Musical Hand Design Document

Spring 2022

Team 24

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1. Introduction

1.1. Problem & Solution Statement:

Musical instruments come in all shapes and sizes; however, transporting instruments often involves bulky and heavy cases. Not only can transporting instruments be a hassle, but the initial purchase and maintenance of an instrument can be very expensive. For example, let us consider stringed instruments. The initial purchase can easily reach 3-4 digits while strings and bows often need replacements or repairs. We would like to address the issues of cost and portability by creating an instrument using electronic synthesis that is lightweight, compact, durable, and low maintenance.

Our project involves a wearable system consisting of two gloves and a chest mount. The left glove will be used to dictate the pitches of three “strings” using relative angles between the palm and fingers. For example, from a flat horizontal hand a small dip in one finger is associated with a low frequency. A greater dip corresponds to a higher frequency pitch. Rotational movement of the right glove will modulate the generated sound by adding effects such as vibrato. Finally, the brains of the project will be the central unit, a wearable, chest-mounted subsystem responsible for the audio synthesis and output. Unlike products such as MiMu Gloves, separate sources of audio synthesis will not be necessary and the user will not need to do any programming of the product themselves [1]. Since the sound synthesis is self-contained within our system, our project provides a lightweight and highly portable solution. We will also be utilizing accelerometers instead of flex sensors to limit wear and tear, which would solve the issue of expensive maintenance typical of more physical synthesis methods.

1.2. Visual Aid:

Figure 1. Visual representation of our solution

1.3. High-level Requirements:

The requirement for a minimally viable product are as follows:

1.1. While wearing the product, the user must be able to fully extend their arms directly to the side and downwards; in addition, the user must be able to bend their fingers by at least 90 degrees without resistance.

1.2. The vibrato effect caused by the right hand's movement can maximally change the extent of vibrato by ±100 cents (one semitone) demonstrated by the equation:

$$fr \pm fr_{\text{vitbrato}} = fr(1 \pm 2^{1/12})$$

1.3. The product must output frequencies ranging from 196 ±15 Hz (G3) to 1760 ±120 Hz (A6); each finger will approximately cover two octaves.

2. Design

2.1. Block Diagram

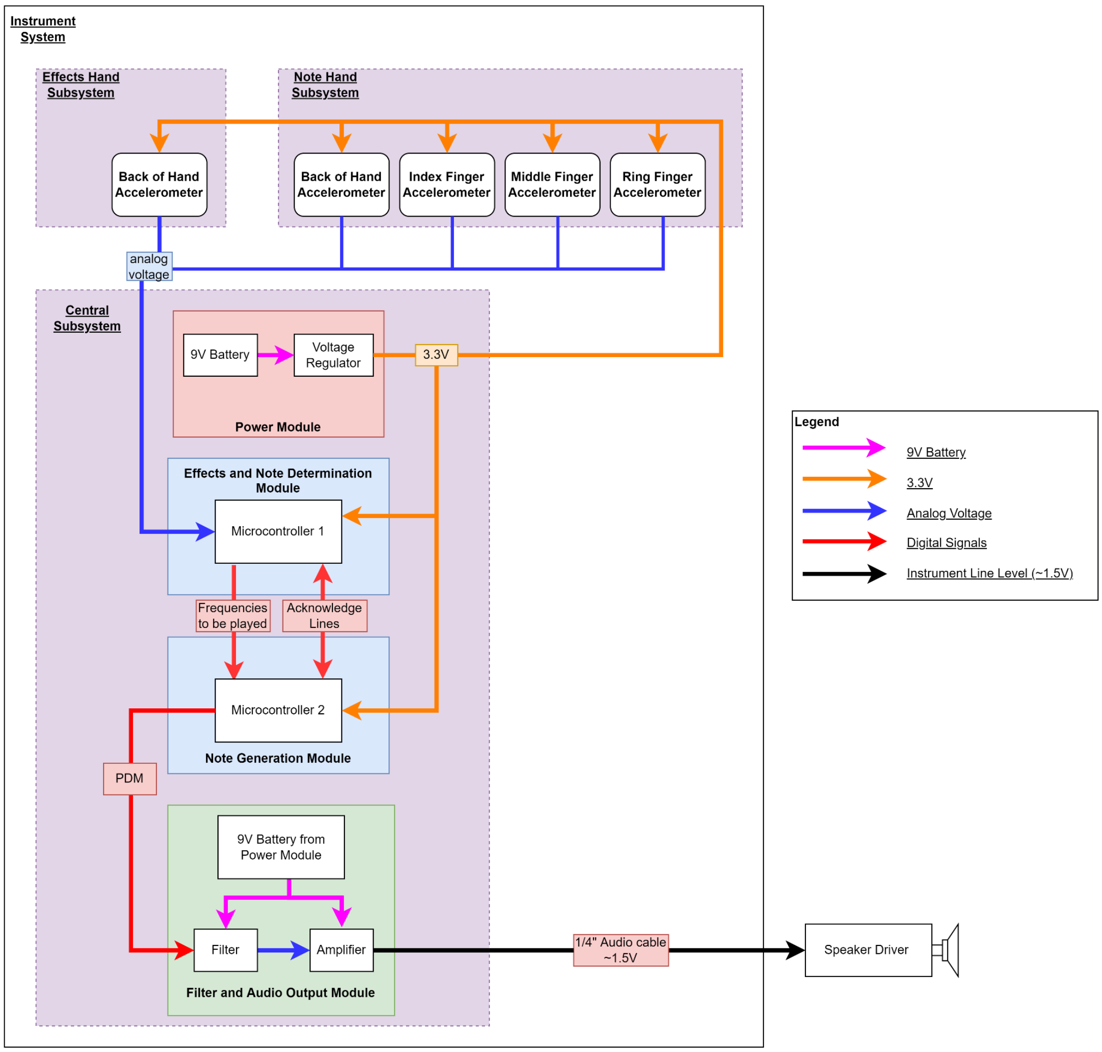


Figure 2. High level block diagram of entire system

Our system consists of three main subsystems: the note hand, effects hand, and central subsystems. The note hand (left hand) subsystem consists of three accelerometers located on the user's ring, middle, and index fingers along with an additional accelerometer on the back of the hand. These sensors will be used to measure the relative angles between the back of the user's hand and fingers; each finger's angle will be correlated with a pitch/note. We utilize one more accelerometer in the effects hand (right hand) subsystem to determine the wrist rotation (roll) of the hand, which will be correlated with a vibrato effect on the notes generated by the note hand subsystem. The sensor data from both of these subsystems will be directly connected to the onboard ADCs of Microcontroller #1 in the central subsystem [2]. The central subsystem processes data from the accelerometers to determine and generate the correct audio output. This subsystem contains two microcontrollers which will process the accelerometer data and perform wave table synthesis to generate the appropriate PDM signal. This PDM signal is fed into the filter and audio output module in the central subsystem, which converts it into the actual audio output to be given to a speaker driver. All three subsystems operate on the voltage provided by the power module housed in the central subsystem.

2.2. Note Hand Subsystem

Block Description:

The note hand will consist of four 3-axis accelerometers; we plan on using Analog Devices' ADXL335BCPZ-RL7 [3]. The measured accelerometer values will be passed as analog signals to the on-board ADCs of Microcontroller #1 in the central subsystem. These sensor values will be used to calculate the angle each finger forms in relation to the back of the hand. Each finger will cover a different range of frequencies (approximately two octaves) and each angle will correspond to a pitch within that finger's range. The smaller the angle/flatter the finger, the lower the pitch is. Capacitors are included in this subsystem to meet the manufacturer's requirements for the accelerometer [3]. Each accelerometer will require its own PCB which has been designed small enough to meet the need of fitting on the back of a finger. The accelerometer PCB design shown below is 1.45 cm wide, with the finger of a team 24 member measuring roughly 1.9 cm wide shown directly next to it. This demonstrates that the accelerometer PCB is narrow enough to keep from impeding a musician's movement.

