Remote Wah Guitar Pedal

ECE 445 Design Document - Fall 2023

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Introduction

Guitar and bass players have a wealth of effects pedals to choose from in order to modify the sound of their instrument, such as adding distortion, echo, reverb, etc. In most cases, the controls for effects pedals are set by the player beforehand and turned on and off with a footswitch, or controlled by a foot treadle to modify a single parameter, such as the sweep of a high-Q bandpass filter in a wah pedal. However, this requires the player to remain fixed in place while using the effect, which can get in the way of the performance aspect of playing live music. It would be very convenient & expressive to have a way of controlling the parameters of certain effects while maintaining the ability to move around a stage unimpeded.

Our idea is that rather than using a foot treadle to control the filter sweep of a wah pedal, the range of the filter sweep is controlled by a sensor mounted to the headstock of a guitar/bass. This allows achieving the characteristic sweep sound of a wah by swinging the guitar up and down rather than using a foot treadle, which allows the use of the effect anywhere on stage and makes for an interesting visual accompaniment that is suited for live performance (it would look pretty cool). To further aid in freedom of movement, the effect will have the ability to be remotely activated via a button mounted to the body of the guitar within convenient reach of the player.

Visual Aid

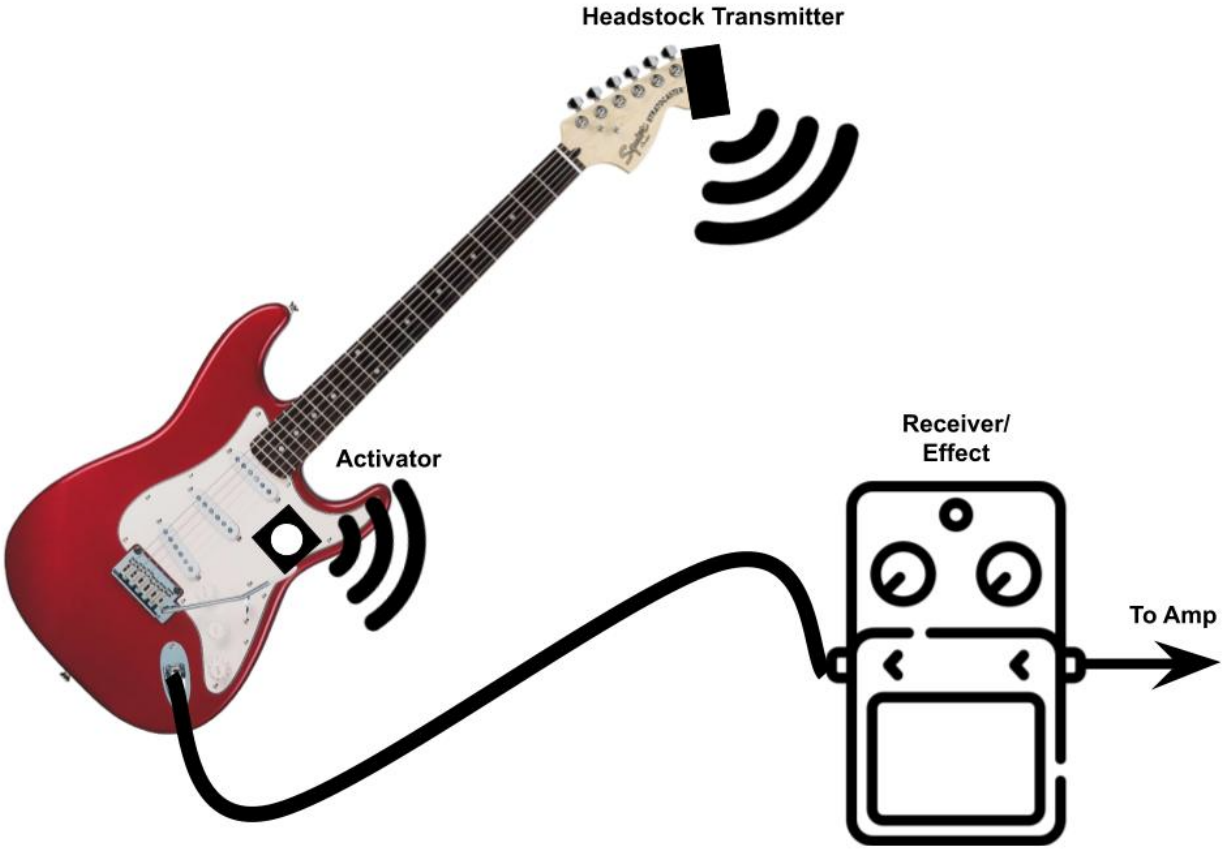


Figure 1: Mock-up of our design in use

High-Level Requirements

In order to satisfy the core of our goals for this project, we should meet the following criteria:

- Successful linkage between transmitters and receivers to control circuit hardware, allowing the effect to be switched on and off and accelerometer to control the filter sweep
- The receiver is able to process the raw accelerometer data from the transmitter into a usable digital potentiometer sweep
- The wah circuit is able to implement a suitably high-Q filter sweep across a musically appropriate range of the audible spectrum, around 350 Hz to 2.2 kHz.

Design

Block Diagram

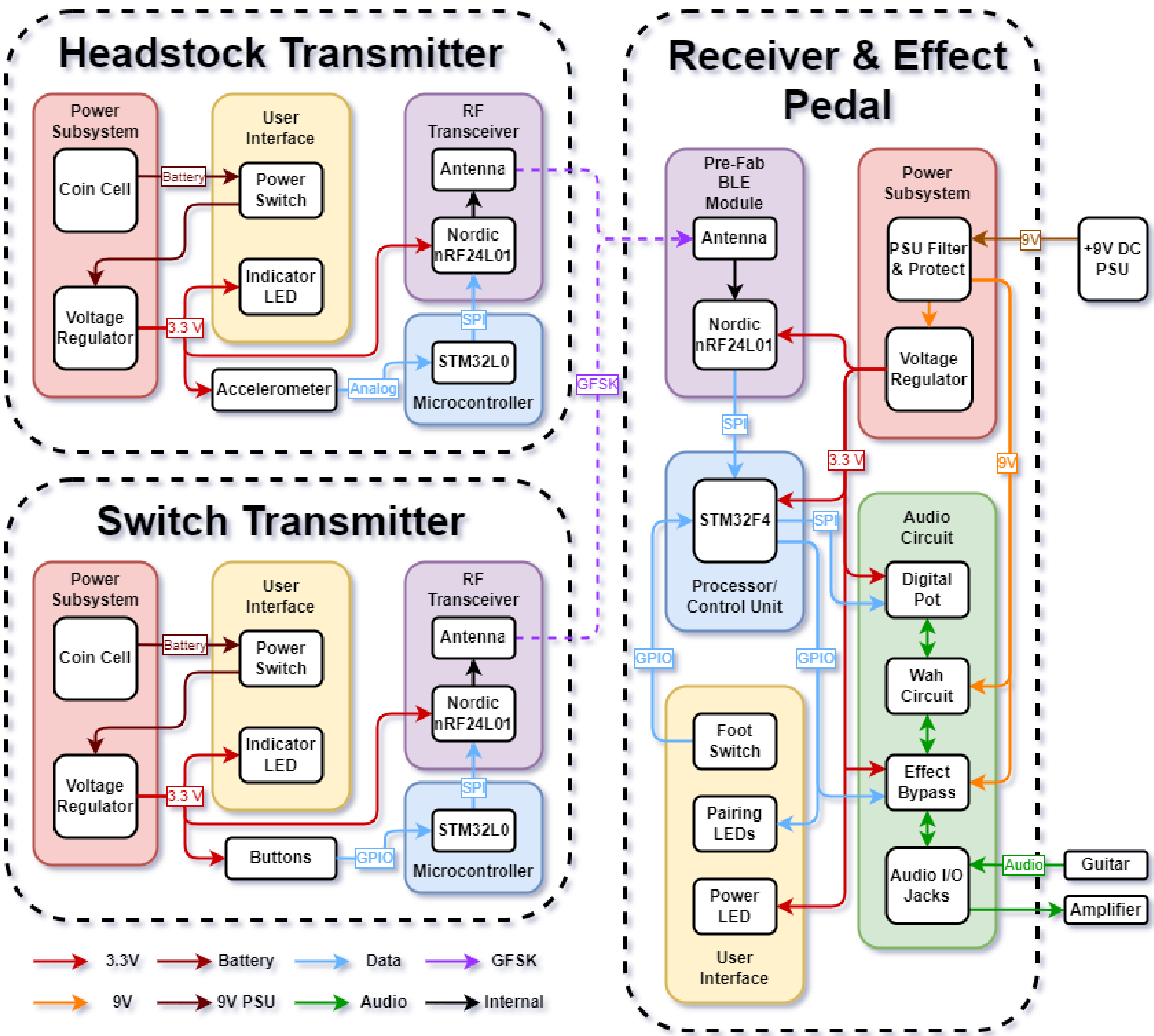


Figure 2: Block Diagram

Our solution involves the creation of three components: A headstock transmitter to wirelessly relay accelerometer data, a button interface that allows the effect to be turned on and off remotely, and the main floor pedal receiver which processes the accelerometer data into the appropriate control signals for sweeping the digital pot and routing the audio path, as well as implementing the actual wah effect.

