the 3D printing surface. This would place all the supports on the outside and in the holes, leaving the inside clean of supports. This alignment and print setting puts any part with a greater than 60° overhang, including the underside of the battery extrusion and the inside of the holes.

Midway through scrapping the supports



The supports proved to be quite the problem with the base of the supports being firmly attached to the part. A one millimetre base would be printed wherever the supports were added, which also included the interior of the holes. And the quantity of supports around the entire part took a considerable amount of time to pluck off, with plenty of force and additional tools that may have warped the piece, too. After the majority of the supports were pried off, the hole interiors were sanded down to fit the trumpet tubes individually; however, due to the force used during the entire support-removing process, the holes were warped and could not both fit on the trumpet at once, requiring a new print.

Warped holes after sanding

It is good to note that the printing of the holes were considered before with the Tubing Test Print, however a vertical print would produce most of the scaffolding on the interior, which wanted to be avoided.

<u>Case 3D Print 2</u>

The second case was printed with the axis of the holes perpendicular to the printing plane, disallowing any supports on the interior of the holes. Unfortunately, most of the scaffolding was now on the interior which needed to be scrapped out. A support was created between the dowel and the top of the case which could not be removed smoothly resulting in the dowel needing to be removed wholly. However, this was not an issue due to the nesting for the linear actuator being very tight already, and putting the linear actuator on the dowel made it very difficult to remove.

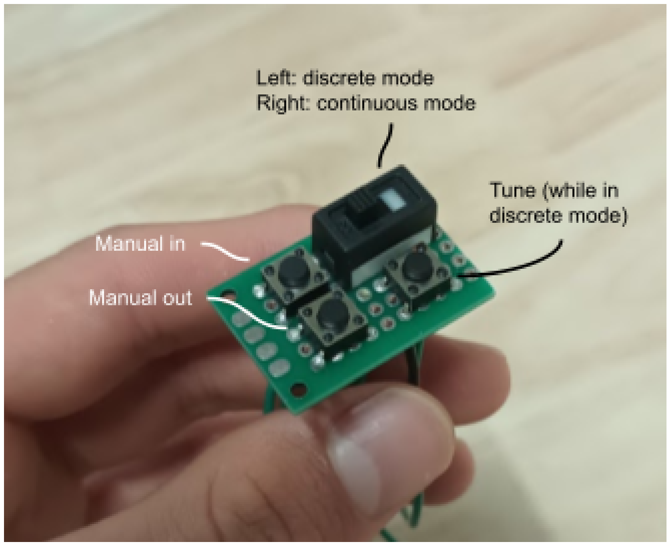
All of the later testing is done with this case.

Electronic Design

User interface

The following controls for the user of the device were determined as such:

- Power switch
    - Necessary to cut power to the device, when not in use and for charging.
- Manual out button
    - For the user to manually move the actuator out in the case that the device is tuning the trumpet to a note higher than it’s fingered note, due to it being so out of tune that it is closer to this higher note than the expected note.
- Manual in button
    - For the same reason as above but in the reverse direction, and also to force the actuator in for device dismounting and storing.
- Mode switch
    - The tuner was determined to have two modes, “discrete” and “continuous.” When in discrete mode, it tunes only when the “tune” button is pressed, in the case that the user does not want the device to automatically tune during a performance, instead only tuning when the user is currently holding the “tune” button down. Continuous makes the tuner continuously tune throughout playing.
- Tune button
    - Used for the aforementioned “discrete” mode.



Final protoboard construction

Piezoelectric signal processing

Since the piezoelectric transducer produces an alternating current that can sometimes produce high voltages (more than the Arduino's 5 volt rated input pin) and is affected by electromagnetic noise, the circuit design needed to:

- Rectify the source into a direct current signal in order to prevent a negative voltage from damaging the Arduino pin by surpassing its -1 volt lower limit, or simply reduce the voltage to never alternate at more than 1 volt.
- Reduce electromagnetic interference and other noise by increasing the impedance to filter out high frequencies.

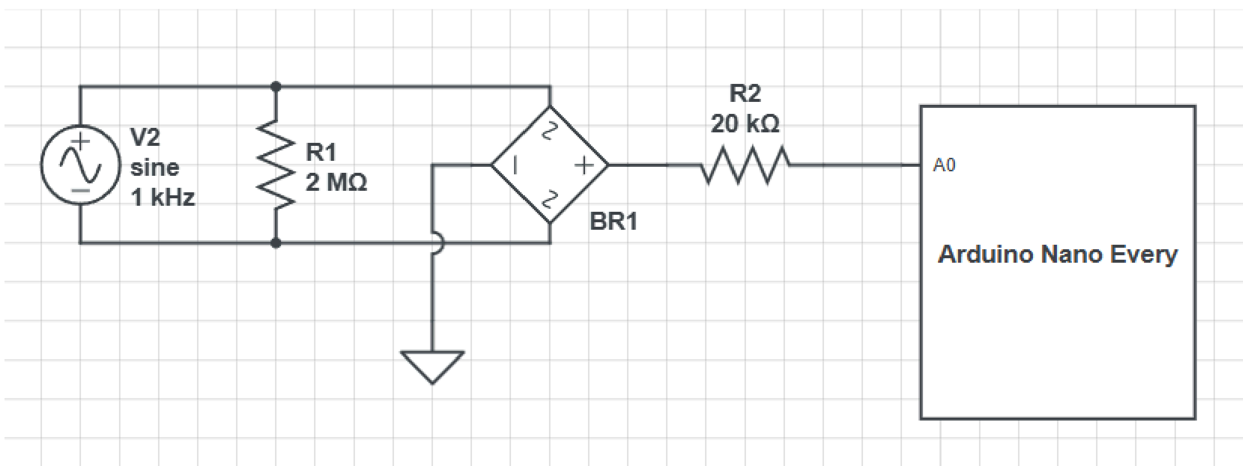
Thus, there were different approaches to process the piezoelectric signal for input into the Arduino:

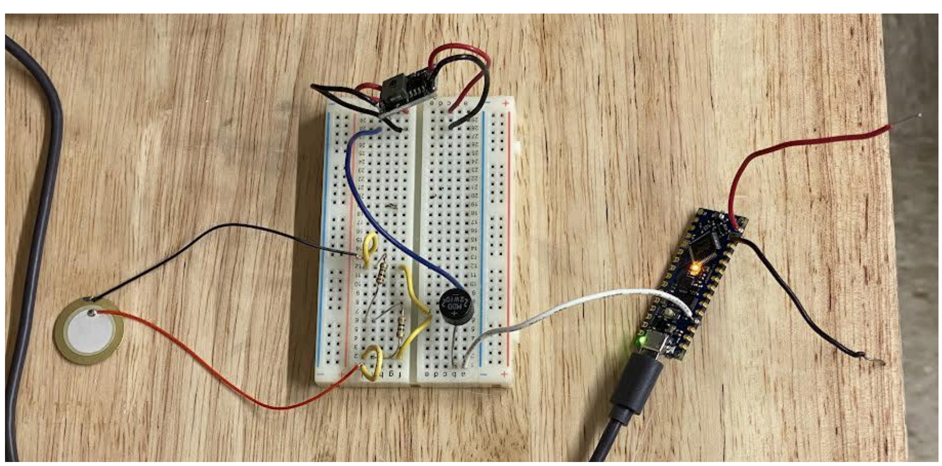
- Using a parallel resistor across both wires of the piezoelectric transducer to discharge the input capacitance and increase the impedance to help filter out high frequencies caused by noise and interference.
- Using a bridge rectifier to ensure that only positive current reaches the Arduino pin.
- Using a resistor after the rectifier and before the input pin in order to further reduce the voltage of the piezoelectric transducer.
- And using a capacitor to smooth out the signal, to further reduce noise.