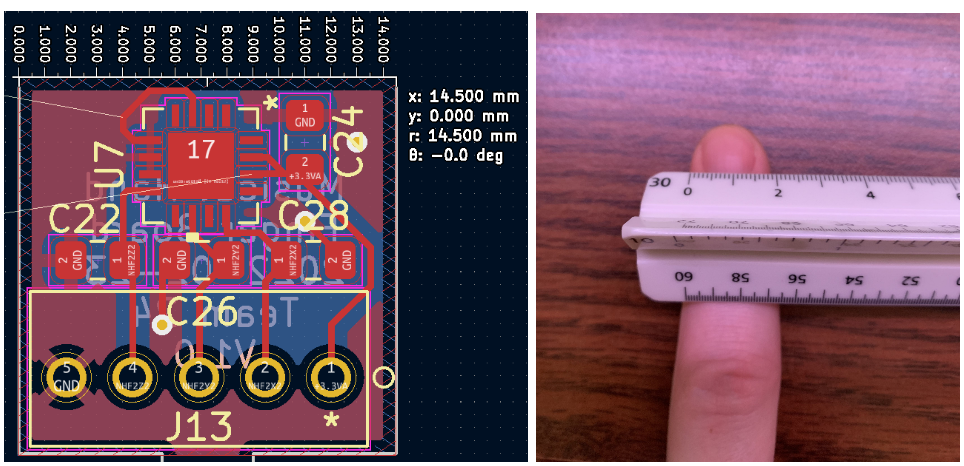
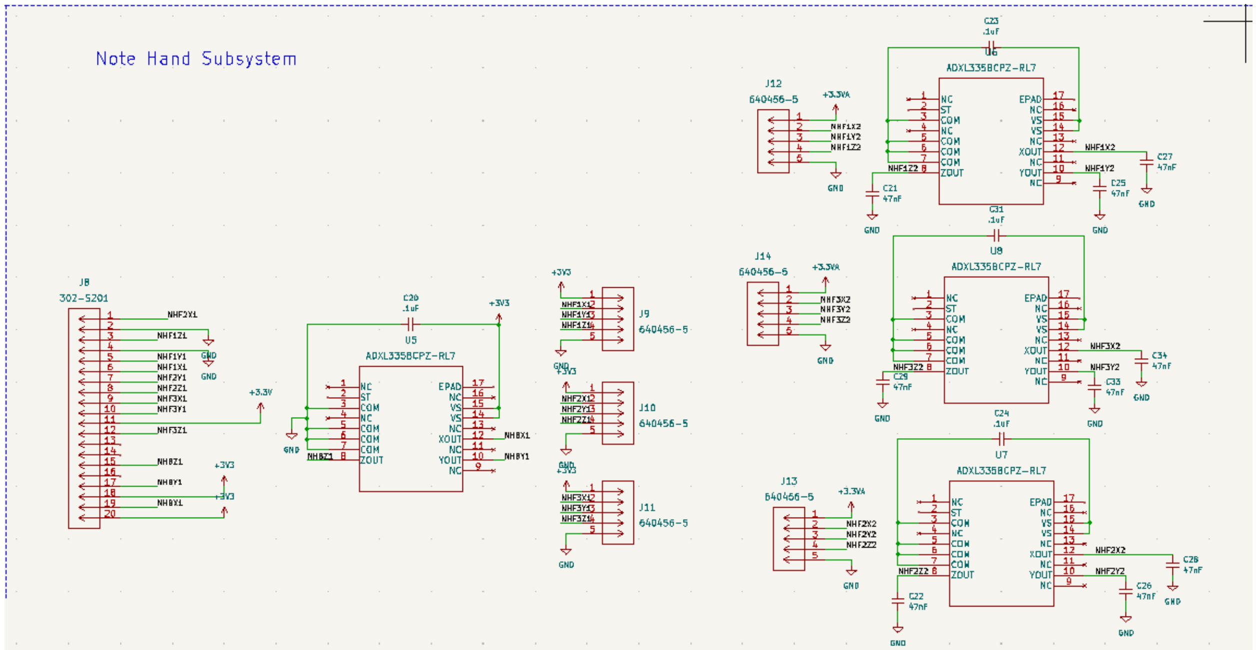


Figure 3. Comparison of PCB width to finger width

Schematic:



R&V Table:

Requirements	Verification
1. Accelerometers must output a voltage between -0.3 - 3.6V	1. a. Using a power supply, connect the PCB-attached accelerometer to 3.3 V and ground. Connect the analog voltage outputs to an oscilloscope for monitoring. b. Quickly moving the accelerometer along the x, y, and z axis, ensure that the output remains between -0.3 and 3.6 V.
2. From a flat hand, a finger dip of 90 ± 10 degrees must cause a change in output voltage of 0.55V ± 0.3V	2. a. Using a power supply, connect the PCB-attached accelerometer to 3.3 V and ground. Connect the analog voltage outputs to an oscilloscope for monitoring. b. Wearing an accelerometer PCB on the back of a gloved finger, dip the finger from parallel to perpendicular to the floor, ensuring the voltage changes by 0.55V ± 0.3V

Table 1. Requirements and Verification for Accelerometers on the Note Hand

Calculations:

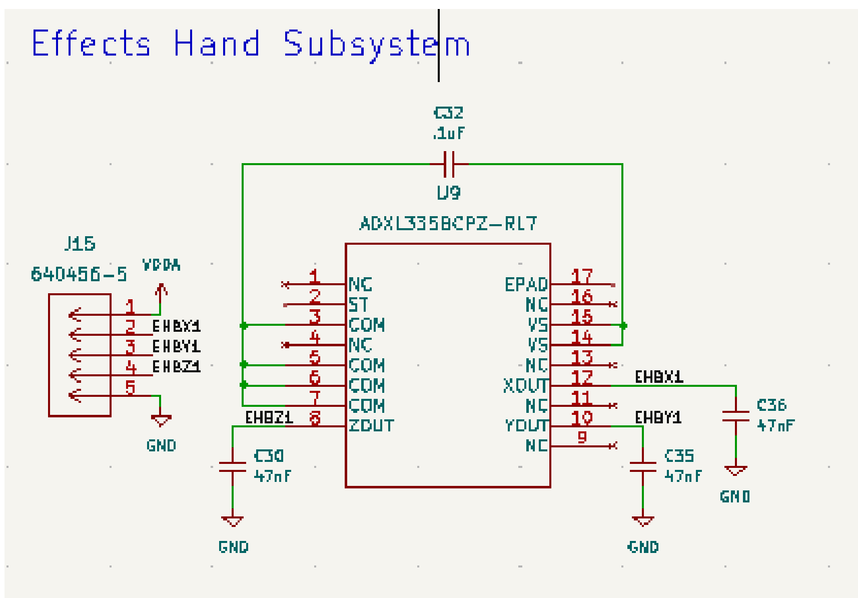
Requirement 2 derivation: Given that the supply voltage will be 3.3V and accelerometers should be able to handle ± 3g to account for hand movement, each g of change will be .55V [3]. This means that when we bend a finger 90 degrees, the net change in gravity will be .55V nominally. This means that a .55V ± .3V range would ensure that we can get the data we need with enough error margin for any tolerances in the part, the acceleration to voltage scaling, or user error.

2.3. Effects Hand Subsystem

Block Description:

The effects hand contains a single accelerometer across the back of the right hand. We are planning to use the same accelerometers from the note hand subsystem in the effects hand: Analog Devices' ADXL335BCPZ-RL7. The accelerometer will be connected to an on-board ADC of Microcontroller #1 in the central subsystem. The sensor values would be used to determine the rolling movement of the right hand. This motion will be used to calculate how much vibrato to apply to the pitches generated from the note hand's data. Capacitors are included in this subsystem to meet the manufacturer's requirements for the accelerometer [3].

Schematic:



R&V Table:

Requirements	Verification
1. Accelerometers must output a voltage between -0.3 - 3.6V	1. a. Using a power supply, connect the PCB-attached accelerometer to 3.3 V and ground. Connect the analog voltage outputs to an oscilloscope for monitoring. b. Quickly moving the accelerometer along the x, y, and z axis, ensure that the output remains between -0.3 and 3.6 V.
2. Using a flat hand as the 0 degree reference point, when the wrist is rotated from -90 degrees (thumb down) to 90 degrees (thumb up) there must be a change in the output value of 1.1V with a ± 0.55V tolerance.	2. a. Using a power supply, connect the PCB-attached accelerometer to 3.3 V and ground. Connect the analog voltage outputs to an oscilloscope for monitoring. b. Attaching the accelerometer PCB to the back of a glove, rotate from -90 to 90 degrees, ensuring an output change of 1.1V with a ± 0.55V tolerance.