Subsystem Designs

Headstock Transmitter

Schematic:

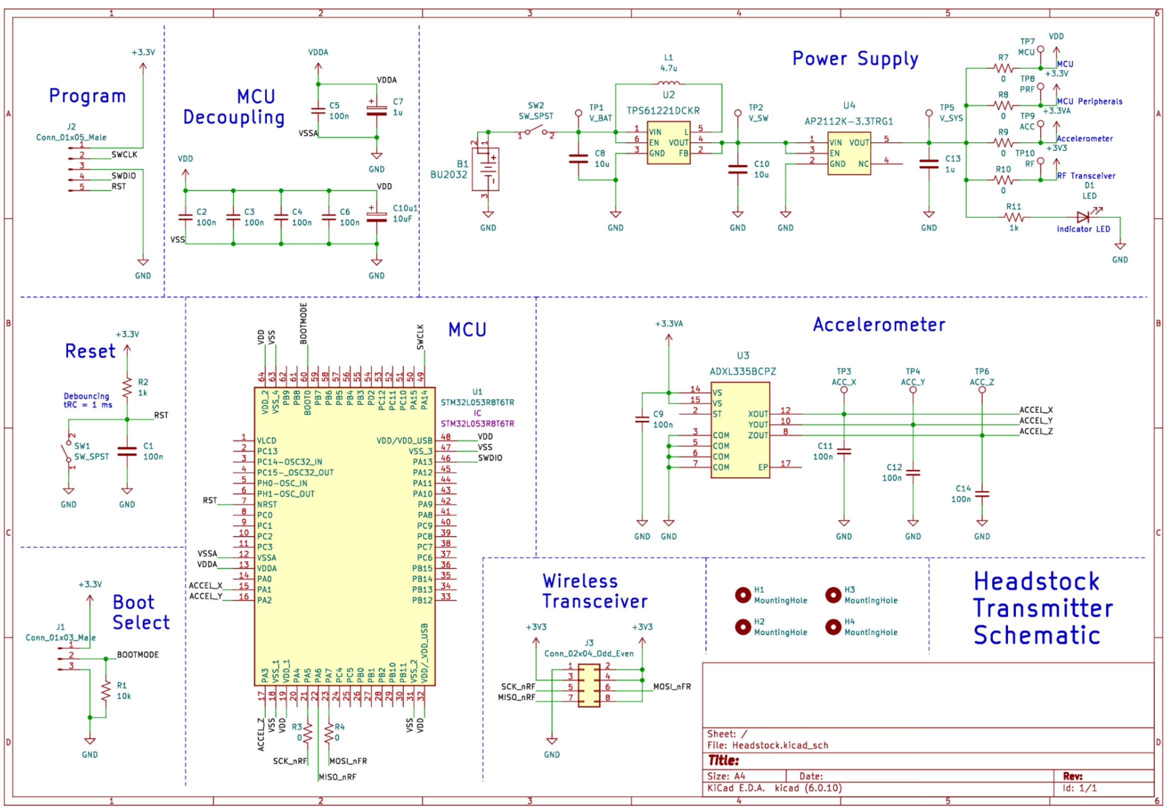


Figure 3: Headstock Transmitter Schematic

Block Description:

The headstock transmitter's primary purpose is to send the sensor data read from the on-board accelerometer back to the floor pedal receiver to be processed. Internally there will be an accelerometer, the Analog Devices ADXL355, which will output an analog voltage proportional to the acceleration of the device. An analog accelerometer was chosen for ease of use, as it keeps the number of serial interfaces that need to be programmed to a minimum. This same chip was also used successfully in previous projects [5], lending us confidence to use it. This voltage is then converted into digital data using the integrated 12-bit ADC included in the STM32L053 microcontroller. Finally, the accelerometer data is sent to a wireless transceiver, a Nordic nRF24L01 based module, and transmitted to the floor pedal receiver.