In order to achieve a well-functioning circuit that achieves the aforementioned criteria, the following configurations were constructed and tested using a breadboard and the Arduino serial port analyzer to analyze both the raw voltage reading and a simple FFT testing program to display a frequency domain to check if it could properly analyze the frequencies.

The following circuits are not the complete list of configurations attempted; they are merely the main variants. The AC source is meant to represent the piezoelectric transducer, as the program did not have such a component.

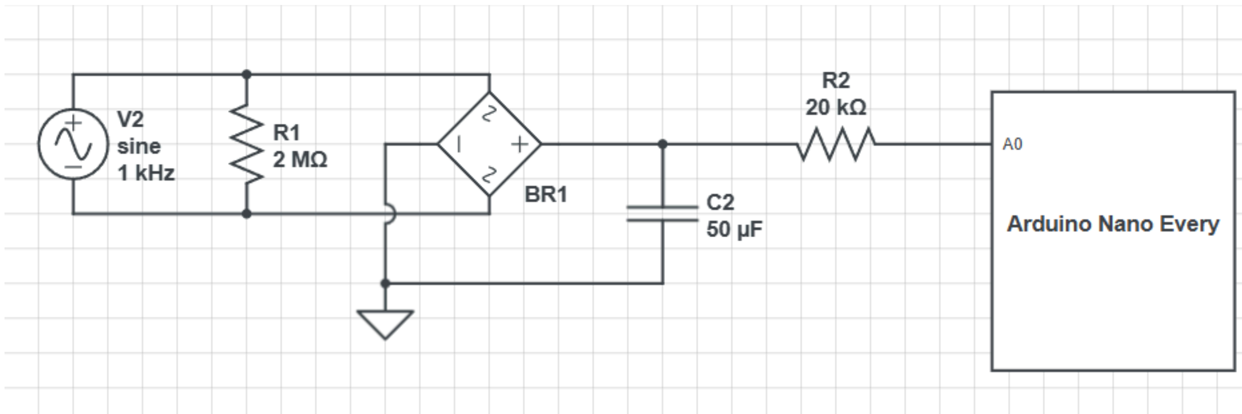
Circuit I

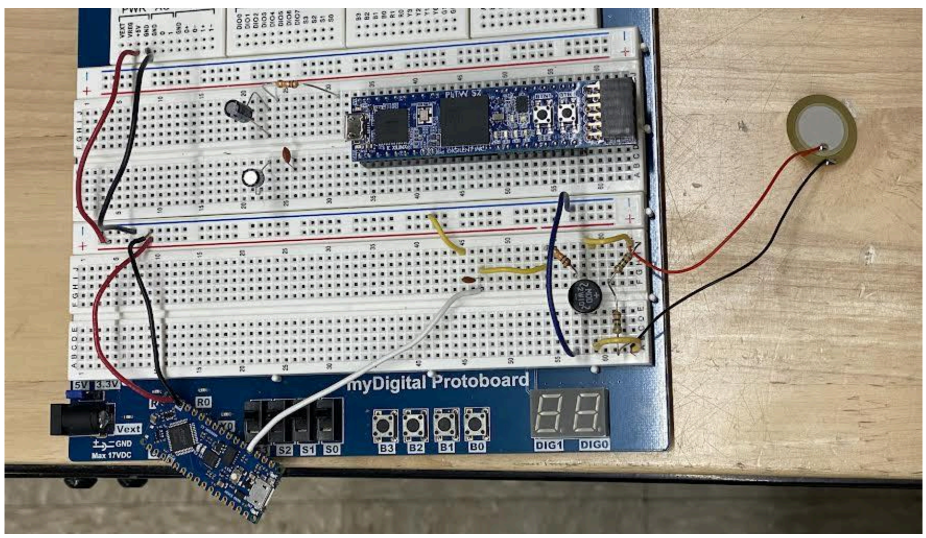




This circuit produced a range of voltages that gave good amplitude for FFT analysis, but the alternating current frequency produced a modulation in the voltage readings which made it unideal for FFT. The FFT itself did not accurately pick up frequencies.

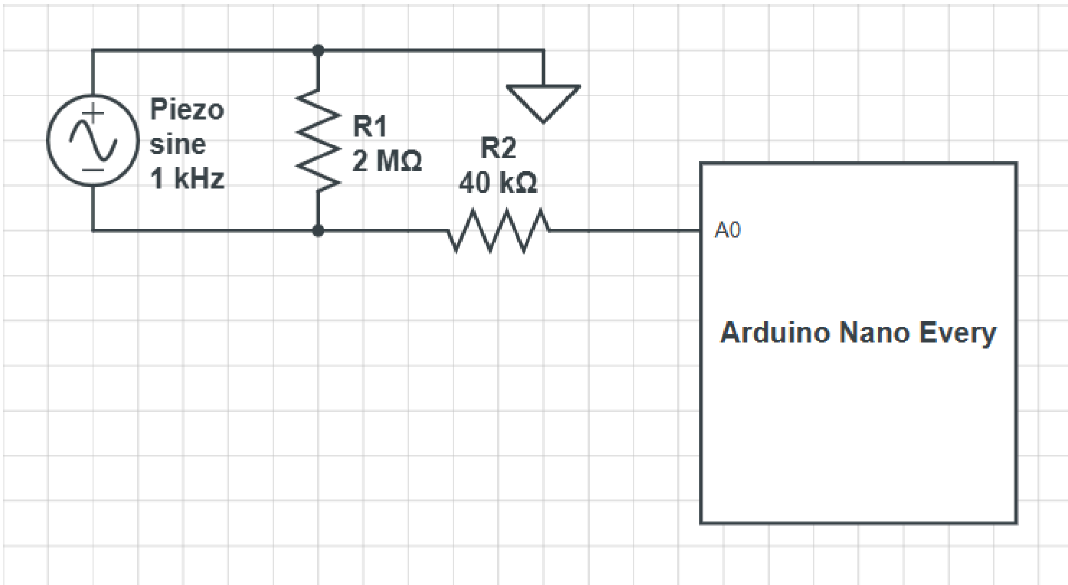
Circuit II





This circuit has an added capacitor in an attempt to further smooth out the signal. However, we did not have access to a capacitor with a small enough capacitance in order to not completely smooth out the signal beyond use.