Table 2: Requirements and Verification for accelerometers on the Effects Hand

Calculations:

Requirement 2 derivation: Given that the supply voltage will be 3.3V and accelerometers should be able to handle ± 3g to account for hand movement, each g of change will be .55V [3]. This means that when we rotate the hand 180 degrees, the net change in gravity will be 1.1V nominally. This means that a 1.1V ± .55V range would ensure that we can get the data we need with enough error margin for any tolerances in the part, the acceleration to voltage scaling, or user error.

2.4. Central Subsystem

Block Description:

The central subsystem takes input from the effects and note hand subsystem to generate audio output. To do this, two microcontrollers from the Microchip PIC32 series will be used [2]. Microcontroller #1 will receive information from the sensors on both gloves through on board ADCs and use it to calculate the corresponding output frequencies. Microcontroller 2 uses these frequencies and wavetable synthesis to generate a PDM signal to feed into the output and filter module. The use of two separate microcontrollers allows for the logic to take longer, accounting for slower human response time, while meeting needs for quicker audio updates. At the output, there will be a second order multiple feedback filter. This will get rid of any switching noise while also allowing us to set a gain. This will be done using an LM358 Op amp along with the necessary resistors and capacitors to generate the filter and gain [4]. This output will then go to an audio jack that will go to a speaker. In addition, bypass capacitors, pull up resistors, pull down resistors, and the necessary programming circuits will be implemented on this board. The central subsystem also contains the power module, which consists of a 9V battery and a voltage regulator.

2.4.1. Power Module

Schematic:

R&V Table:

Requirements	Verification
1. The linear regulator needs to supply 3.3V ± 0.05V tolerance to power the system. 2. The 9V battery must be able to supply 9V ± 2V tolerance to the amplifier under operating conditions before a voltage divider creates a 3.3V ± 0.3V DC offset. 3. Under operating conditions, the regulator will not exceed 125°C [5]	1. Connect output of linear regulator to oscilloscope or voltmeter, observing the output voltage is 3.3V ± 0.05V. 2. a. Connect the 9V battery of the power module to the amplifier. b. Drive the amplifier with a 3.3V peak-to-peak sine wave from a function generator. c. Using an oscilloscope, observe that 9V ± 2V is provided and the DC offset of the amplified signal is 3.3V ± 0.3V. 3. Using an IR thermometer during verification 1, observe the linear regulator stays beneath 125°C

Table 3. Requirements and Verification for the regulator and battery

2.4.2. Microcontrollers

Schematic:

Figure 4. Schematic of both microcontrollers

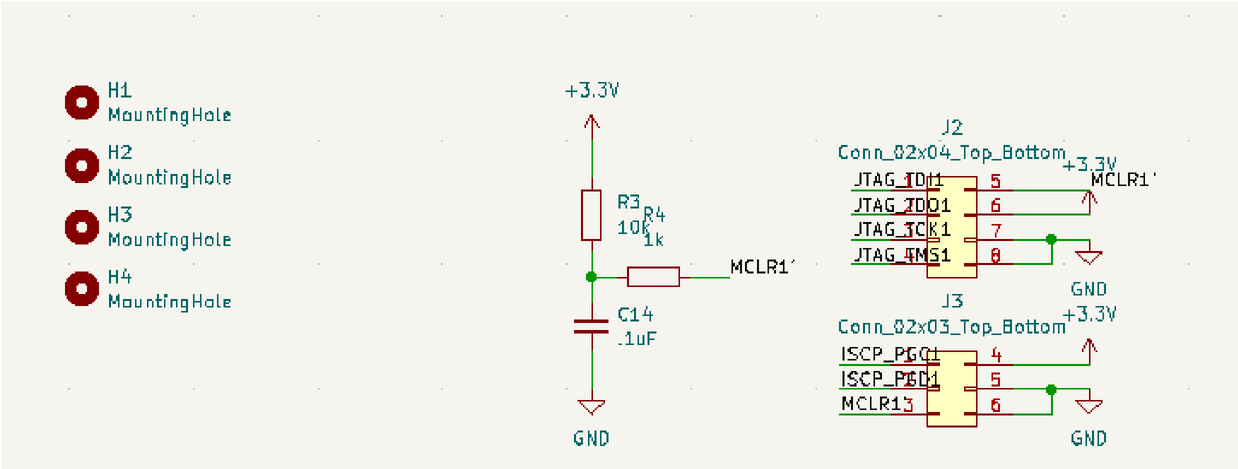


Figure 5. Supporting circuitry for Microcontroller #2

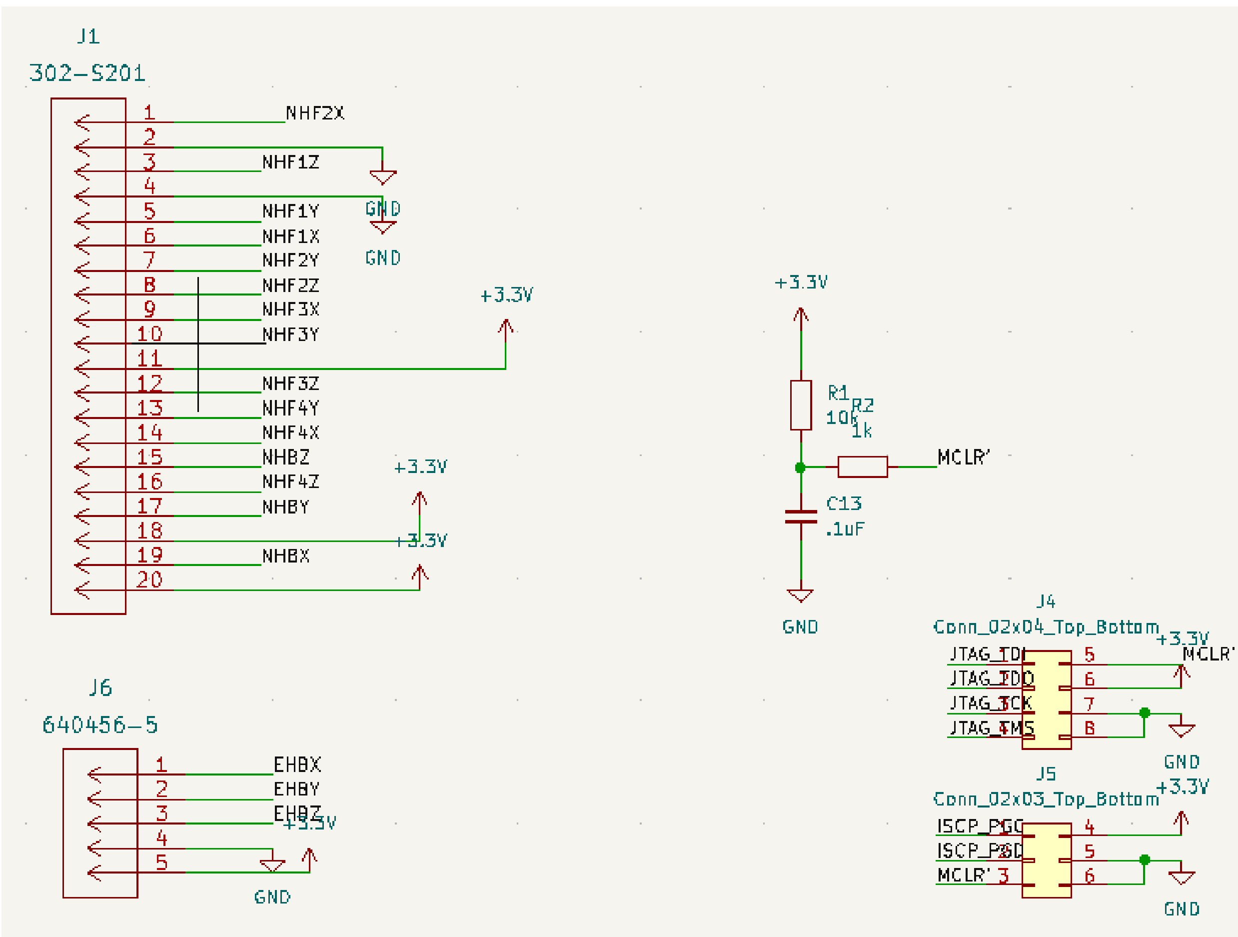


Figure 6. Supporting circuitry for Microcontroller #1

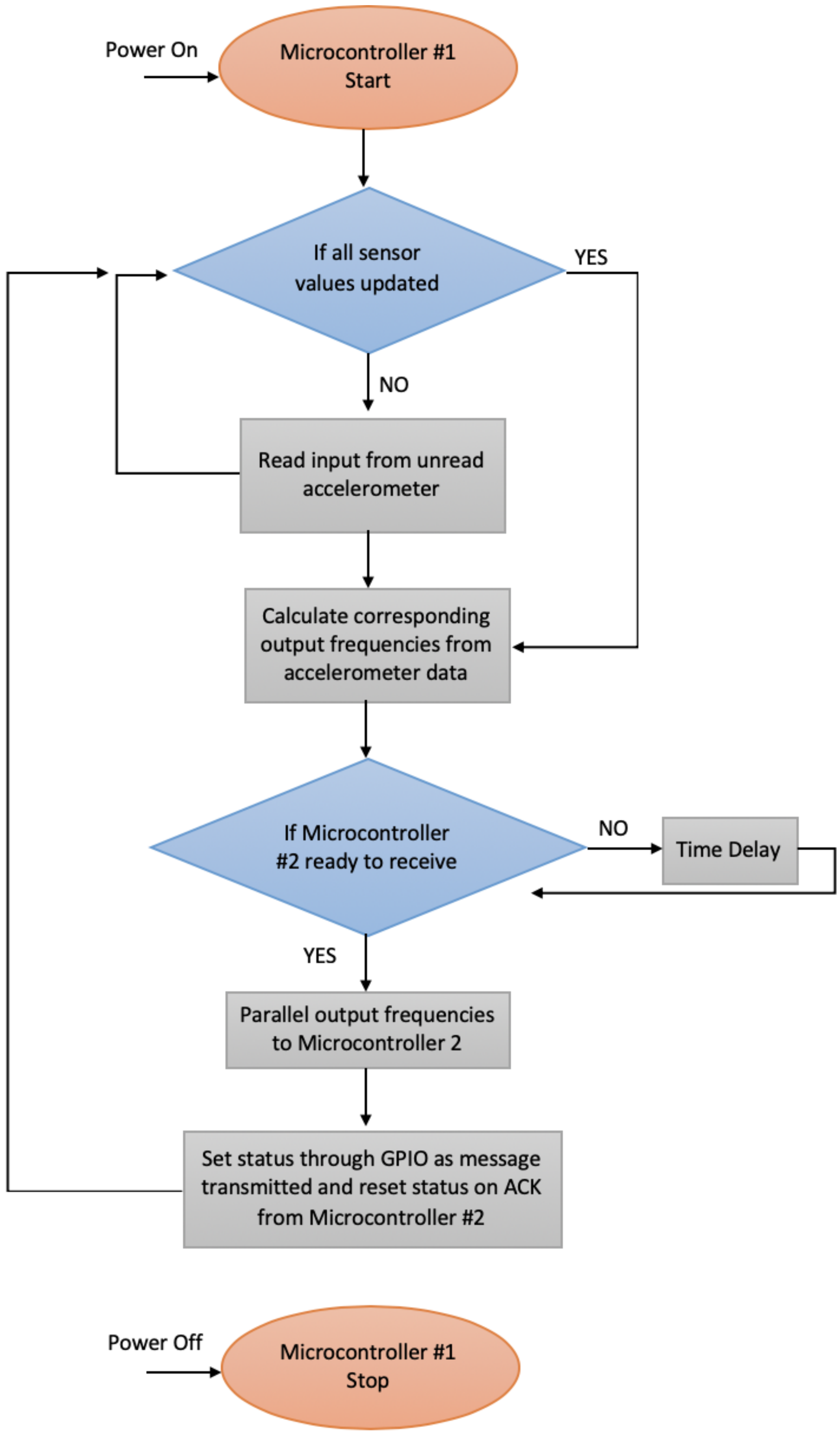


Figure 7. Program flowchart for Microcontroller #1

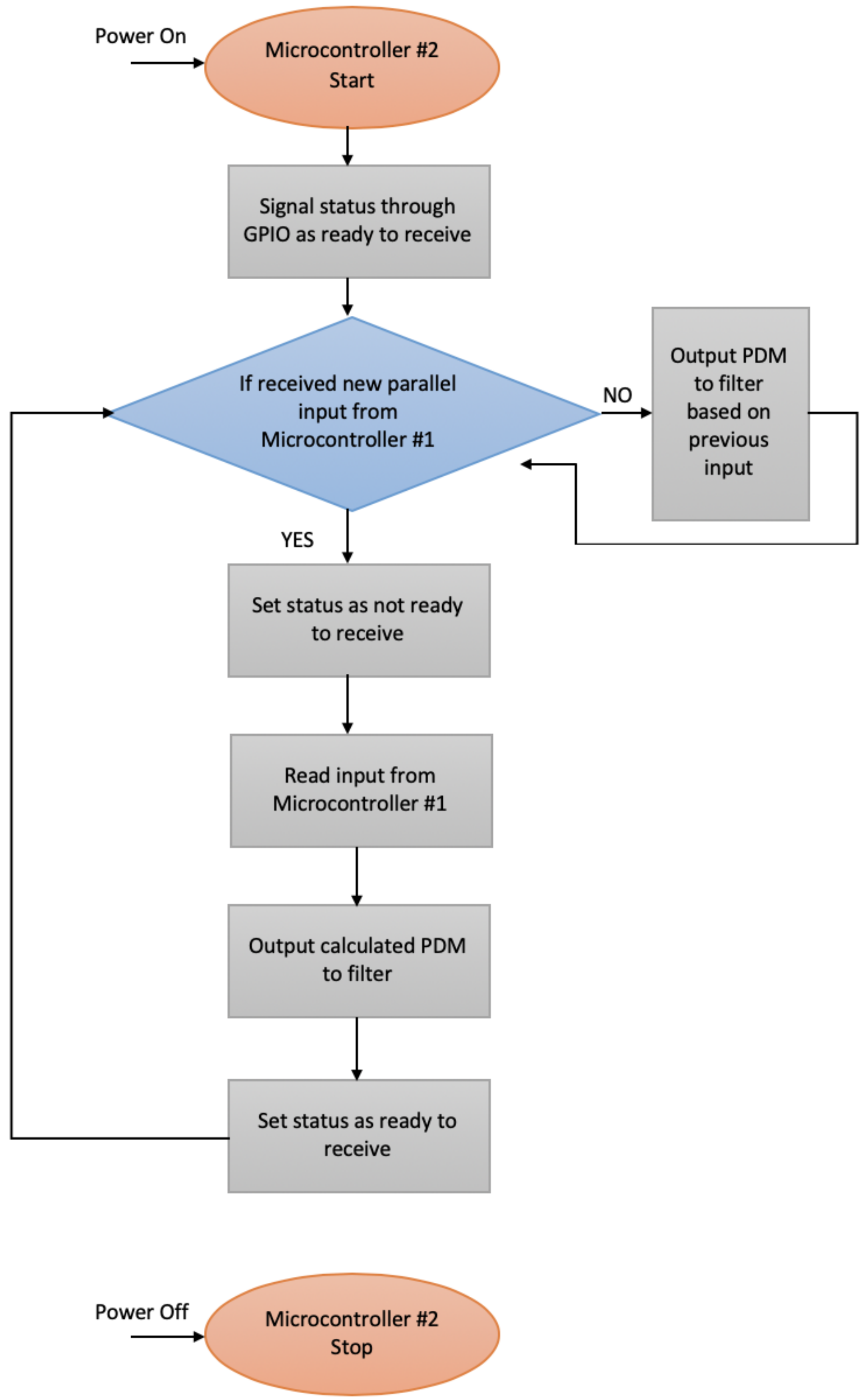


Figure 8. Program flowchart for Microcontroller #2

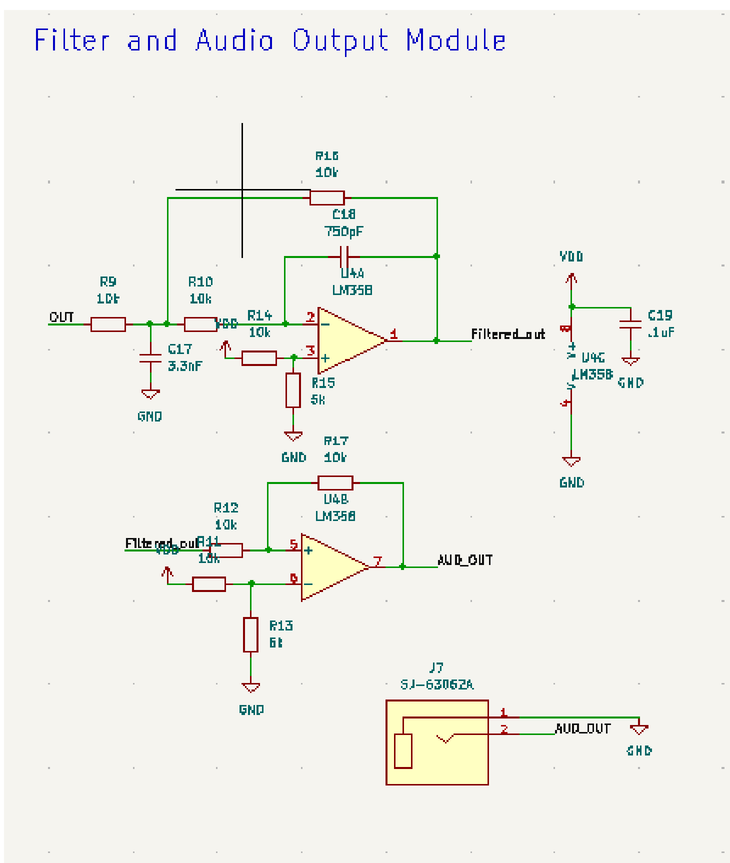
R&V Table:

Requirements	Verification
1. Microcontroller #1 needs to map finger angles to frequencies between 196 ±15 Hz (G3) to 1760 ±120 Hz (A6)	1. a. Hold sensor input stable with flat hand b. Use SNAP debugger to iterate through the program and observe output values. c. Connect oscilloscope or voltmeter to probe test points/breakout pins on Microcontroller #1 and confirm the output matches the software output d. Repeat b and c for a sensor input of a completely bent hand
2. Microcontroller #2 needs to output PDM signal	2. Connect output of Microcontroller #2 to oscilloscope to observe signal shape.

Table 4. Requirements and Verification for Microcontroller #1

2.4.3. Output Filter and Amplifier

Schematic:



R&V Table

Requirements	Verification
1. Output waveform voltage must be between 0.25V - 3.3V when driven by a 3.3V Peak- Peak PDM signal.	1. With a function generator set to a 3.3V peak-peak square wave, measure the output voltage of the filter with an oscilloscope, ensuring that it stays between 0.25V - 3.3V sweeping the DC% from 0-100% during the test.
2. Cut-off frequency of filtered signal is 10 kHz +/- 11% with 40dB/dec +/- 10dB/dec attenuation after cut-off point.	2. a. Connect filter input to a function generator set to drive a 3.3 V peak-peak sine wave. b. Connect filter output to oscilloscope. Starting at 7 kHz, sweep the frequency upwards to 20 kHz. c. Record oscilloscope output data, verifying the location of cut-off is within +/- 11% of 10 kHz and the attenuation follows a 40dB/dec slope within +/- 10dB/dec.
3. The Op-Amp IC must not exceed the maximum temperature rating of 70°C under operating conditions. [4]	3. Using an IR thermometer, monitor the temperature of the Op-Amp during Verification 1 and 2, verifying an under 70°C temperature throughout.

Table 5. Requirements and Verification table for Multiple Feedback filter

2.5. Tolerance Analysis:

One source of tolerance analysis that needs to be considered is the accelerometers. From the accelerometer data sheet, the sensitivity will be about 360 mV/g [3]. Given that the ADCs in the microcontroller have 12 bits of resolution, we will have a resolution of $\frac{3.3V}{2^{12}}$ = .806 mV per division. This means that if the sensitivity is off by a factor of 10, we will still be able to differentiate between 1g differences with $\frac{36}{.806}$ = 44 points between them.

Consider the worst case scenario; the difference between the lowest note and highest note (2 octaves) that a given finger can play is mapped to a 1g difference (90 degree finger bend). Given that there will need to be 24 points of resolution at minimum per g in order to hit all 24 semitones in the two octaves that are required, and that there is a .808 mV per division resolution, this means that as long as the accelerometers change the output voltage by 20 mV for a 1g change, the system will be able to hit all semitones in the range that the finger can do. Since the expected sensitivity is 360mV/g, this is not going to be an issue.