The STM and nRF chips were chosen for their extensive individual documentation [7] [8] [9] [10] [11], as well as resources that aid in their operation together [6]. The microcontroller will communicate to the transceiver using SPI, and the transceiver will send the data using GFSK in the 2.4 GHz frequency band. Nordic devices are certified by the FCC to operate in this frequency range [12], which gives us confidence to use it in our design.

The headstock transmitter is powered using a standard 3V CR2032 coin cell battery, which is then up-converted using a boost converter [14] to achieve 3.3V operation for the rest of the circuit and further regulated with an LDO [15]. Boost converters operate at high frequencies which can leak into the supply rails [16], so the additional LDO is included to reduce any ripples should they occur. A power switch is also included to turn the effect off when not in use, as well as a power indicator LED.

Requirements and Verifications:

• Accelerometer axes output ± 990 mV from 1.5 V bias point through range of motion, within a maximum ± 25% tolerance (1)	1. Connect accelerometer supply rail and ground to + 3.3 V external supply 2. Connect accelerometer axes test points to oscilloscope 3. Record output voltage reading from the accelerometer while moving it at the maximum reasonable speed the device will be used, and verify reading is

	within acceptable boundaries.
• Output of power supply maintains 3.3V across maximum load of 150 mA within ± 5%, including both voltage sag and power supply ripple	1. Plug in coin cell battery, or attach 3V supply to the input test point of boost converter 2. With all internal power rails disconnected, attach 47 Ohm resistor to LDO output test point 3. Measure output voltage across load across resistor and verify it remains within ± 5% of 3.3 V

(1) Tolerance bound is derived and examined in Tolerance Analysis section

Effect Switcher

Schematic:

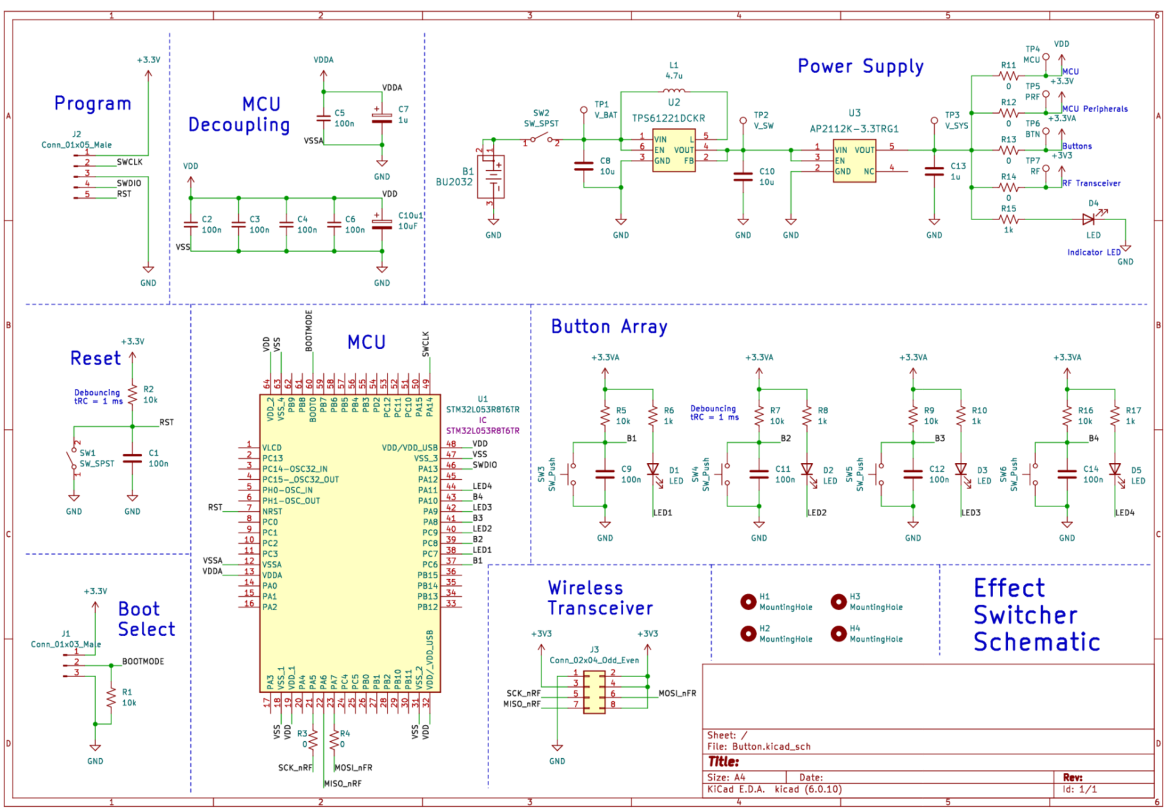


Figure 4: Effect Switch Schematic

Block Description:

The effect switcher is designed to remotely turn the wah effect on and off from the pickguard of the user's guitar. On the exterior of the package will be four buttons, each with a corresponding indicator light, which can control the routing of the audio signals in the floor pedal receiver. Our initial design only necessitates a single button to turn the effect on and off, but as a reach goal we plan on having two effects embedded within our pedal with increased routing flexibility. The buttons then can serve both as on/off switches, and as user-configurable "macros", which can turn on multiple effects with the same button, reverse effect order, etc.

Buttons that are mapped to be On/Off switches have their corresponding LEDs turn on and off to indicate their position. Buttons that are mapped to have a macro function will override the settings of the On/Off buttons and their LED status, turning them off and turning on the corresponding macro LED. This behavior is outlined in greater detail in the Software section. Buttons and their corresponding LEDs are connected to the microcontroller through GPIO pins.

The microcontroller and wireless transceiver used are the same STM32L053 and Nordic nRF24L01 parts from the headstock transmitter, which allows us to cut down on design complexity by reusing design elements. In the same manner as before, the button data is sent from the microcontroller to the wireless transceiver via SPI, and then wirelessly using GFSK. The power supply scheme is also the same, and thus will have the same testing requirements.

Requirements and Verifications

• The corresponding LEDs for each button behave according to our specification, as highlighted above and in the Software section	1. Plug in coin cell battery, or attach 3.3V supply to the V_SYS test point 2. Press buttons in various sequences and verify correct LED & signal behavior is being observed
• Output of power supply maintains 3.3V across maximum load of 70 mA within ± 5%, including both voltage sag and power supply ripple	1. Plug in coin cell battery, or attach 3V supply to the input test point of boost converter 2. With all internal power rails

	disconnected, attach 47 Ohm resistor to LDO output test point 3. Measure output voltage across load across resistor and verify it remains within ± 5% of 3.3 V

Floor Pedal Receiver

Control Unit:

Schematic:

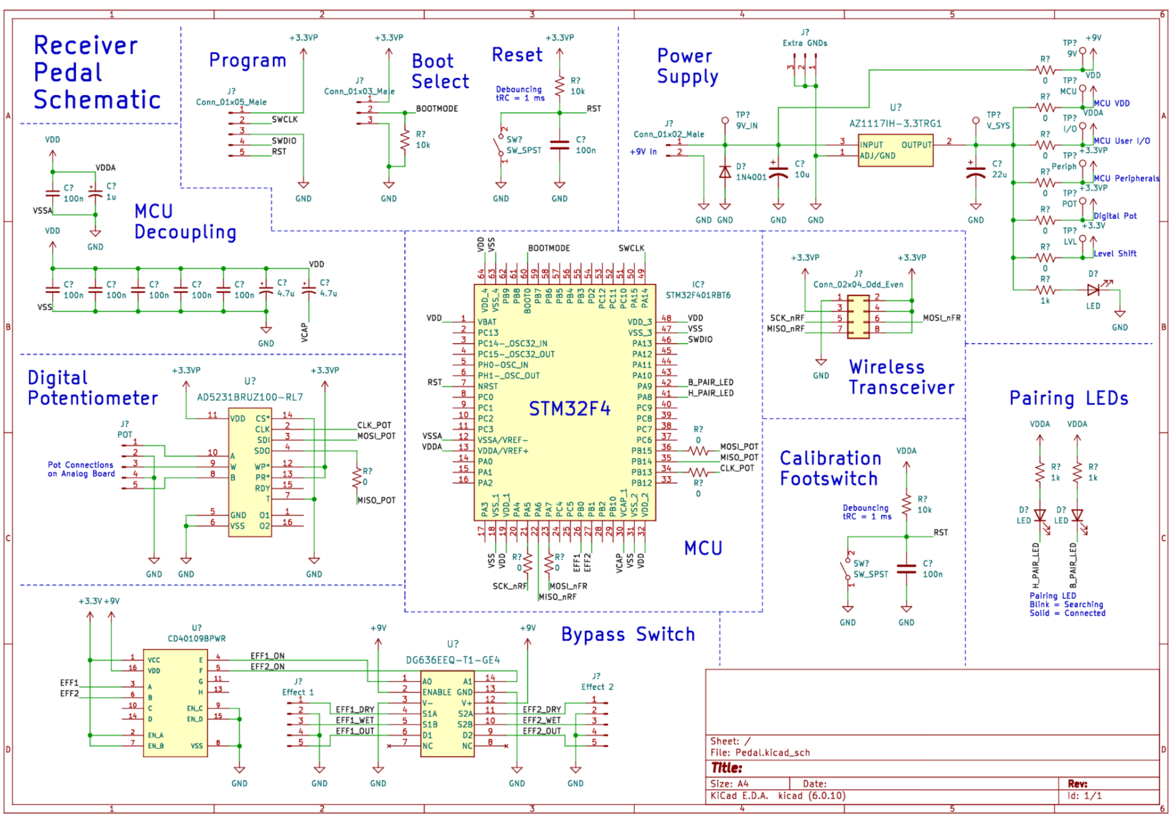


Figure 5: Floor Pedal Schematic

Block Description:

The control unit board for the floor pedal receiver is designed to control both the sweep of the filter in the audio board and the routing of audio signals from it. This starts with the wireless transceiver, another Nordic nRF24L01 module, which receives data from both of the transmitters and sends it to the microcontroller via SPI. A useful feature of the nRF module is that it can communicate with up to 6 devices concurrently [11], which is mostly designed for mesh network applications but allows us to have multiple transmitters connected to one receiver. Two pairing LEDs are included to indicate the connection status of the transmitters, with blinking indicating that connection is being established, and a continuous light indicating that connection has been achieved.

The microcontroller is an STM32F4 [17], which is conveniently available in the ECE Service Shop Inventory, and also has more computing power than the STM32L0s in the transmitters. This extra processing power is needed to convert the raw accelerometer data into positional data that can be used to generate a sweep of the digital pot, the algorithm for which is detailed further in the Software section. This also offloads most of the processing away from the transmitter MCUs, which allows them to run at much lower clock rates and thus conserve power, which is ideal for battery powered devices. To aid with the processing of the accelerometer data, a footswitch is included to set a calibration point for the headstock transmitter that corresponds to an initial position. This will also allow the user to choose the range of the sweep they wish to use, as well as the spatial position that range moves through, which is useful for accommodating the various playing positions that a user may prefer to use.

Once the accelerometer data is processed into a 10 bit position value, it is sent to the digital potentiometer [18] via SPI. We chose to have the digital pot located on the control board, despite taking the place of a pot located within the circuit of the audio board, in order to ensure signal integrity of the digital communication interface. Low frequency audio signals are much more tolerant of longer signal paths than high frequency serial interfaces, whose signal paths start to behave as transmission lines. Thus in order to keep the serial interface traces short and avoid the undesired effects that arise from this behavior, it was chosen to keep the digital pot close to the microcontroller on the control board. This will lead to slightly worse noise performance of the audio signal compared to the alternative, but this is much more desirable than a faulty digital interface, which can cease to function entirely.

Signal routing for the audio board is included on the control board for roughly the same reasons. Audio signals are routed through an analog mux that behaves as an SPDT switch [19], allowing either an unaffected “dry” signal or effected “wet” signal to pass through. In the same manner as the buttons, switching for two audio effects is possible through the use of a dual analog mux, in the event we have time to implement a second effect. In order to interface between the 3.3 V logic of the microcontroller and the 9 V operation of the analog circuitry, a level shifter [20] is needed to interface with the analog mux.

