Final Report: PulseWeaver

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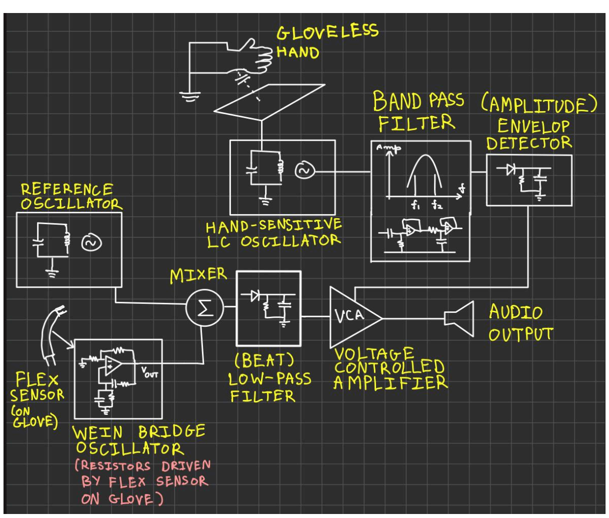
Proposal

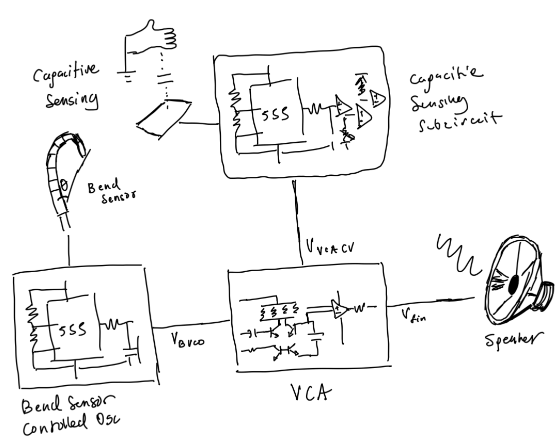
The PulseWeaver project aims to create a new custom musical instrument. This instrument was created to actualize the concept of a conductor's hand directly producing music without any physical touch, bringing to life the vision of producing musical sounds through direct hand gestures.

We knew that since this was a musical instrument, we needed to develop a system which would provide complete control of the pitch of the sound waves the instrument produces, thereby allowing us to actually play music on the instrument with some degree of accuracy. Since our musical instrument relied on hand movement, we knew we would have to implement some sort of gesture detection system. Our idea for this was to use a glove which controlled a variable resistor, thereby cementing the form factor of the final instrument. We also knew we wanted to produce a change in the music by just moving our hand around, similar to how an orchestra conductor controls the music being produced by moving his baton. To do this we needed to fix some point relative to which the distance of our hand could be detected to produce different sounds.

We decided to let the bend of a finger control the pitch, and a capacitive plate sensor detecting hand distance control the volume of the audio signal our circuit produces. This provided the initial vision for the sub-circuits we arrived at, with a circuit controlling the volume processing, a circuit controlling the pitch processing, and a VCA to merge the two into a final signal. We realized the similarity between our project and the Theremin[(PDF) Musical Applications of Electric Field Sensing (researchgate.net)], a musical instrument created with a similar motivation. As to promote musical expressiveness we wanted the pitch to vary by two octaves, centered around middle A and have a continuous volume change from completely quiet to quite audible.



Original Design



Final Design

Milestones

1. Test Speaker and Bend Sensor ✅(MET)
2. Capacitive Sensing controlled Oscillator with Control Voltage Output ✅(MET)
3. Bend Sensor controlled Oscillator ✅(MET)
4. VCA ✅(MET)
5. Final Integration ✅(MET)

Timeline

Milestone	Description Breakdown	Date Completed
Test Speaker and Bend Sensor	Test resistance for various angles of each bend sensor and plot for future reference	Feb 22
	Test speakers with function generator input to confirm operation conditions (frequencies for human hearing)	Feb 22
Capacitive Sensing	Building and Testing Capacitive sensing Oscillator	Feb 29
	Low pass filters to extract voltage information from the capacitive sensing oscillator with Testing	Mar 21
	Converting frequency to proper voltage range (0-10) and Testing	Apr 4
Bend Sensor controlled Oscillator	Utilize 555 timer to create frequency controller	Feb 29
	Filter signal in order to interface with VCA	Apr 11
VCA	Read up on Theory, designing circuit schematic	Feb 22
	Build Circuit	Feb 29
	Debugging	Mar 7, Mar 21
	Revise circuit	Mar 28
	Testing and Verification	Apr 4
Final Integration	Testing and Verification	Apr 25
Final Report	**Completed**	Apr 28

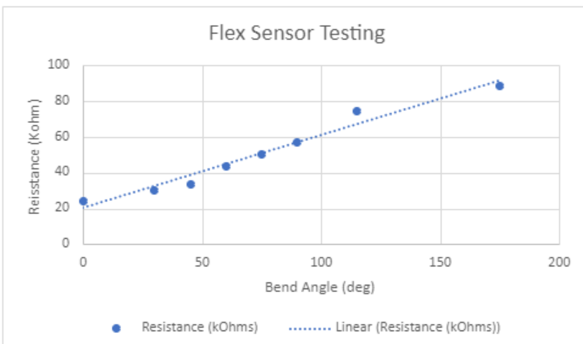
NOTE: We organized the Communication/Analysis/Tool/Design sections under each of the milestones as we found it to have better organization but they still exist for each major milestone.

Test Speakers and Bend Sensor Milestone

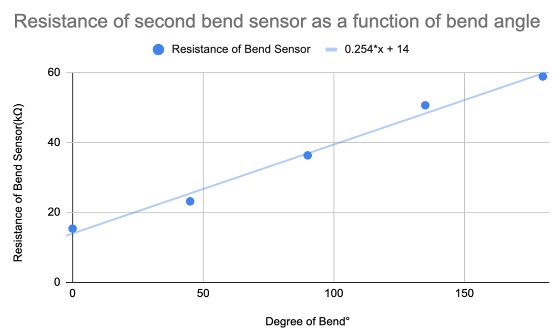
Communication/Design

For this Milestone, we measured and plotted the bend angle to resistance curve for our flex sensor.
The datasheet claims 7k-13k ohms for 0 degrees and at least 2x this resistance for a full 180 degree angle (touching itself).