The filter and amplifier module is the part of the design that requires the most consideration in regards to tolerance. The system uses a LM358 dual op-amp to make a second order filter with a 10kHz cutoff frequency and an amplifier with a gain that can be easily adjusted by modifying a single resistor. The second order filter topology used is a multiple feedback architecture. This sort of architecture has a cutoff frequency equal to $\frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$. These values and the equation were found from this application report [6] from TI. We set all resistors to 10kΩ and capacitors with 3.3nF and 750pF, this gives us a cutoff of 10.12kHz. If all resistors and capacitors are 5% larger than expected due to their tolerance, we get a cutoff of 9.17kHz, and if all were 5% lower than expected, we would get a cutoff of 11.21kHz, both of which fall within the 11% range that we specified. The reason that this is an important figure is that the highest frequency that we will output is 1.76kHz. By ensuring that the cutoff frequency is far away from this maximum value, we can ensure that little to no attenuation will occur at our notes and that the noise from the PDM switching will be attenuated to a significant degree.

Another tolerance analysis that needs to be done revolves around the battery and the op-amps. The op-amps have a certain range of the supply rails that it can drive a voltage. For the op-amp used, the output needs to be 1.5V away from the positive supply and 20mV from the negative supply if the supply is at 5V, with the difference increasing as the supply increases. This means that with the 3.3V input logic, we need a supply voltage of at least 5V to ensure that our op-amp works as intended. Given that we want the system to be portable, this means that the powering method can't be 3xAA batteries as the 4.5V would not be enough. For this reason, a 9V battery will be used to power the system. This will give the filter a larger range to work with which in turn will allow us to have more tolerance on the biasing for the op-amp and allow for a larger gain at the output.

The following plots are simulations to demonstrate these considerations. The schematic used is shown first. This is the same circuit that will be used in the actual design. The first plot is with the 9V supply, a unity gain, and an input frequency for 440Hz. We can see that the output voltage is about the same amplitude, just at a higher DC bias. We can see from the second plot what happens with a 5V supply. The signal gets clipped at both ends due to it getting too close to the supply rails at different points in the circuit. While some tweaking of values can make this effect minimized, it will be incredibly reliant on proper matching of values. For example, if the voltage divider of the filterstage gets a resistor larger than 5.7k in series with the 10k resistor, the simulation breaks down due to ill-behaving outputs. Plot three shows the 9V supply and a 100kHz input while plot 4 shows a 1MHz input voltage. As we can see, there's significant attenuation at these frequencies, and at 1MHz, the output looks like a DC voltage.