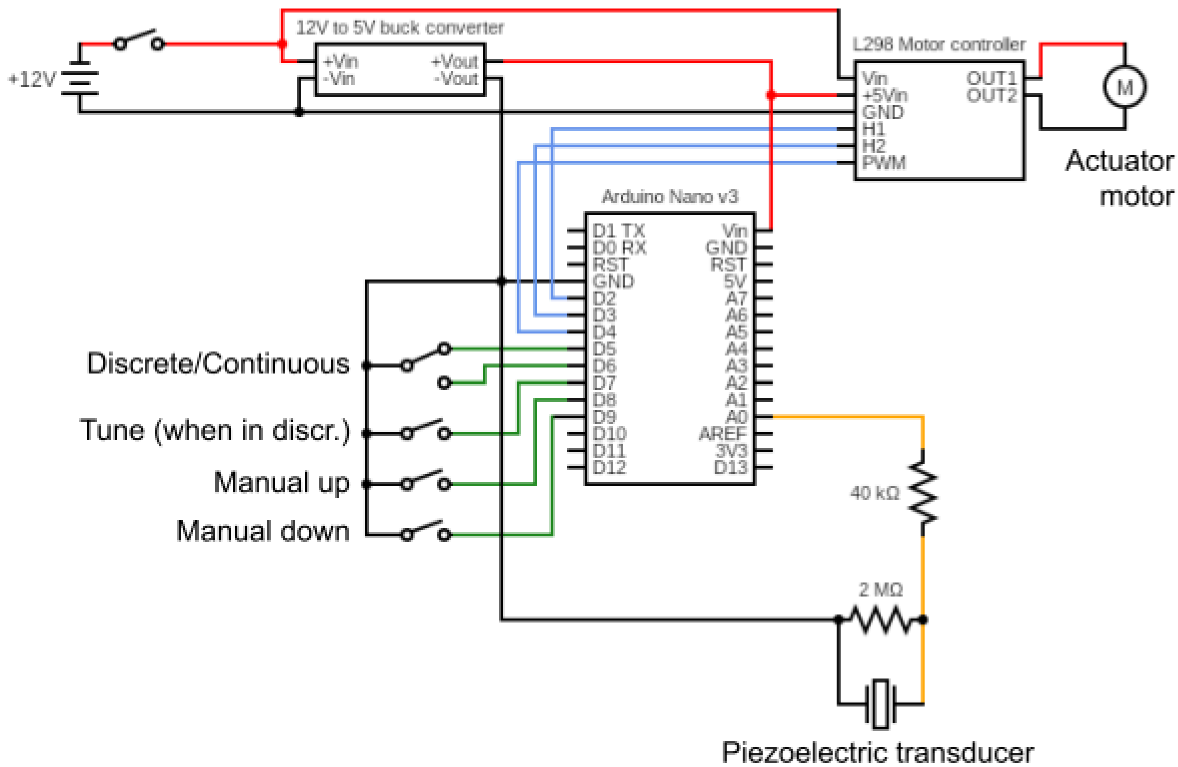
Circuit III



We tried removing the rectifier since it is not needed as long as there is sufficient resistance and the piezo is not struck too hard as to cause a negative voltage below -1 volt. Upon testing, the signal was significantly cleaner, and the FFT started working far more consistently than with the rectifier, despite the smaller amplitude in signal (due to the increased resistance for safety of the arduino). This was our final piezoelectric signal processing circuit.

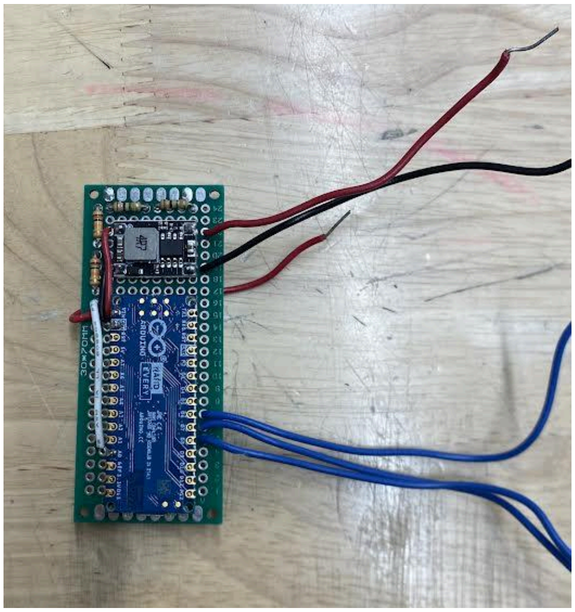
For a future version of this prototype, it might be beneficial to use an operational rail-to-rail amplifier in order to further ensure the safety of the arduino by limiting the voltage from 5 volts to -1 volts and amplifying the signal to have a greater amplitude, which might be easier and more accurate for the FFT to process.

Overall circuitry

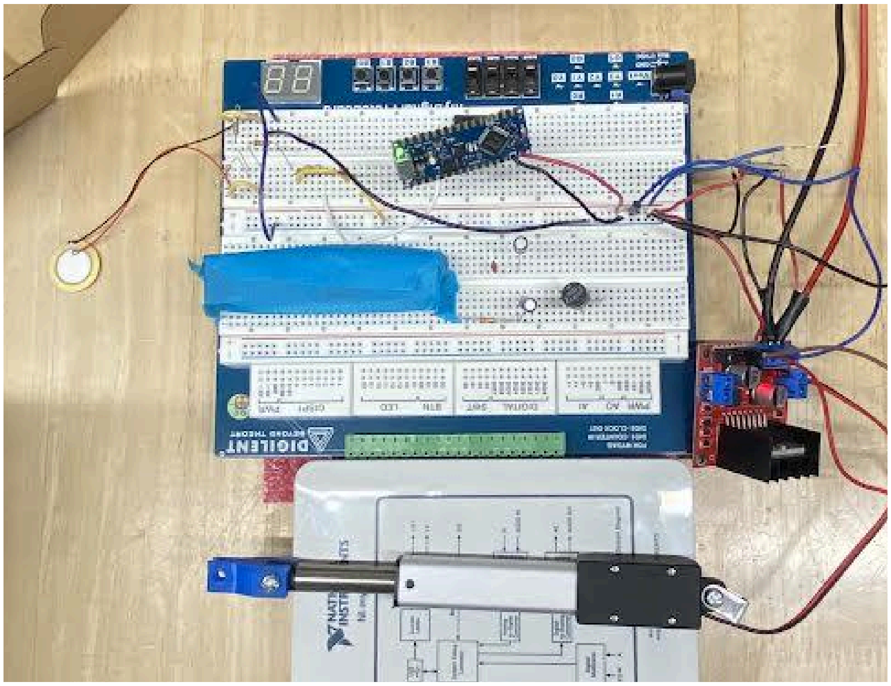


Final circuit diagram. We use pull-up resistors to read the switches.