Analysis

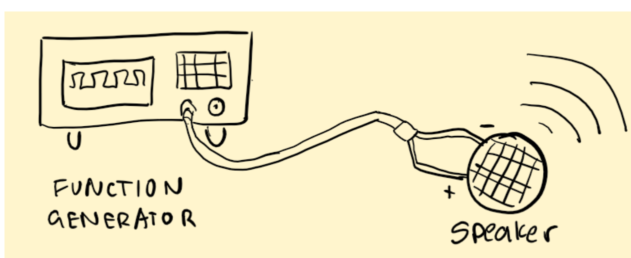


Flex Sensor 1



Flex Sensor 2

Then, to test the speaker, we used a function generator and directly plugged it into the speaker, making sure to control the frequency and amplitude (Vpp) such that it would not blow up this very essential component. The setup was as such and we tested various frequencies and amplitudes, as well as both sinusoidal and square waves. We heard audible frequencies for all and thus we concluded this test as a success. Below is the setup we used:

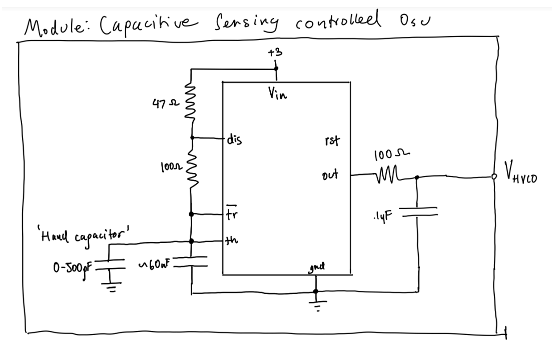


Speaker testing setup

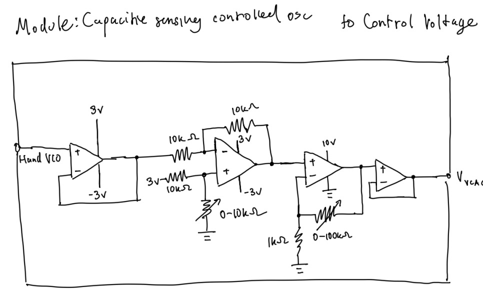
Capacitive Sensing Milestone

Communication/Design

The goal of this subcircuit was to take the distance of one's hand from a static reference point and convert it into a control voltage that could be used to produce a DC control voltage that could be used in the gain of the VCA. The method behind this was by using the fact that a hand some distance away from a charged plate could be thought of as a capacitor with the distance of the hand from the plate being a varying capacitance. This variable capacitance could be used as a discharge path for an oscillator thus allowing for frequency to vary depending on the distance of the hand. This variable frequency could then be turned into a control voltage by using a low pass filter. Since low pass filters attenuate different frequencies by different amounts we could get a voltage differential between high and low frequency circuits. The goal was then to feed this through a peak detector (though this changed and will be commented on later) to get a DC voltage. This would produce a voltage in some range $V=V_{Low}-V_{High}$. The main function of the next subcircuit “Oscillator to Control Voltage” was to take this range and map it to 0-10V using differential and non inverting amplifying op amps. This would look like this equation $\frac{10V}{(V_{High}-V_{Low})}(V - V_{Low})$. In reality given that V_{Low} and V_{High} are extremely sensitive to the orientation and connection of the metal plate these need to be tunable which was achieved by potentiometers. This would finally then be outputted as a control voltage that could be used by the VCO.



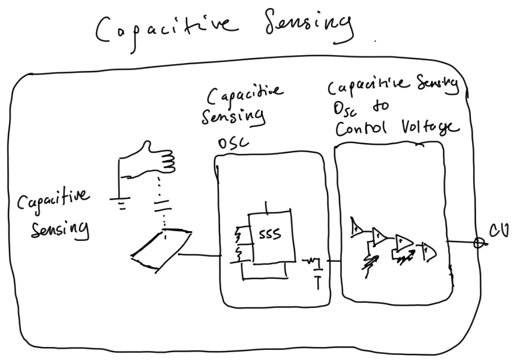
Capacitive Sensing Controlled Oscillator



Oscillator to Control Voltage

To construct the capacitive sensing controlled oscillator we had used the design used by a musical instrument called a theremin which would similarly use a variable capacitance to control an oscillator frequency then use a series of filters and an envelope detector to extract voltage information. This was much of our inspiration and we set off on building using a 555 timer instead of the traditional colpitts oscillator. Some of the challenges we faced in this process is that the oscillator had to be driven at such high frequency given the small capacitance a hand provides. This had given us a challenge as even the smallest RC constant in the lab was not enough but we discovered that parasitic capacitance within the breadboard was actually small enough for the frequency to be high enough. Then we moved toward the filtering and we used trial and error to determine the most fitting resistor and capacitance value to get the greatest change in peak voltage on our signal.

Then the next step was creating a peak detector. In the lab I had first buffered the signal but noticed that this essentially averaged the signal. Confused, I tested on the function generator and discovered that at high frequency op amp buffers seemed to create an averaging almost flat DC voltage which is what we desired as it would increase and decrease depending on the filtered signal. From there it was enough to map this range with a differential op amp and non inverting amplifying op amp and a final buffer to be fed into the VCA.



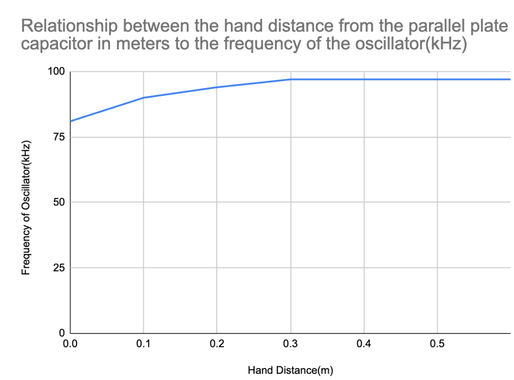
Full Module

Analysis

There were 3 verification steps completed for this subcircuit. The first was testing the frequency of capacitive sensing oscillator frequency, then the peak voltage of the filtered signal, then the final voltage being mapped from 0-10V.

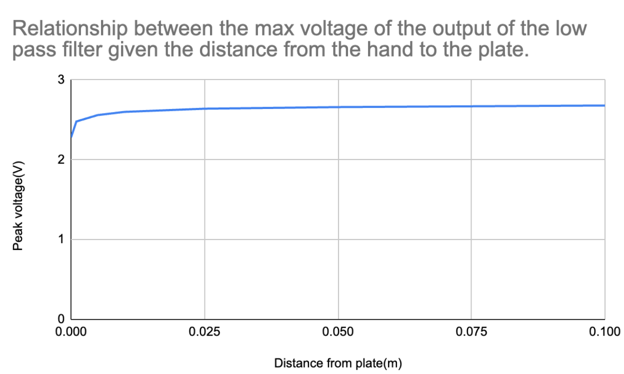
Test 1

Hand Distance	Frequency of Oscillator
0m	81kHz
0.1m	90kHz
0.2m	94kHz
0.3m	97kHz
0.6m	97kHz