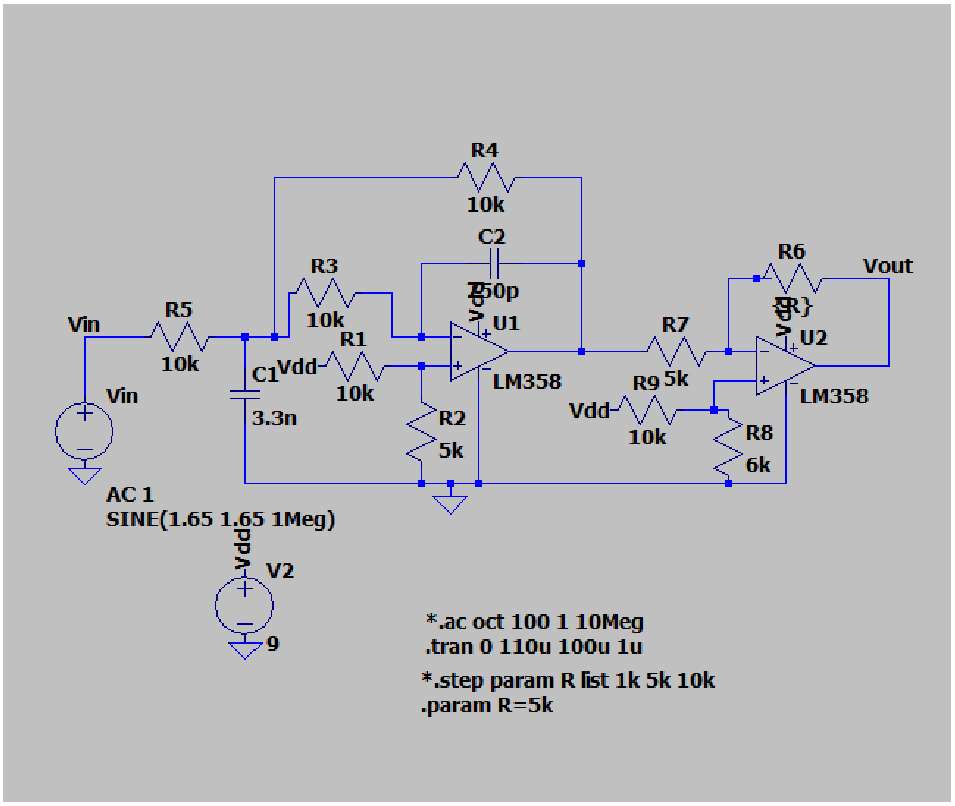


Figure 9. Multiple Feedback filter and amplifier circuit

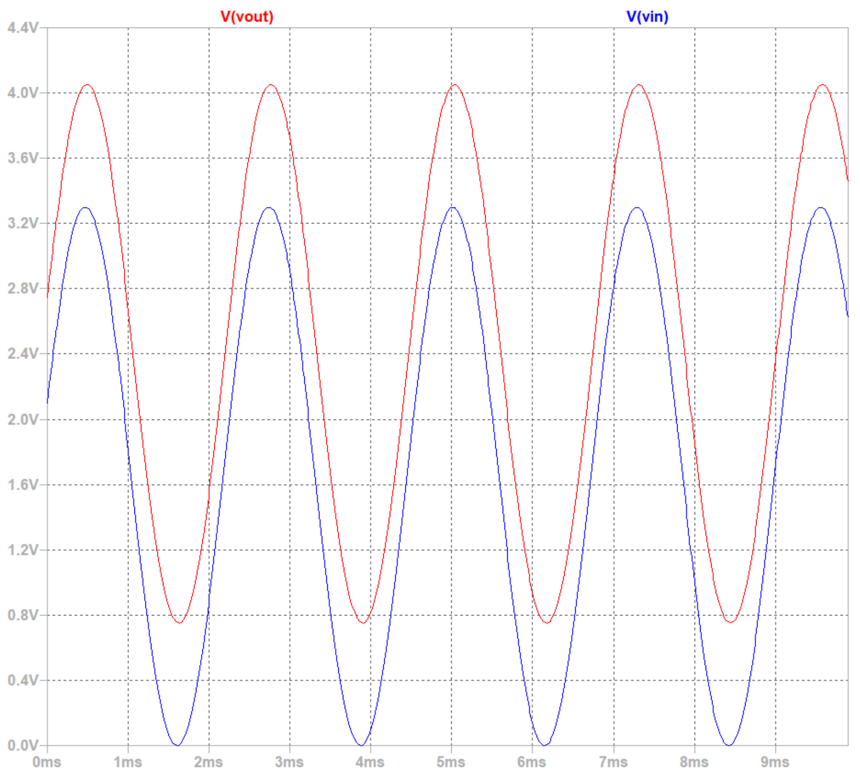


Figure 10. Nominal output of circuit in Figure 6

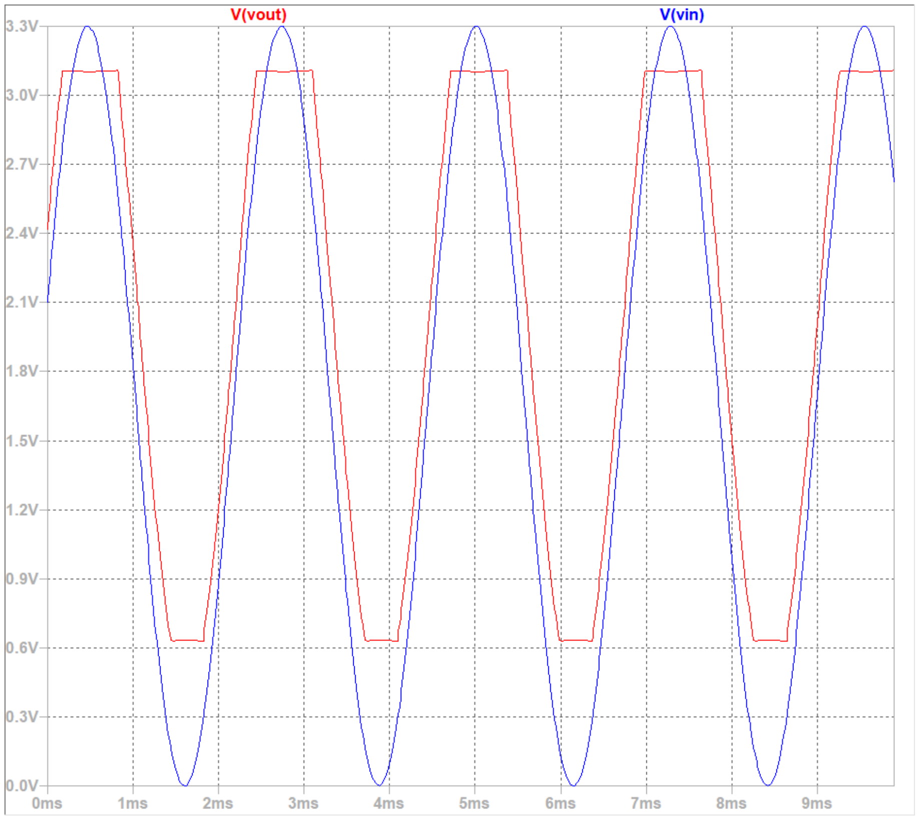


Figure 11. Output of Figure 6 circuit with 5V supply and 440 Hz input

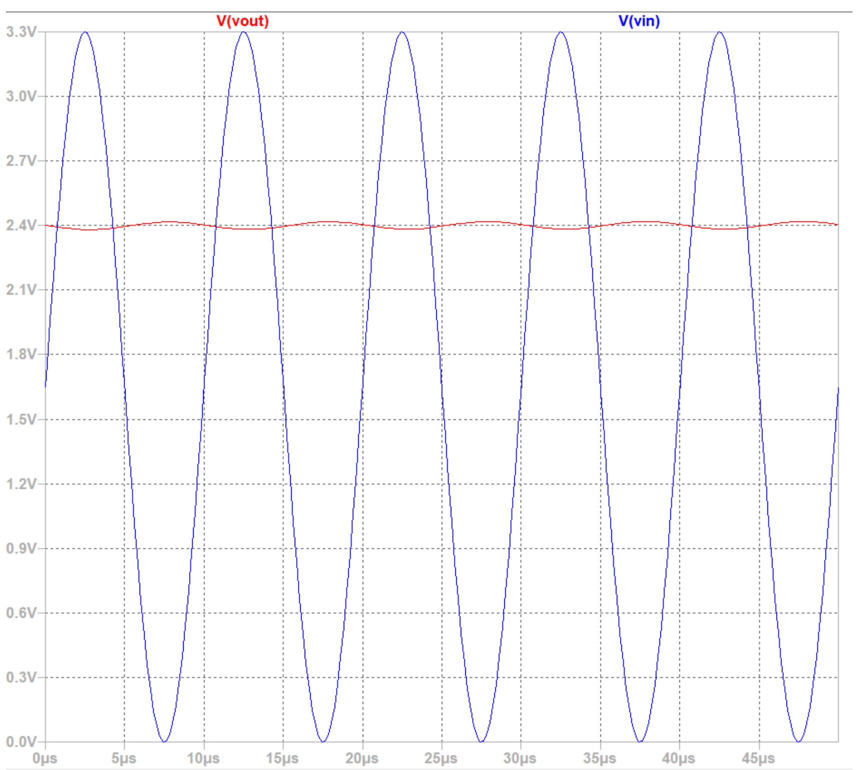


Figure 12. Output of Figure 6 circuit with 9V supply and 100 kHz input

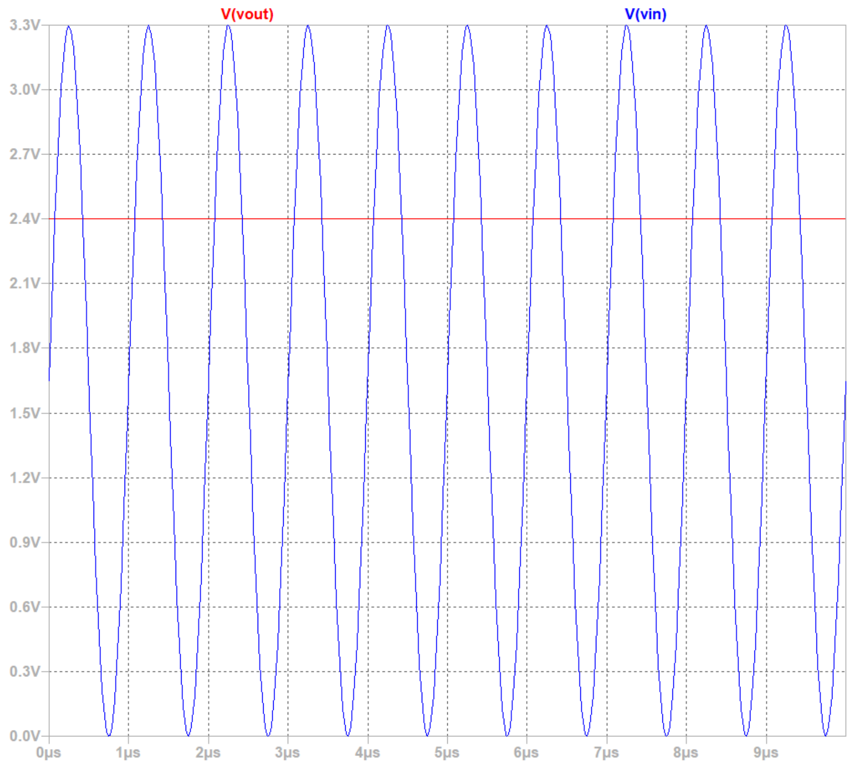


Figure 13. Output of Figure 6 circuit with 9V supply and 1 MHz input

3. Cost & Schedule

3.1 Cost Analysis

Labor:

Accounting for labor costs requires an analysis of the average starting salary for UIUC ECE graduates as well as a more project-specific positional average across relevant companies. To calculate an accurate figure for this, the differing engineering disciplines of creation need to be considered. Overall, the finished product is a fully contained audio synthesizer. Moog is a relevant company to this style of electrical product, so the starting salary average of an electrical product engineer has been included. The DSP coding requirements of our microcontroller are important for synthesis so the starting salary of an Analog Devices DSP engineer is also included. The analog nature of the accelerometers and audio output used needs to be integrated into the overall design, explaining the inclusion of a Texas Instruments Analog Applications Engineer. Finally, the starting salary of an audio software designer for Shure is used. To begin calculating overall labor cost, the aforementioned salaries were averaged and divided by 2080 hours (the amount of hours worked in a year based off of 40 hour work weeks and 52 weeks/year) for a $/Hour figure. Then, the calculated rate was multiplied by 2.5 and 132 hours (based on 12 hour work weeks and 11 weeks of actual product design and assembly in ECE 445). This yielded a project salary figure for each student in the group, which was multiplied by 3 students for a total labor cost.

Company	Position	Average Starting Salary	$/Hour	Project Salary/Person	Total Labor Cost
Moog	Electrical Product Engineer	$76,610.00	$36.83	$12,154.47	$36,463.41
Analog Devices	DSP Engineer	$109,807.00	$52.79	$17,421.30	$52,263.91
Texas Instruments	Analog Applications Engineer	$85,188.00	$40.96	$13,515.40	$40,546.21
Shure	Software Engineer	$83,023.00	$39.91	$13,171.92	$39,515.75
Grainger College of Engineering	Electrical Engineer	$79,714.00	$38.32	$12,646.93	$37,940.80
Grainger College of Engineering	Computer Engineer	$96,992.00	$46.63	$15,388.15	$46,164.46
Average	Musical Hand Engineer	$88,555.67	$42.57	$14,049.70	$42,149.09

Table 6. Spreadsheet for calculating labor cost of Team 24

Parts:

In the following cost analysis for the parts used in the Musical Hand, a few estimates were made. The fabrication of the chest plate for mounting of the central subsystem will be done by 3D printing a custom model specifically for our project. Also, all capacitor and resistor prices were based off of bulk pricing per unit, as the majority of these parts are provided by the ECE department.