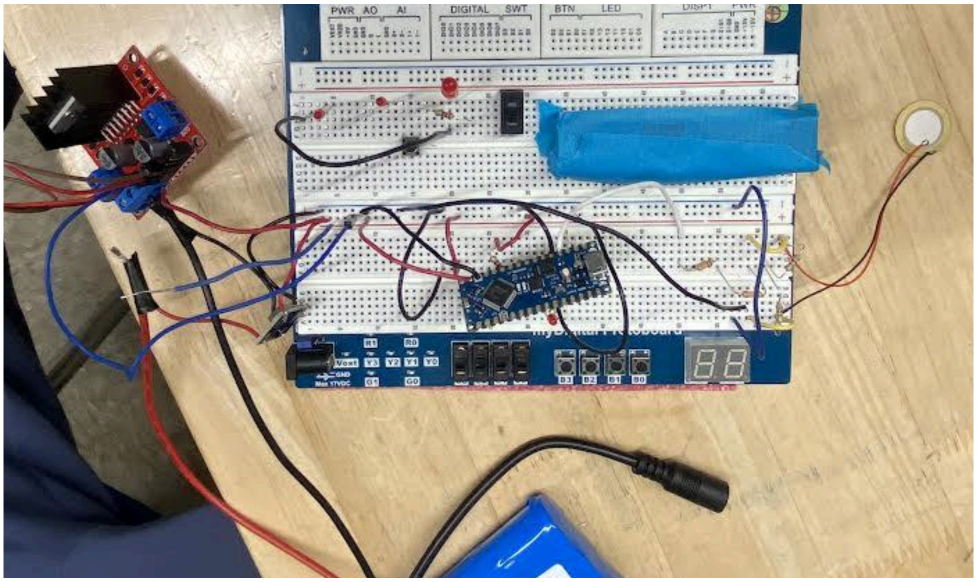
Arduino protoboard soldered with power and motor controller connections



All circuitry (not fully interconnected) on breadboard, excluding user interface connections



Circuitry setup for testing user interface connections



Fully soldered circuit, with interface protoboard

Arduino program

After creating multiple small programs to test the FFT library and testing various circuit configurations, the main program was beginning to be created.

Finding the tune of the detected note

Musical tuning is measured in cents—the percentage between the current fundamental frequency and the corresponding note in equal temperament. Since musical note frequencies vary logarithmically, ie. an octave above a note is double the frequency, an equation needed to be developed to linearize this scale into some that could be used to find the nearest note frequency to the measured fundamental and threshold it to move the actuator.

To find the frequency *f* of a note *N* semitones relative to a reference note (*r* = A4 = 440 Hz) the following equation is used:

$$f = r \cdot 2^{N/12}$$

Solving for N produces a value that indicates how many semitones off the measured fundamental *f* is from the reference *r*.

$$\frac{f}{r} = 2^{N/12}$$

$$log_2(\frac{f}{r}) = N/12$$

$$N = 12 \cdot log_2(\frac{f}{r})$$

Plugging in the reference of *r = 440*:

$$N = 12 \cdot log_2(\frac{f}{440})$$

However, since the Arduino math library only supports log base 10, the change of base formula must be used in order to get an equivalent in base 2:

$$N = 12 \cdot \frac{log(\frac{f}{440})}{log(2)}$$

Now this can imputed as a function into the Arduino code:

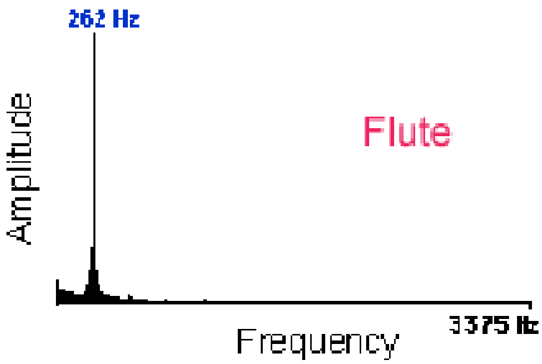
```
float calculateCents(float frequency) {
```

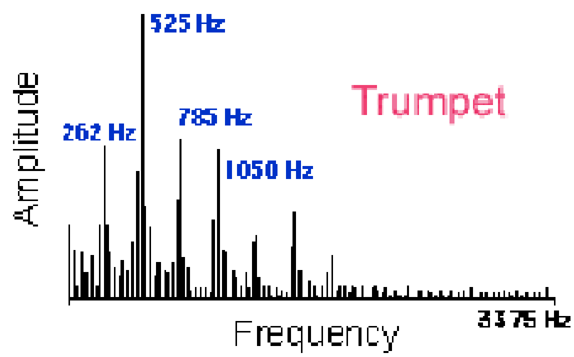
```
    float fromA4 = 12 * (log(frequency / 440) / logTwo);
    return fromA4 - round(fromA4);
}
```

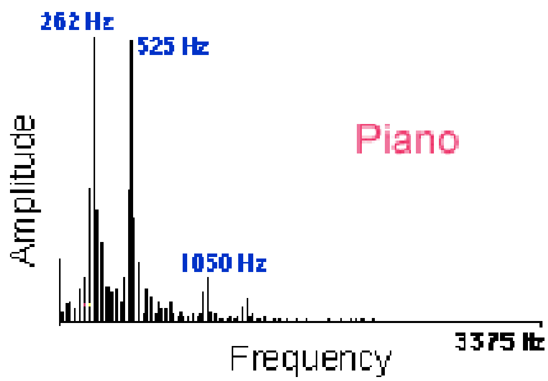
The variable logTwo is defined at initialization, and is used to decrease the amount of calculations the Arduino has to run per second, as log(2) will always be constant. Taking the measured semitones away from A4, and subtract from that the rounded value. This produces a value between -0.5 and 0.5 that represents the cents and direction the measured frequency is deviating from the closest note, which can be used to threshold actuator movement and decide which direction to push the slide in.

Finding the fundamental frequency of the played note

A problem occurred during rudimentary testing of the code that was not encountered previously in initial research—the trumpet produces stronger overtones than it does the fundamental frequency [20].







Note played is C4 = 261 Hz [21].

Thus, in order to find the fundamental frequency, there are two options, either:

- Find the overtone frequencies and from them calculate the fundamental frequency, OR

- Only search for low-frequency spikes that could only be fundamental frequencies.

As the Arduino Nano Every does not have the processing power to perform FFT at a sample rate fast enough to detect the higher overtone frequencies accurately (a minimum sample rate of), nor is there sufficient time to develop an algorithm to calculate the fundamental from these overtones, the second option was deemed the best. While it does limit the device to only tuning the trumpet while low notes (below ~235 Hz) from being played, it does still function as a proof of concept, with the limitation being resolved if given more time and upgraded components.