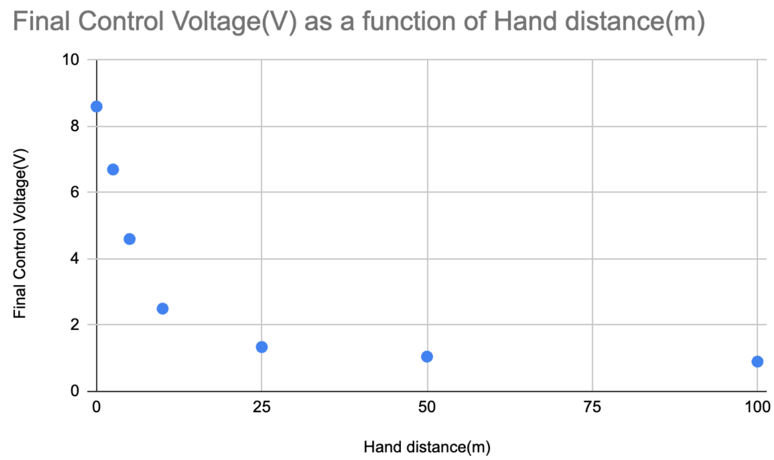
Test 2

Distance(m)	Peak voltage(V)
0.1	2.68
0.05	2.66
0.025	2.64
0.01	2.6
0.005	2.56
0.001	2.48
0	2.28

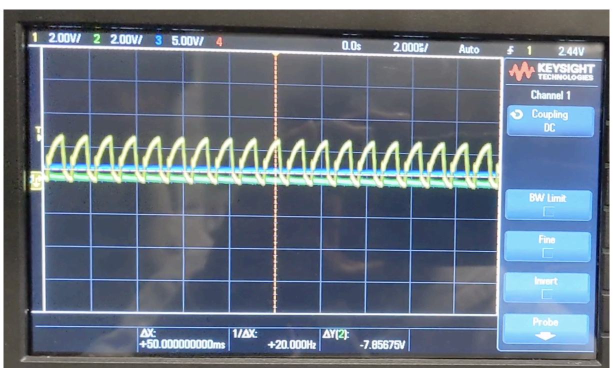


Test 3

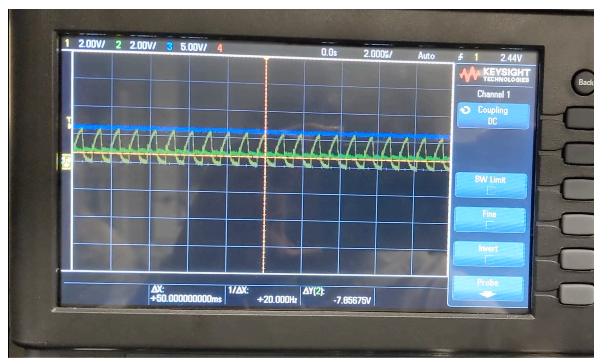
Hand distance	Final Control Voltage
100	0.9
50	1.05
25	1.34
10	2.5
5	4.6
2.5	6.7
0	8.6



Tools



Hand Close



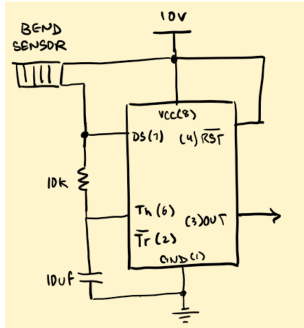
Hand Far

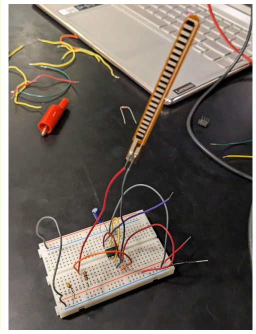
Yellow: After low pass filter, Green is control voltage after subtractor, Blue is final control voltage. We can see they both vary within the ranges shown in the graph.

Bend Sensor controlled Oscillator

Communication/Design

In the first few days of creating a frequency-variance oscillator with the bend sensor, we utilized a simple 555 timer circuit design with the Bend Sensor as one of the 2 resistors in the voltage divider for trigger input. There is a video demonstrating the functionality. Below is the simple design we used:

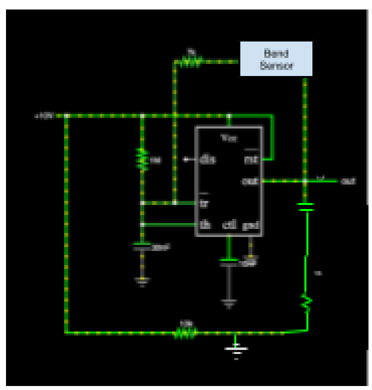




Schematic Physical Circuit

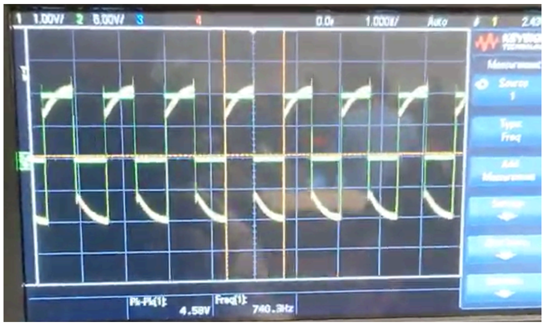
After this, we needed to adjust the values of our resistors and capacitor in order to get an audible frequency range. After testing in Falstad Circuit Simulator online, we were able to get the following resistance and capacitor values that worked to get us to a 0V-10V ranging signal with a frequency range of 220 Hz-880 Hz, an audible range for connection to our VCA.

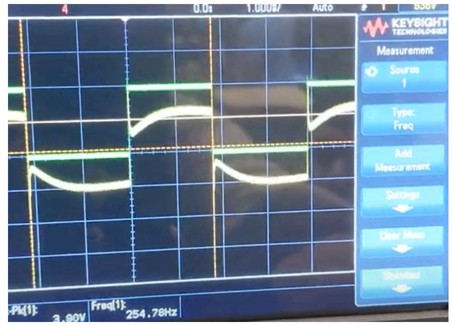
It is important for us to alter this signal so that we can connect to the VCA such that it will work without causing damage to the speaker. The speaker requires an oscillating voltage range that goes from negative to positive with the same Vpp (amplitude of the signal). As a short term solution to our DC offset problem, we utilized a high pass filter.