Part Name	Part #	Manufacturer	Description	# of Units	Cost/Unit	Total Cost
Dual OP Amp	LM358	Texas Instruments	Used in amplifier block for appropriate analog output level	1	$1.54	$1.54
1/4" Female TS Jack	SJ-63062A	CUI Devices	Used in audio cable block as output for synthesizer	1	$2.09	$2.09
10cm x 10cm PCB Housing	BC-AGS-10 1007	Boxco	Used as housing for central subsystem	1	$11.10	$11.10
Electrolytic Capacitors	P53XX-ND	Panasonic	Used in Power Module block	2	$0.22	$0.44
Ceramic Capacitors	CK-05	NTE Electronics, Inc	Used in Filter block for switching noise reduction	3	$0.44	$1.32
0805 Surface Mount Capacitors	SMC0805K 104	NTE Electronics	Used in applications across all subsystems for noise reduction	34	$0.09	$3.06

0.5W 5% Carbon Resistors	293-VAL-RC	Xicon	Used in	9	$0.07	$0.63
0805 Surface Mount Resistors	ERJ-P6WJ103V	Panasonic	Used in	8	$0.08	$0.64
1' 5-Conductor Ribbon Cable	8124/05 100	3M	Used for device connection in note hand and b/w effects hand/central subsystems	6	$2.10	$12.60
3.3' 20-Conductor Ribbon Cable	M3DDA-2040K	3M	Used for device connection b/w Central and Note hand subsystems	1	$9.00	$9.00
Microcontroller	PIC32MK0512GPD064T-E/PT	Microchip Technology	Used as Effects and Note Determination and Note Generation modules	2	$9.32	$18.64
Accelerometer	ADXL335BCPZ-RL7	Analog Devices Inc.	Used in Effects Hand and Note Hand subsystems as analog inputs	5	$7.00	$35.00
20-Position Through-Hole Header	302-S201	On Shore Technology Inc.	Used on Note Hand and Central Subsystems for PCB connection	2	$0.50	$1.00
5-Position Through-Hole Header	640456-5	TE Connectivity AMP Connectors	Used on Note Hand, Effects Hand and Central Subsystems for PCB connection	8	$0.38	$3.04
5-Conductor Receptacle Connector	3-643813-5	TE Connectivity AMP Connectors	Used for terminating and connecting 5-conductor ribbon cable	8	$0.40	$3.20
Linear Voltage Regulator	LT1963ET-3.3#PBF	Analog Devices Inc.	Used in power module to regulate 3.3V logic voltage	1	$6.91	$6.91
Pair of Cotton Gloves	DNA	COYAHO	Used as mount for Effects Hand and Note Hand Subsystems	1	$1.00	$1.00
Plastic Chest Plate	DNA	Ramsey	Used as mount for Central subsystem	1	$0.25	$0.25
1" Woven Nylon Straps with buckles	DNA	Vtete	Used to make Plastic Chest Plate wearable	1	$8.95	$8.95
3/4" Adhesive Velcro Tape - 1'	DNA	Velcro Brand	Used to mount PCBs to Cotton Gloves and Plastic Chest Plate	2	$0.63	$1.26
9V battery	L522	Energizer Battery Company	Used as main power source to Op-Amp and Voltage Regulator	1	$12.60	$12.60
9V battery connector	234	Keystone Electronics	Used to connect 9V battery to PCB	1	$0.57	$0.57
2 x 3 header	PREC003DFAN-RC	Sullins Connector	Used to connect programmer to PCB	2	$0.16	$0.32

2 x 4 header	PREC004D AAN-RC	Sullins Connector Solutions	Used to connect programmer to PCB	2	$0.19	$0.38
Programmer	PG164100	Microchip Technology	Used to program the microcontrollers in the central subsystem	1	$30.99	$30.99
Total						$166.53

Table 7. Spreadsheet for determining total cost of project parts

Total:
With the labor and parts analysis concluded, the total cost of the project is labor + parts = $42,149.09 + $166.53 = $42,315.62.