With this new finding, the former use of the FFT.majorPeak() function must be scrapped, as it does not allow filtering peaks based on frequency or amplitude, replacing it with a custom peak finding function:

```
// Finds the fundamental frequency by looping through samples and
finding the peak that fits through the filter
float findFundemental(float *vData, uint16_t bufferSize) {
  // Pre-calculates the index range to reduce loop iterations
  int firstIndex = frequencyIndex(lowFrequency);
  int lastIndex = frequencyIndex(highFrequency);
  float bestFrequency = 0;
  float bestMagnitude = 0;

  for (uint16_t i = firstIndex; i < lastIndex; i++) {
    // Calculates frequency currently being tested
    float frequency = ((i * 1.0 * samplingFrequency) / samples);
    float magnitude = vData[i];

    //Filters out based on magnitude and frequency
    if (magnitude > bestMagnitude && magnitude > magnitudeThreshold
&& frequency > lowFrequency && frequency < highFrequency) {
      bestMagnitude = magnitude;
      bestFrequency = frequency;
    }
  }
  return bestFrequency;
}
```

Since the device must be limited to a small range of frequencies in order to avoid the aforementioned issues with overtones, the frequency band must be set rather tightly:

```
const float lowFrequency = 210;
const float highFrequency = 235;
const float magnitudeThreshold = 15;
```

This allows the trumpet to be tuned to an A3 without the chance of it being mistaken for any overtones, as the only possible overtone that could be produced in this range would be one played by an A2, which is below the widely accepted lowest trumpet note of an E3. The magnitude of each sample of the Fast Fourier Transform is believed to be unitless, this the magnitude threshold was chosen through trial and error, being low enough to pick up a reasonably voluminous note, while being high enough to filter out noise.

```
const uint16_t samples = 512;
const float samplingFrequency = highFrequency * 2; // Hz
```

The sampling rate is set to twice the upper frequency limit (235 Hz), as the sampling rate must always be at least twice that of the highest frequency that should be included in the domain. However, the less the sampling rate, the more the accuracy will be achieved with the Arduino Nano Every's maximum capacity for 512 samples, which takes up an estimated 70% of available memory.

Piezoelectric sensor

With the piezoelectric sensor detecting the trumpet's vibrations for analysis by the FFT function, its location on the trumpet is vital for accurate signal measurements. Initially, a clip to attach the piezo to the edge of the bell was anticipated but brief testing later refuted that. While working on the circuit and testing to see if the device was responsive, the piezo was determined to only detect the vibrations accurately about 4 inches into the interior of the bell, requiring a longer wire and other methods of attachment.

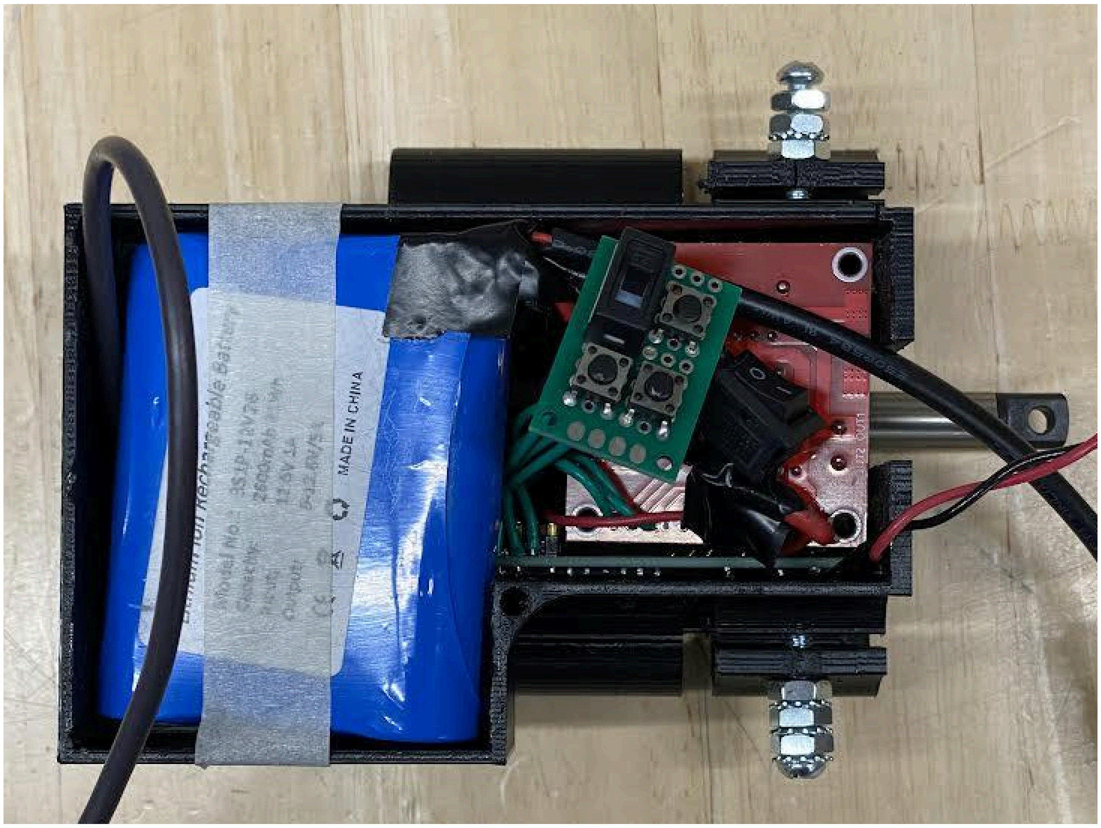
However, after additional rudimentary testing of the code, fixing other issues that were abrading signal quality, the piezoelectric sensor was found to be most effective on the outer edge of the bell, where the most amount of vibrations occur. Different methods of attachment were used to affix the piezo to the bell such as tape, magnets, a binder clip, and clay. From brief testing, it was determined that the piezo had to be directly contacting the bell in order for it to detect the frequencies accurately, with no cushioning piece as that would dampen the vibrations. Additionally, excessive pressure applied to the piezo would degrade its ability to resonate with the trumpet, so strong clips (such as the binder clip) could not be used.

Through qualitative testing, masking tape was determined to be the most effective attachment method of the piezo for ease and to allow for the best resonance and signal detection possible. The piezo is tucked under the outer edge of the bell and taped down.

While its aesthetic and repeatability could be improved, we did not have sufficient time to produce additional hardware to accomplish this.