Filter Schematic

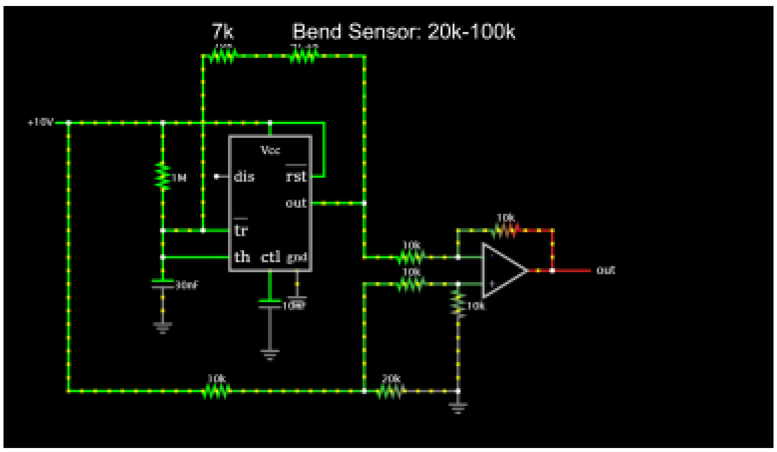
Below are some oscilloscope readings of how the High-Pass Filtered solution worked. It is evident that as the frequency shifts, so does the amplitude. This will cause problems in our volume control when putting everything together:



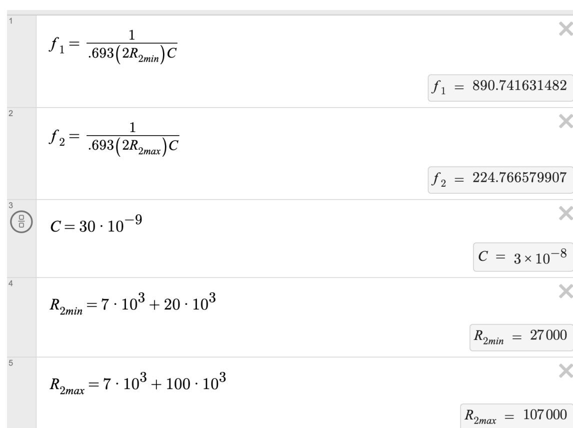


Unbent Position Oscillation Full Bent Position Oscillation

A solution we implemented for this issue is to use a differential amplifier to subtract 5V from our signal, thus converting our [0V,10V] range to a [-5V, 5V] range. Below is the schematic of this circuit:



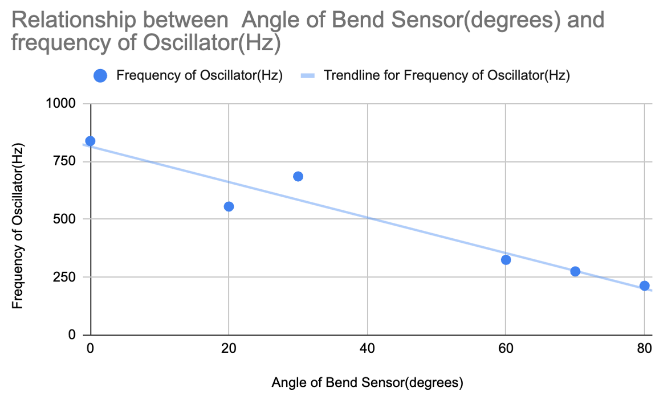
Final Bend Sensor Pitch Controller



Glove Attachment Calculation of component values

The design choices made to make the resistor 7k to be in series with the bend sensor and use of the 30nF capacitor was chosen such that the final frequency would be between 220Hz and 880Hz as seen above.

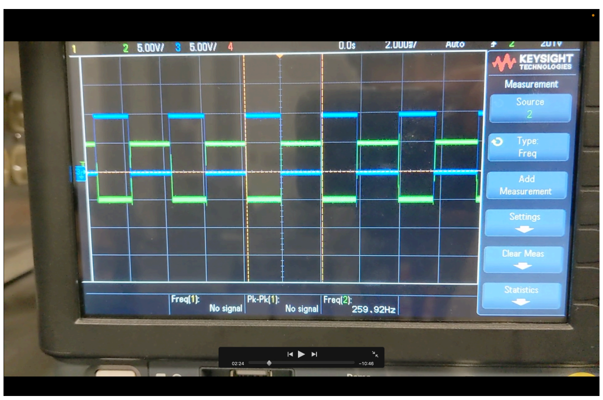
Analysis

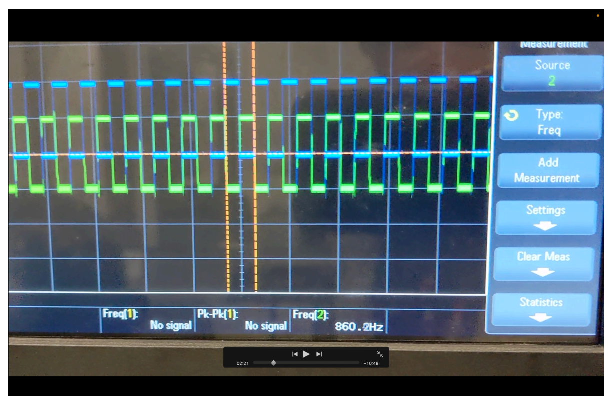


We also validated the frequency by bending through the whole angle range and validating that it would output results one octave above and below middle a (440Hz) which it did very well.

Tools

Output Signals:





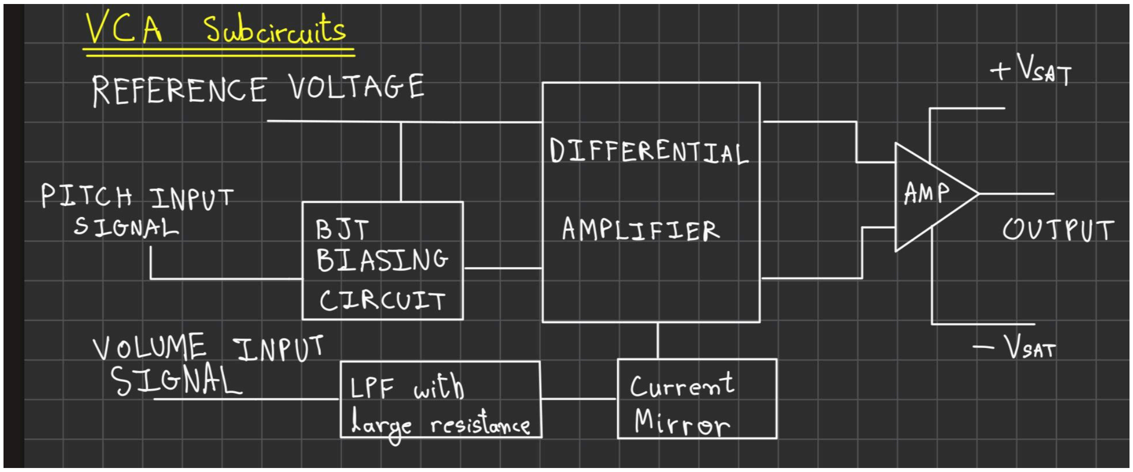
Low Frequency High Frequency

In the above oscilloscope readings, the blue signal is the original output of the 555 timer while the green signal is the signal after being put through the subtractor and our final output signal for this subcircuit. After this, we simply attached the bend sensor to a glove as shown below.