3.2 Schedule

Week	Summary	Ramsey	Thomas	Michelle
Feb 21 - 25	Finish Design Document and preliminary PCB board layout.	Draft preliminary PCB board layout	Write and format design document.	Write and format design document.
Feb 28 - Mar 4	Finalize PCB design and finish ordering all components. Begin development of code with evaluation board.	Finalize PCB design.	Order remaining components.	Begin development on evaluation board and familiarization with IDE.
Mar 7 - 11	Ensure PCBway order is submitted and breadboard to test voltage regulator, filter, and amplifier. Continue program development.	Breadboard testing of voltage regulator, filter, and amplifier.	Breadboard testing of voltage regulator, filter, and amplifier.	Continue program development and work on interfacing with sensors.
Spring Break	N/A	N/A	N/A	N/A
Mar 21 - 25	Solder PCB and perform I/O testing of subsystem connections. Fix any errors in the second round PCBway order. Use	Fix errors and layout for second PCB order.	Soldering and PCB I/O testing.	Help with soldering and continue program development.

	development board for preliminary code testing.			
Mar 28 - Apr 1	Complete soldering and all I/O between subsystems. Convert and develop program for pcb microcontroller	Finish soldering and I/O testing.	Help with program development. Finish soldering and I/O testing.	Convert program from evaluation board to pcb board
Apr 4 - 8	Finish final physical design with gloves and chest mount. Develop and debug program	Glove, PCB housing, and chest mount fabrication.	Glove, PCB housing, and chest mount fabrication.	Develop and debug program and calculations.
Apr 11 - 15	Debug and fine tune program and calibrations. Finish final touches on physical design. Begin preparations for mock demo.	User verification testing of musical hand. Begin preparations for mock demo.	User verification testing of musical hand. Begin preparations for mock demo.	Debug and fine tune program and calibrations. Begin preparations for mock demo.
Apr 18 - 22	Mock demo and prepare for final demo	Prepare for demos, presentations, and paper.	Prepare for demos, presentations, and paper.	Prepare for demos, presentations, and paper.
Apr 25 - 29	Final demo and mock presentation	Final demo. Prepare for presentations and paper.	Final demo. Prepare for presentations and paper.	Final demo. Prepare for presentations and paper.
May 2 - 6	Deliver presentation and finish final paper	Finish final touches on presentation and paper.	Finish final touches on presentation and paper.	Finish final touches on presentation and paper.

Table 8. Team 24 schedule to complete ECE 445

4. Safety & Ethics

Keeping with the IEEE code of ethics [7], safety and health must take priority. In this regard, the main ethical and safety concerns of our project involve the audio output and power source. Since the power source is part of the chest mount, we must ensure that it does not overheat and burn the user. As for the audio output, we must ensure that our product maintains a reasonable volume and does not generate any frequencies that cause discomfort or harm (ex: very high frequencies).

To mitigate the chances of risk, a few tests and procedures must be done. First is stress testing the system to ensure that at all points of operation pose no risk to the user. This would imply running the system for significant amounts of time while monitoring the temperature of components without the device being worn. This will provide a controlled environment and not put anyone at risk during testing while effectively testing the system in the most intensive use cases. Another stress test is to test the maximum frequencies that the system can produce by slowly increasing the frequency from the lowest value to the highest. This will allow us to ensure that the pitch will never be so high that it can cause harm to humans. Finally, we will test volume by first having the external amplifier that will be used set to the lowest volume then increasing it from there. This will allow us to test that our output voltages are within the range needed to provide an audible output without being loud enough to cause damage.

5. Citations

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3. “ADXL335 (Rev. B).” Analog Devices, Norwood, 2009.
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5. “LT1963 - 1.5A, Low Noise, Fast Transient Response LDO Regulators.” Linear Technology Corporation, Milpitas, 2005.
6. M. Steffes, “Design Methodology for MFB Filters in ADC Interface Applications.” Texas Instruments, Texas, 2006.
7. “IEEE Code of Ethics,” *IEEE*. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: 21-Feb-2022].

6. Appendix

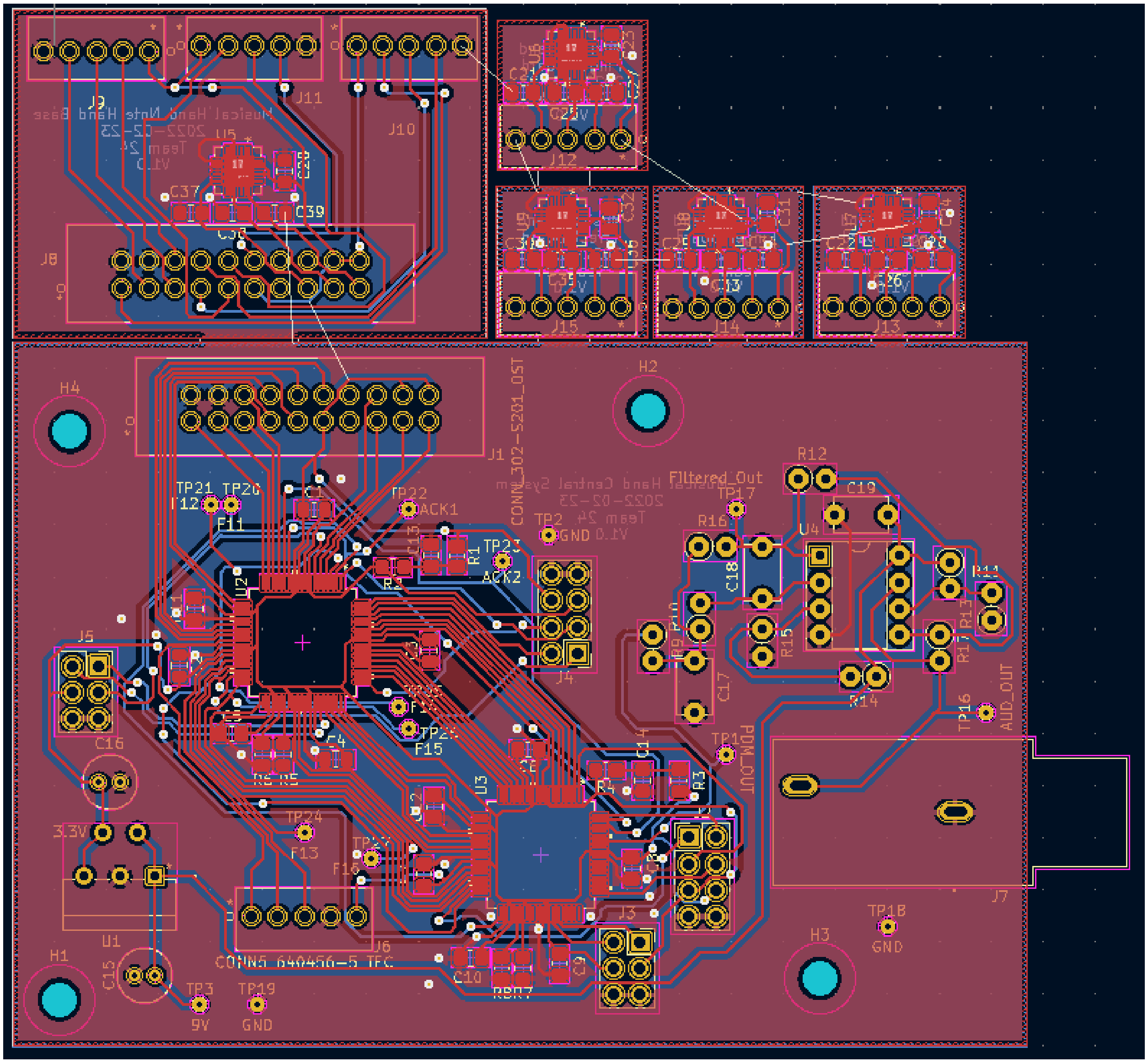

Figure 14. Overall view of PCB board