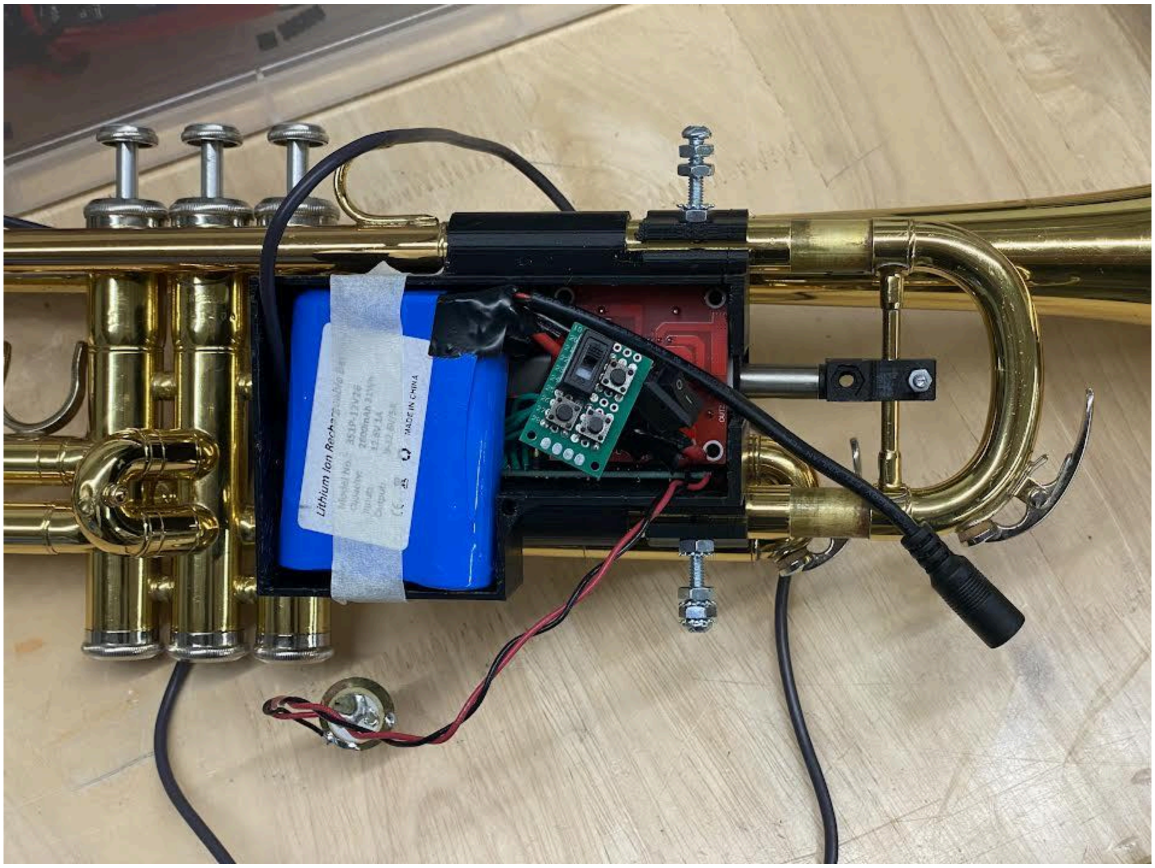
IV.3. Final Prototype

Below is our final prototype, featuring our 3D printed case and all of the electrical components encased on its interior.



The tape is to ensure the battery will not fall out of the case while being handled for easy accessibility as a lid was not printed.

Below is the final case on the trumpet, with the linear actuator affixed to the tuning slide.



The piezoelectric sensor is loosely attached and not mounted to the exterior edge of the bell.

IV.4. Testing, Data Collection, and Analysis

Test Plan

Efficacy of the tuner

Design Goal(s) to be Addressed

- Ensure the tuner can detect a specific sound frequency and activate the linear actuator effectively

Purpose

- Verify the code and the internal electrical components of the tuning device are working appropriately
- Verify the piezoelectric sensor is receiving the correct signal and activating the linear actuator accurately

Variables

- Independent Variable: Distance manually offset of the tuning slide
- Dependent Variable: Frequency of the sound produced
- Control Variables: The key, volume, speaker, the location of the piezoelectric sensor, note played by the trumpet

Pass/Fail Criteria

- Sensor detects the proper frequency within 10 cents (± 10 percent between the target frequency and the next closest semitone's frequency, measured so due to the logarithmic scale). This is a commonly acceptable threshold for being "in tune."
- Tuning device activates the linear actuator in the correct direction as a negative feedback loop to the pitch.
  - A flat sound will activate the actuator backward (toward the player) to increase the pitch.
  - A sharp sound will activate the actuator forward (away from the player) to decrease the pitch.

Data Analysis Plan

- The frequency of the initial sound played by the trumpet will be predetermined and emitted. The tuning device's original location will be offset and its cent difference of the sound produced will be recorded. The data will be analyzed to determine if the sensor is detecting the accurate frequencies and if the actuator is moving appropriately.

Materials

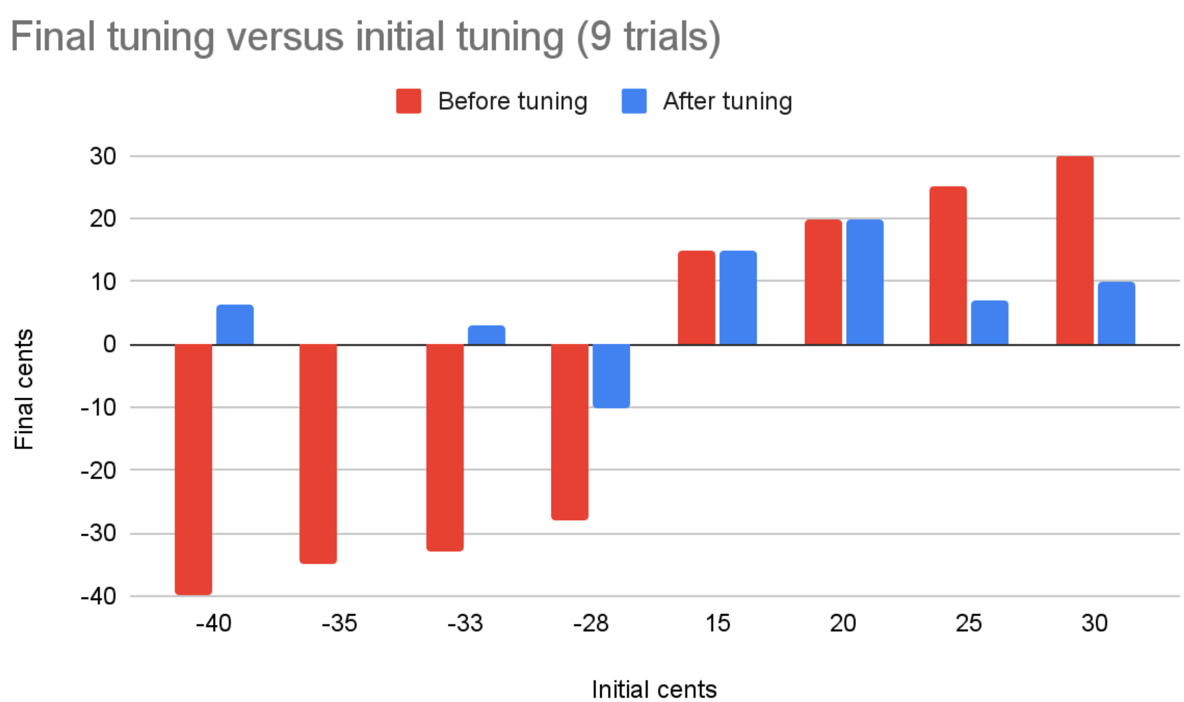
- Tuning device
- Trumpet
- Trumpet player
- Reference tuner (smartphone app)

Procedure

1. Using the trumpet, emit a sound frequency of a A3, 220 Hz
2. Adjust the tuning slide of the trumpet to a “random” location that varies roughly 2 cm surrounding the ideal slide location - to imitate a difference of greater than 10 cents
3. Activate the tuning device
4. Measure the new cent difference after the linear actuator has activated and record data
5. Repeat steps 1-4 with varying starting frequencies.
6. Analyze data

Data Collection

Measuring the initial and final tuning values in cents for nine trials, the data was compiled into the graph below, showing in red the initial frequency in cents from A3, and then in blue the frequency at which the tuner stopped moving the slide due to it meeting the internal threshold value for being in tune.