VCA Milestone

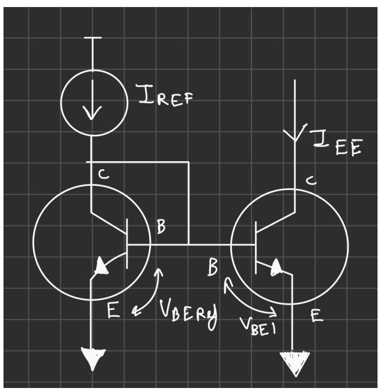
Communication/Design

A voltage-controlled amplifier (VCA) is an electronic amplifier that changes its gain based on a control voltage. The higher the control voltage, the gain of the output signal is.Our basic idea for our VCA is to use a differential amplifier to eliminate noise (in theory) and to use a current mirror to drive the differential amplifier output. Then we use an op amp to convert the differential output into a single output that can be fed into a speaker. Below is a block diagram of the circuit:



VCA block diagram

Current mirror circuit:



In our circuit we need some way of biasing the emitters of the BJT's in the differential amplifier circuit. For this we need to vary the output of a current source using variation in control voltage. We first use the control voltage to generate a reference current source (I ref). We feed this into the collector of a transistor which has its collector and base connected.

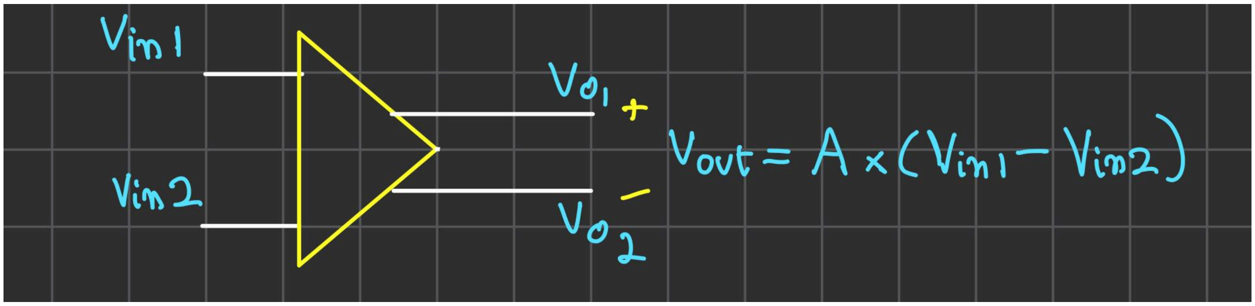
Now Iref = Isat(exp(VbeRef/Vt)) Rearranging, VbeRef = Vt (ln(Iref/IsatRef)

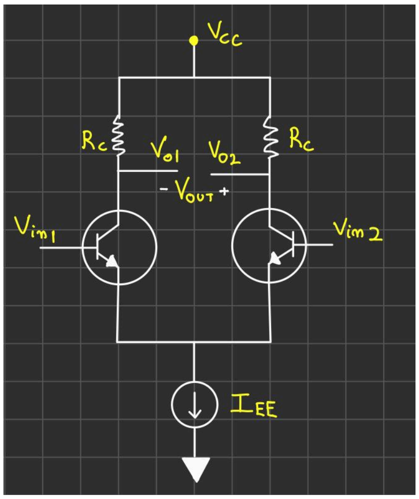
So we have obtained VbeRef as a function of Iref. But since that voltage is applied to the base of the second transistor, we have Iee = Isat1 (exp(Vbe1/Vt)) and Vbe1 = VbeRef

Substituting the formula for VbeRef obtained we get Iee = (I sat1 / I satRef) I ref thereby replicating the reference current (as we are using the same transistor so I sat1 = I satRef). More simply explained, since the base currents are the same due to symmetry, the collector currents must also be same as Ic = **β**Ib This replicated current is then used to drive the differential amplifier's BJTs.

Differential amplifier:

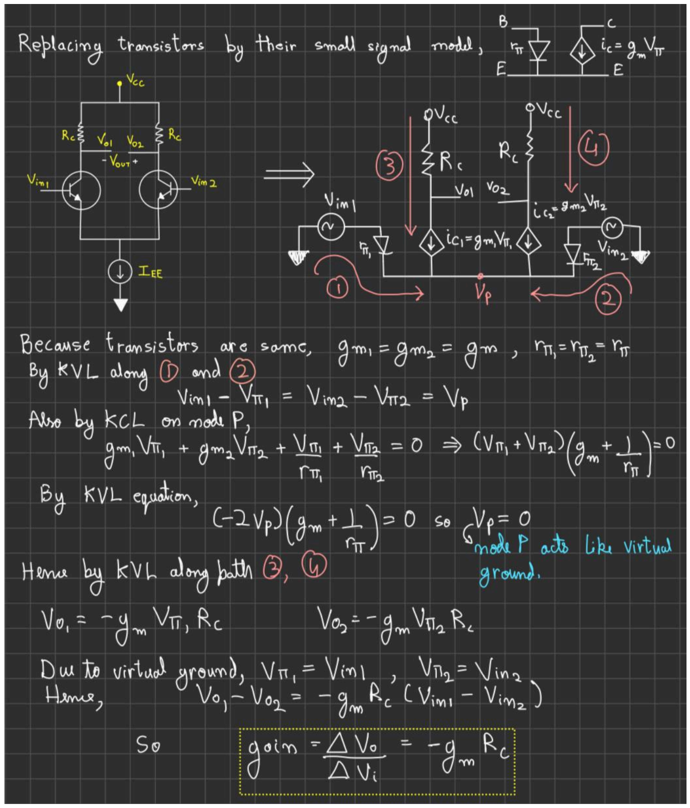
This type of amplifier basically takes two input signals and outputs a signal that equals that gain times the difference of the two voltages as shown below:





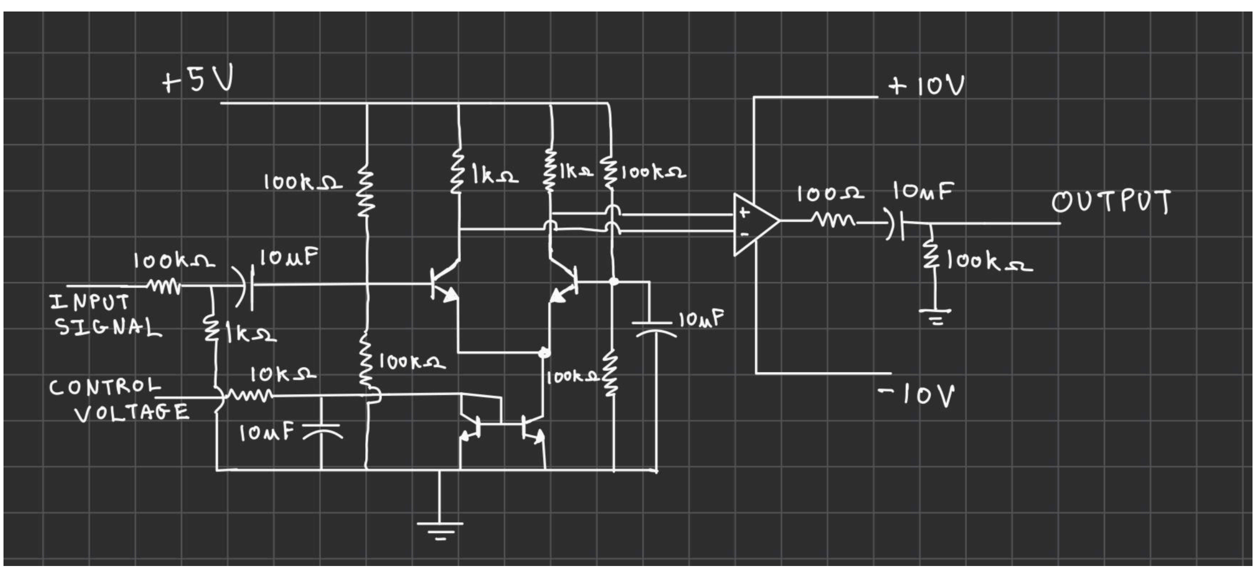
This amplifier is necessary for our circuit because we need some way to reduce the transfer of noise in the output signal. For a single ended amplifier, when some noise gets coupled with the input, it also appears on the output side. To solve this issue, we have two inputs (Vin1 and Vin2) feeding into the amplifier and assume Vn is the common noise feeding into both input signals. Then, Vin1 = Vin1correct + Vn and Vin2 = Vin2correct + Vn. So the differential output is: Vout = A((Vin1correct + Vn) - (Vin2correct + Vn)) = A(Vin1correct - Vin2correct). Hence the noise won't appear at the output signal. We can make this circuit using two BJTs as shown to the left.

We are only concerned with small signal analysis as we heavily attenuate our input voltage before feeding it into the base of the BJT.



Using data from the datasheet of the BJT we get a theoretical maximum gain of 500x from the differential amplifier. The minimum is when the transistors are not biased and so will be off giving 0 output. However, since we attenuated the input signal to 1% of its value, we can amplify it from 0 to 5 times its original value.

<u>Overall VCA schematic</u>

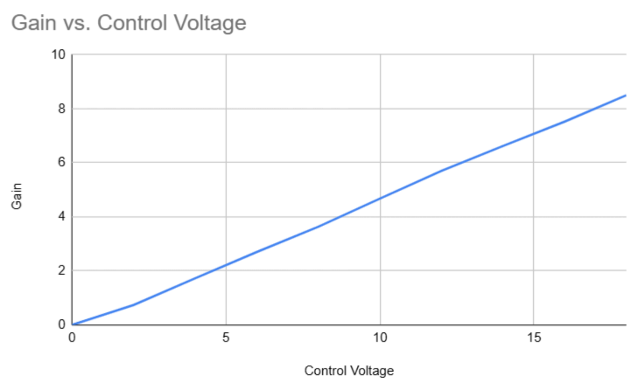


Analysis

We tabulated the change in the gain of the VCA as the control voltage changes.

Input Voltage	Control Voltage	Output Voltage	Gain
1Vrms	0V	0Vrms	0
1Vrms	2V	0.7375Vrms	0.7375
1Vrms	4V	1.725Vrms	1.725
1Vrms	6V	2.7Vrms	2.7
1Vrms	8V	3.625Vrms	3.635
1Vrms	10V	4.675Vrms	4.675
1Vrms	12V	5.7Vrms	5.7
1Vrms	14V	6.625Vrms	6.625
1Vrms	16V	7.525Vrms	7.525
1Vrms	18V	8.5Vrms	8.5

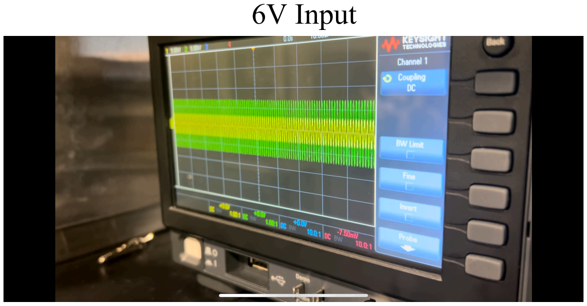
Plotting this data we get a roughly linear relation between the control voltage value and the gain of the VCA.



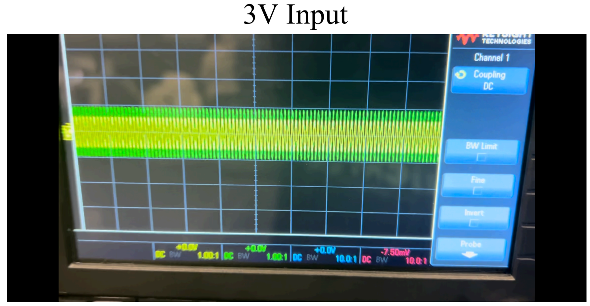
Tools

Here are some oscilloscope readings which show this gain. The yellow signal is the input signal and the green signal is the output signal.
The left picture is the oscilloscope reading with a 6V control voltage and the right picture is the oscilloscope reading with a 3V control voltage.

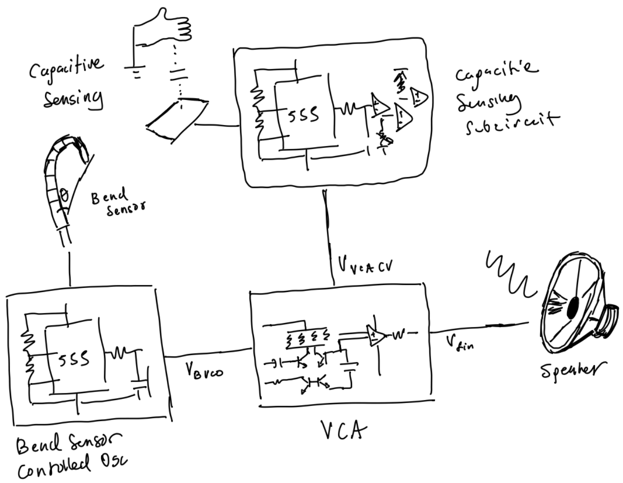
6V Input



3V Input



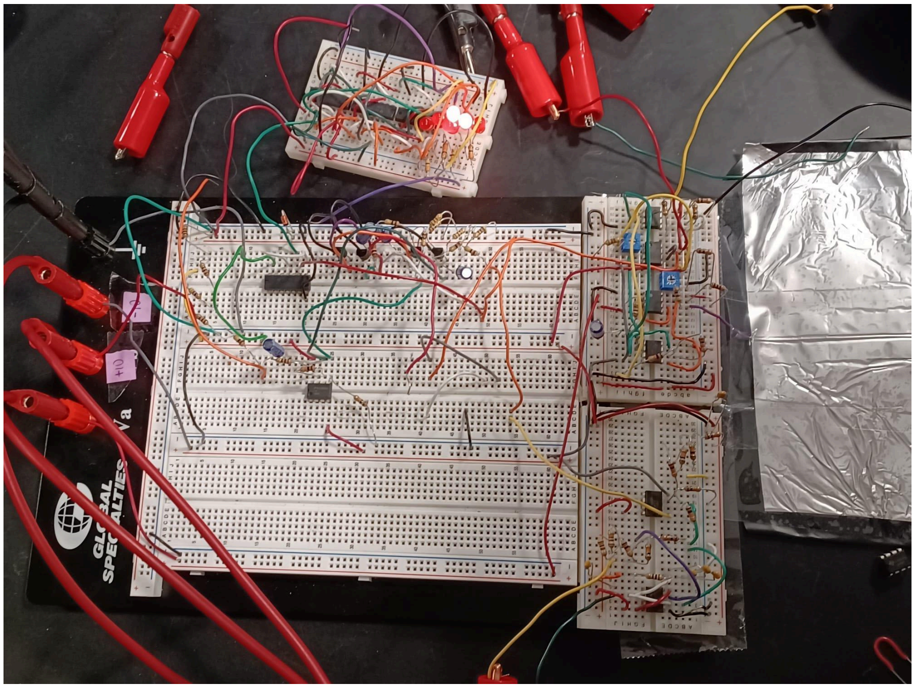
Final Product



Final Schematic

<u>Reducing number of power supplies used</u>

During the individual testing phase we needed 4 DC power supplies just for the VCA, 3 supplies for the capacitive sensing circuit, and 2 for the pitch circuit. Along with all the function generators and oscilloscopes we needed for each of our individual circuits, this made us take a significant amount of time to set up our circuits before we could even start to debug them. To solve this issue we reduced the number of power supplies we needed to 2 by using a zener diode to create a 5V powerline from the 10V line of the VCA and used that to power the differential amplifier instead of using a separate 5V power line. We also connected the 10V and -10V line of the VCA circuit to the capacitive sensing circuit and the pitch circuit, thereby connecting all of our breadboards together and powering all the op amps in our project using a single 10V and -10V channel. The 5V powerline generated for the differential amplifier was used to power the counter circuit which allowed us to implement a digital logic circuit without using extra DC power supplies.

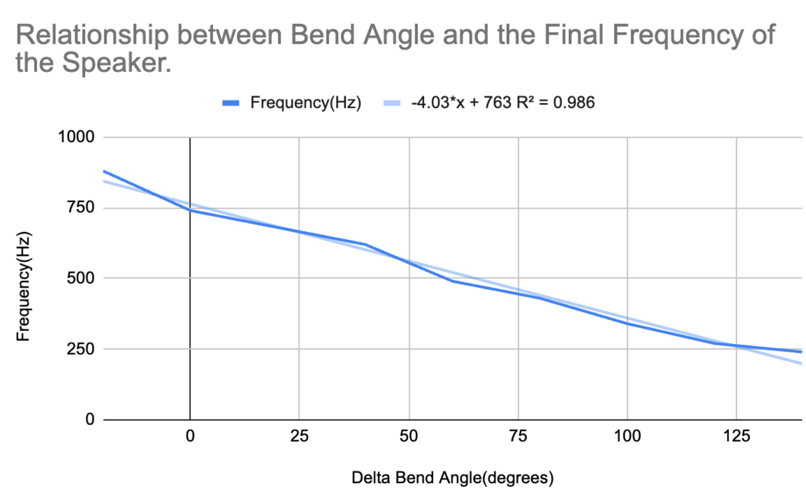


Finalized Circuit Breadboard

Final Validation

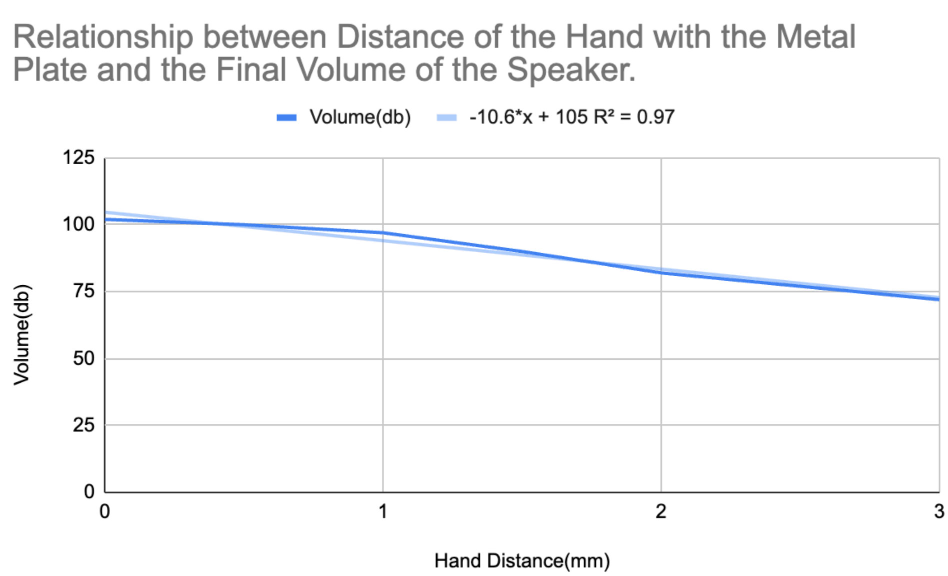
For our final validation we independently tested the effect of each of the inputs (bend angle of the bend sensor and the distance of the hand from the capacitive plate) on the final speaker sound by measuring the frequency of the tone generated and the amplitude of the tone generated.

For the Bend Angle and Frequency we found the following relationship.



Low frequency (274Hz) High frequency (841Hz)
Note:Yellow is output signal, Blue is base oscillator, green is control voltage.

Where the largest possible frequency we could obtain was 880 Hz (around a A_5) and the smallest possible frequency we could obtain was 220Hz (around an A_3). This would give the whole circuit about two octaves of playing range. This is exactly the octave range we set out in our initial planning and we found that it had enough range to promote musical expressiveness while also being small enough such that we could play any song we'd like accurately. As for hand distance we had found the following relationship with the volume of the final signal.



Low Amplitude (1V) High Amplitude (6V)
Note:Yellow is output signal, Blue is base oscillator, green is control voltage.