Values closer to the x-axis are closer to 0 cents of deviation—perfectly in tune.

Results

Overall, the tuner does move the slide towards a "tuned" position, sometimes getting really close and even perfectly in tune. These results seem to be unrelated to the starting frequency.

However, for two trials, the tuner detected the frequency to be in tune, and thus did not move the slide at all. This does not meet the ± 10 cent threshold for being "in tune," thus the results of these two trials can be considered a failure. The reason for this could possibly be attributed to the low number of samples the arduino can process, limited to 512, and since the maximum frequency being detected is 250 Hz, a sample rate of 500 Hz only gives an accuracy of 0.97 Hz, which could be enough for the tuner to detect a 222 Hz sound (not within 10 cents) to be closer to 220 Hz, causing it to incorrectly calculate the cent deviation of the real frequency.

Conclusion

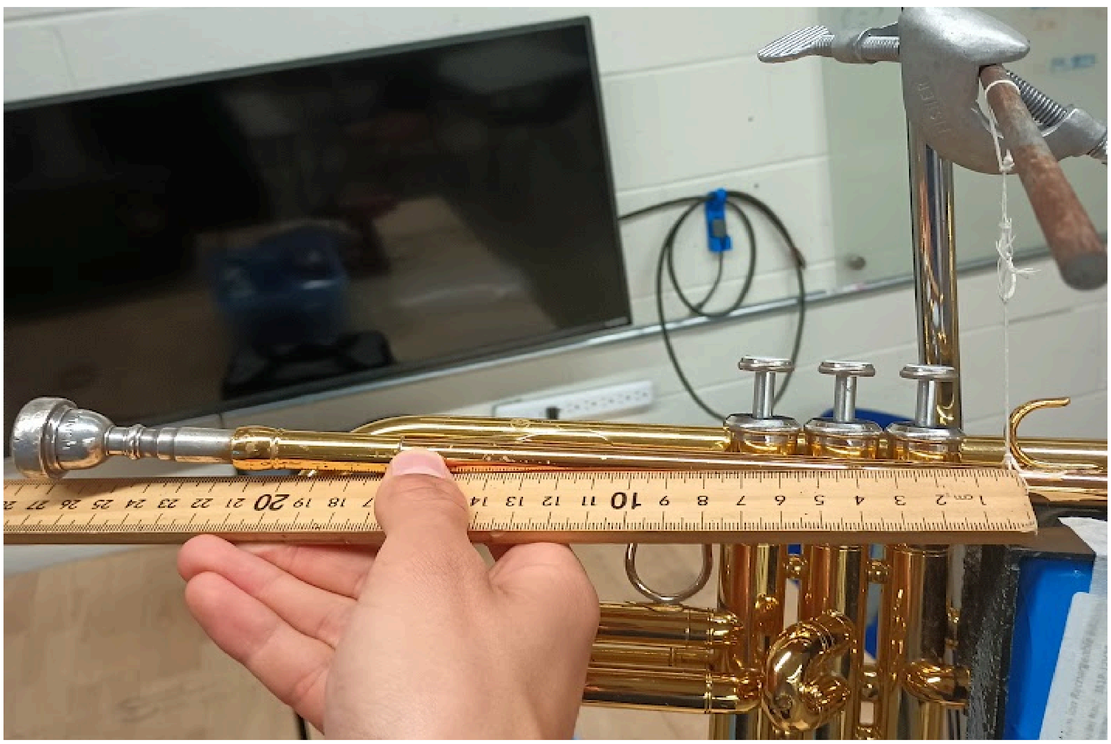
The tuner works semi-consistently, often tuning the trumpet to the threshold of ± 10 cents, however sometimes failing to detect it has sufficient deviation to move the actuator. This has happened in two of the 9 trials, and is likely due to the limited number of samples the Arduino can take, causing a sufficient level of inaccuracy in the measurement of the frequency to think that it is sufficiently in tune, even if it is not.

Due to time constraints, administering the same test under extreme temperature conditions was not feasible for another design goal. While the original idea was to test the device and trumpet in simulated hotter and colder conditions (using appliances such as a refrigerator), this test was deemed to be less prioritized as if the product works in room-temperature environments, it would also be able to continue and function in warmer or colder environments outdoors assuming no mechanical damage.

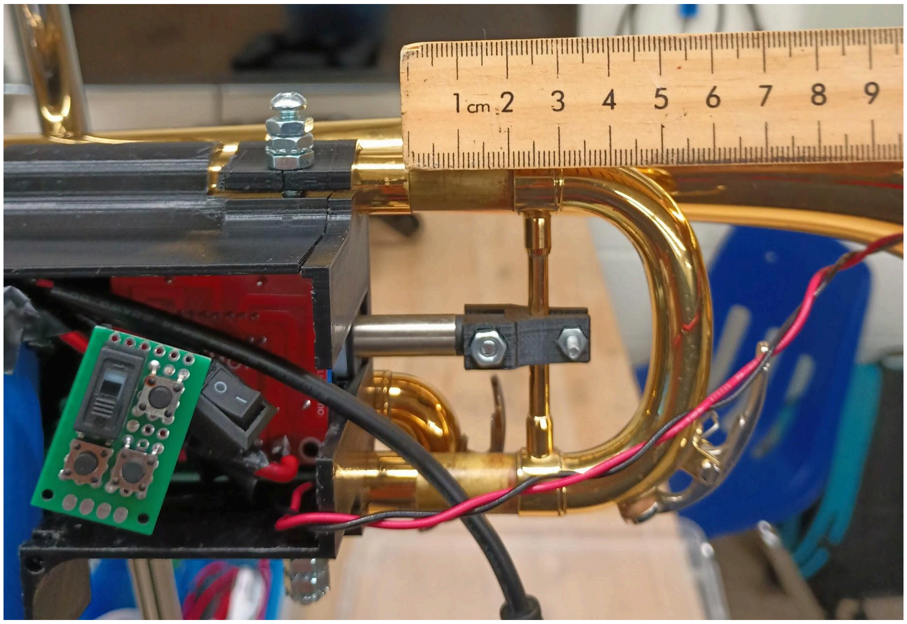
Additional measurements

We decided to also test the ergonomics of this device, measuring how it will change the mass distribution, and if this would have any significant effects on the force exerted by the player to keep the instrument in proper playing position.

To find the centre of mass, a string is tied to the first tube and the trumpet is hung from a stand, adjusting the string's position on the tube until we find a point at which the trumpet will balance completely leveled on the horizontal axis. The distance from the string to the opening of the tube is then measured.



Measured from end of brass tubing (left) to string (right, next to finger catch). This image is for demonstration; the real measurement was done more precisely using a more accurately aligned ruler.



This measurement was performed both with and without the device installed, and in both cases the slide length was kept at a consistent 2.1 cm.