It's important to note that the baseline of 72db (which was experienced at 3 mm away from the plate) was only background noise with no sound being produced by the speaker. We also placed our microphone on top of the speaker. With our maximum volume of about 102db, we found we could get an output 1000x louder than the background. This continuous change in dynamics fits the goal we outlined initially.

Though the sensitivity of the plate is only really experienced a few millimeters away from the plate we found this result to be quite intuitive in playing as it allowed small adjustments of the hand which could more quickly be made to easily change dynamics making the playing experience far nicer.

Challenges and Successes

Capacitive Sensor - Volume Control

Throughout the process of building the capacitive sensor, the team encountered various challenges alongside notable successes. Challenges included difficulties in achieving the required frequency response which required us to notice the parasitic capacitance in the board. To streamline the design, a plan was formulated to swap the functions of the plate capacitor and finger resistor, simplifying the circuit from what was originally a mixer, beat detector, and voltage divider. However, converting frequency information into a 0-10V voltage range posed a challenge, addressed through a low pass filter and peak detector, though mapping the output voltage range accurately remained problematic.

Despite these challenges, we successfully implemented key components such as the filtering and subtractor. That said we are still facing issues with the noise in the circuit and how the tuning can be time consuming so we hope to make a more realistic peak detector to filter out noise and also better attach the plate to the circuit to remove the variability we face every time. We are also noticing a square wave in the output which we believe was an artifact of the integration and so we would like to do more debugging to figure out the issue.

Bend Sensor - Pitch Control

Initially we had used a wein bridge oscillator but we moved away from this as we found it was quite difficult to get a good sine wave out of it and it required the use of many additional subcircuits like a mixer and beat detector.

Designing a bend-sensor resistance-controlled output posed both challenges and successes throughout the process. Initially, we utilized a basic 555 timer circuit design with the bend sensor as one of the resistors in the voltage divider for trigger input. While this setup demonstrated functionality, adjustments were necessary to achieve the desired audible frequency range.

After testing various resistor and capacitor values using online simulation tools, we identified combinations that produced a signal ranging from 0V to 10V with a frequency range of 200 Hz to 700 Hz, suitable for connection to our voltage-controlled amplifier (VCA). However, we encountered a DC offset problem that required addressing to ensure compatibility with the speaker, which necessitated the implementation of a high-pass filter as a temporary solution.

While the high-pass filter mitigated the DC offset issue, it introduced amplitude variations as the frequency shifted, potentially impacting volume control when integrating all components. To address this, our solution involved using a simple subtractor to subtract 5V from the signal, converting the range from [0V,10V] to [-5V,5V].

<u>VCA</u>

Being a fairly complicated circuit, we had to spend a lot of time debugging this circuit. First, due to the circuit having 5 inputs and two separate grounds, along with the 3 oscilloscope probes needed to observe its behavior we needed to use 18 wires with 4 DC power supplies just to set the circuit up each time we needed to work on it. We arrived at a solution to this problem by using a zener diode to obtain the 5V powerline needed for the differential amplifier using the 10V power supply for the op amp amplifier, and combining all the grounds of the circuit after eliminating the possibility of unexpected current redistribution at the ground node. (after confirming the proper working of each of the circuits individually).

We also had electrolytic capacitors in the current path being driven by an AC voltage with no DC offset. This resulted in the oxide layer of the capacitor being depleted and creating a short between the 5V and ground and causing high amounts of current being drawn from the power supply. We eventually decided to remove each capacitor in the circuit one by one until we found the capacitor that was causing the short. We then removed that capacitor and found that the circuit worked fine as the capacitor was intended to clear the noise in the 5V power supply but the DC power supplies in the lab were largely noise free, and removing it solved the shorting problem.

Conclusion and Future Direction

In summary, the PulseWeaver project has undergone significant development towards the creation of a novel musical instrument controlled by hand gestures. Despite encountering challenges along the way, the project has reached several key milestones and demonstrated promising progress.

Successful testing of speakers and bend sensors provided valuable data for subsequent circuit design, while the implementation of the capacitive sensing controlled oscillator marked a significant advancement. Although challenges arose in achieving the desired frequency response and voltage range, diligent efforts in circuit construction and testing yielded positive results.

The voltage-controlled amplifier (VCA) also posed many challenges, requiring extensive debugging due to its complexity. However, through meticulous problem-solving and optimization of power supply configurations, significant progress was made. Additionally, we faced many challenges with the Capacitive and Bend sensor, setting us back on our timeline. However, we were able to make progress and currently have a working capacitive sensor voltage controller, utilizing tuning techniques with potentiometer adjustment.

Looking ahead, our focus will be on resolving remaining compatibility issues with the pitch controller and filtering the sound produced to make it less metallic sounding and more smooth. Additionally, efforts will be directed towards ensuring the circuit's compactness for convenient glove attachment. Despite the encountered challenges, the PulseWeaver project remains on track towards a fully functional musical instrument controlled by hand gestures. With continued work and refinement, we are optimistic about achieving this goal. We also tried a bonus milestone, a ripple counter that could count the number of notes played with the rising of the control voltage but we found given the noise the counter would not activate properly. In the future this is another avenue we could use to improve.

Contributions and Teamwork

Kai:
Worked on testing the individual components when they arrived. Helped test the bend sensor and speaker. Had a special emphasis on testing the plate capacitor which turned into leading the hand sensing circuit. This involved building and testing the plate capacitor circuit and the differential and amplifying op amps to map the change in voltage to a control voltage. Worked on integration and removing power supplies.

Harini:
Worked on testing the individual components when they arrived. Helped test the bend sensor and speaker. Supported Kai with the testing of the plate capacitor and the building of the initial hand sensing circuit. Also led the development of the oscillator after we found the wein bridge to be too difficult. Built and tested the oscillator and implemented the differential amplifier to map the range to -5 to 5. Worked on integration and removing power supplies.

Vaibhav:
Worked on testing the individual components when they arrived. Helped test the bend sensor and speaker. Started work on the wein bridge oscillator thought this was never completed. Lead the building and testing of the VCA, building the current mirror, differential amp and unit testing with base oscillator and control voltage. Worked on integration and removing power supplies.

Our team worked very well together as we were able to divide and conquer. By breaking our entire circuit into 3 main subcircuits we were each able to lead our and get a very deep grasp of our circuit allowing us to keep needing to ask each other questions on some subcircuit which we found would impede progress. We also helped each other in the brainstorming component which we found helpful. For example, working with Harini helped us with experimentation when we needed to develop a 555 timer circuit that would oscillate fast enough. At the same time each of us was a good tool to each other when we needed to debug as the subcircuit leader would explain their problem to a teammate leading to great suggestions. An example was debugging the VCA, where talking with teammates led to the understanding that there was a short in the circuit.

References

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