Additionally, the total mass was measured:

	Total mass	Centre of mass (from tube end)
Without tuner	1179.9 grams	20.1 cm
With tuner	1538.2 grams	21.5 cm
Percent change with tuner	+30.36%	+6.97% forward

However, the change in mass and centre of mass from the tube end are not the most direct way to measure a change in ergonomics. One measure that we found to be particularly impactful on the comfort of the trumpet player is the amount of torque they must apply to keep the horn up. To calculate the change in this metric, we must know what distance the force of gravity is in relation to the player's hand (roughly the centre of the middle valve). We measured this with the same origin as our centre of mass measurements (from the tube end), finding it to be about 17.3 centimetres. Transforming the centre of mass measurements to be in relation to this new origin, we can now utilise the formula for weight and torque in order to find the change in torque applied to the player's hand:

$$\tau = Fd$$

	Centre of mass (from hand)	Weight	Torque on player hand
Without tuner	2.8 cm	11.6 N	0.325 N · m
With tuner	4.2 cm	15.1 N	0.634 N · m

So, the device exerts an additional 0.309 N · m of torque on the player's hand, which is almost twice of what the player would have to exert without the tuner installed. Although this might seem like a large jump in strain, when asking our testers about the comfort of holding the trumpet with the device installed, they did not observe a significant difference in strain.

V. Reflection

Successes

- Working prototype - proof of concept
    - While the final prototype is not completely consistent, nor does it cover the full range of the trumpet, the base functionality of tuning the trumpet automatically was achieved. Generally, the prototype tuner serves as a proof of concept that has proved that an automatic trumpet tuner could be effectively designed and manufactured.
- Case
    - The components and designs were composed to fit a form factor that remained mostly inside the trumpet, protruding only a little out the side, allowing for a not-too-bulky device that fit everything in one casing (except for the piezoelectric sensor). The case dimensions and fittings were perfect, with the tube rail and clamp fitting perfectly around the trumpet tube, and the interior geometry fitting the components in tightly.
- Functions
    - The device has all of the intended interface functions implemented, albeit not to the full extent of functionality that we would intend for a shelf product. The manual in/out buttons are delayed while in continuous mode, and any toggling/enabling of the tuning function was also delayed (this was all due to the FFT loop taking between 1.0-1.6 seconds to run).

Cost

The final prototype's price to manufacture was well below our group's budget, and while being slightly attributable to our free access to tools and equipment, as well as to 3D printing filament and small electronic components, the off-the-shelf parts were kept affordable.

The total amount of components that were purchased for the prototype amounted to $114.43, however only about $76.17 worth of off-the-shelf components were used in the final prototype, both due to unused components that we initially thought were needed, and also due to some components being purchased in quantities exceeding what the prototype utilized.

Below is a table listing the off-the-shelf components we used, including those we purchased and those that we were able to obtain for free.

Key:
Originally purchased, used
Not originally purchased, added
Originally purchased, partial quantity used
Originally purchased, unused

Part	Purchased cost	Utilized value	Function
2x protoboards		~$0.32	For circuit construction
3x buttons, 1x switch		~$0.24	For interface
Rocker switch		$1.40	For battery, main power switch
Arduino Nano Every	$17.90	$17.90	Microcontroller
Li-ion battery, 12V 5A 2.6Ah	$20.99	$20.99	Rechargeable battery for QoL
AWINLI 2 Mini Linear Actuator	$32.99	$32.99	To move the slide
L298N Motor DC Dual H-Bridge Motor Controller	$9.99	$2.49	Motor controller for linear actuator
20PCS 20mm Piezo Disc Transducer	$7.99	$0.40	Sensor
5pcs DC 5-30V to 5V Buck	$9.59		Voltage regulator
Bridge rectifier	$5.99		Converts AC to DC
1/2 inch cable clamp	$8.99		To affix the device to the trumpet
Total:	**$114.43**	**$74.77**	

Modifications

- Case adjustments
  - Much of the user interface components were forgotten about, including a toggle on/off switch as well as manual buttons to move the actuator for optimal user experience. The case could not be covered with a lid to access these buttons during testing thus, if the case was modified with holes to accommodate the buttons, it would improve the overall experience and look.
  - The screw holes to clamp the case on the tubes also were not of the right tolerance, resulting in a drill needing to be used in order to manually thread the holes and tighten them. We also failed to consider how to tighten the screws on the clamps with the components inside which we would need to revisit.
- Lid
  - A lid was considered for the case to cover all the components, and modeled, affixed with one screw hole; however, it was never printed. For testing, the lid would be unnecessary and the time constraint was too close for comfort.
- Piezo attachment
  - The piezoelectric sensor attachment with tape is very apparently a quick work around. With the varying pressures on the piezo and its sensitivity to the vibrations also requiring a precise pressure, it was difficult to have the piezo consistently working in the first place, so an attachment for it given our time frame was not deemed feasible.
- Hardware limitations
  - In order for the tuning device to be more accurate in its detected fundamental frequency, as well as allowing a greater range of frequencies, a greater sample size for the FFT must be used. However, the Arduino Nano Every does not have enough memory to store and process any sample size above 512 (they must be in powers of 2). Thus, to improve this aspect, a more powerful processor must be utilized.

Grievances

- Softwares on the school laptops
  - The main CAD software the school uses is Inventor, however we wanted to use Fusion360 for its cloud capabilities for collaboration and out-of-school access. There were plenty of issues early on including getting access in the first place as

well as update compatibility issues over time, which delayed our early CAD work.
    - The school laptops also did not have access to the Arduino IDE software with administrative overrides to run the code, forcing reliance on the 3D printing computers in the engineering suite, which are of quite poor quality and were sometimes occupied.

- No flux
    - The lack of a supply of soldering flux made it difficult to properly solder components, causing many wires to constantly come loose from the PCB and overall conspicuously poor soldering connections on larger components such as the battery leads.

- Time constraints
    - We missed nearly every deadline by roughly a week or more, mostly by having too many components in the prototyping process that required many steps and iterations. Each mentor meeting we had with our engineering mentor discussed the step prior, with our last meeting that was supposed to have our final prototype and testing results only consisting of a half-baked prototype that was never yet tested on the trumpet itself.

Final Notes

Overall, we are very happy with our final automatic trumpet tuner proof-of-concept! We have made a GitHub repository containing all of the resources that made up this project, including the complete source code, CAD models, and other data/documents:

github.com/uncookednehuel/TrumpetTuner

Here are some videos of the prototype in action:

Video of automatic trumpet tuner in (slow) action: trumpetTuner.MOV
Video of automatic trumpet tuner in the trumpet owner's hands: trumpetTunerGavin.MOV
Extra pictures: Automatic trumpet tuner bonus

Special thanks to:

Mr. Arsenault, our Engineering Capstone teacher, for initiating our project and suggesting deadlines;

David Hart, our professional engineering mentor, for guiding us through our project and supporting us with all of his wonderful feedback;

and Gavin Courville, our friend, for lending us his trumpet each and every class.

VI. Citations

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