The power for this board will be supplied externally from a 9 V DC wall adapter that is commonly used for guitar effects [13], which is already filtered and certified for sale as a commercial product. A reverse bias protection diode is included in parallel to the rest of the circuit to prevent damage from a user plugging in an incorrect supply. In such a scenario, this arrangement will destroy the diode, but using this arrangement also avoids the voltage drop associated with a protection diode in series during normal operation, allowing us to use the 9 V directly for the analog board. For the digital hardware, an LDO steps down the voltage from 9V to 3.3V.

Requirements and Verifications

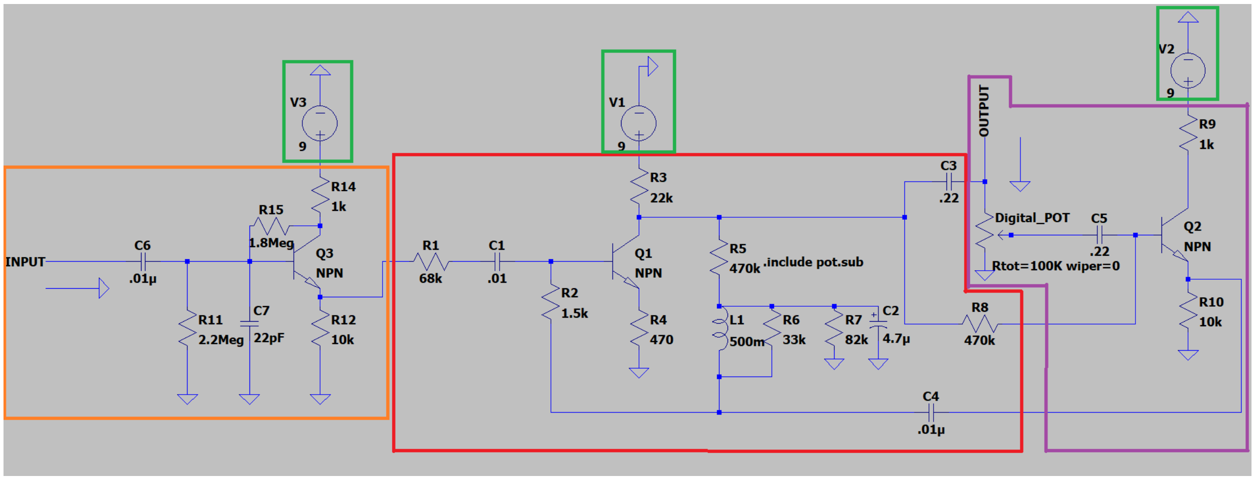
• Receiver pedal is able to receive data from both transmitters simultaneously	1. Power on all transmitters and receiver 2. Pair both transmitters to receiver, verify that indicator lights display correct status 3. Test that button data and accelerometer data is correct using procedures below
• Digital potentiometer implements a voltage divider which is able to output a voltage from 0 V to 9 V, ± 5%	1. Power on board with 9V supply 2. Connect outer pins of pot output connector to +9V and GND, and center pin to a multimeter/ oscilloscope 3. Create test program for microcontroller which increases the number of taps slowly between 0 - 1023

	4. Measure output voltage and verify that it sweeps from rail to rail, 0 V to 9 V.
• Microcontroller maps accelerometer data to a 10 bit position value which is able to sweep the digital potentiometer from 0V to 9V, $\Delta V \pm 5\%$	1. Power on board with 9V supply 2. Connect outer pins of pot output connector to +9V and GND, and center pin to a multimeter/ oscilloscope 3. Pair headstock transmitter to receiver pedal and load accelerometer data processor program 4. Move headstock transmitter up and down and record potentiometer output voltage, verifying that it sweeps between 0 V and 9V rail to rail.
• Button is able to select between dry and wet audio signals, with attenuation of less than 3 dB	1. Turn on and pair button transmitter and pedal receiver 2. Connect inputs of analog mux pins to two voltage sources outputting sine tones of different frequencies 3. Load button control program to microcontroller 4. Verify that the frequency of dry input is present at the output with button off, and wet input frequency is present at the output with button on 5. Connect analog mux output to oscilloscope and verify that it is attenuated less than 3 dB from the input signal amplitude

• Footswitch calibrates	1. Turn on and pair headstock transmitter and pedal receiver, connect digital pot leads to their respective outputs 2. Run accelerometer data processor program and verify that it works as previously stated 3. Move headstock transmitter to different starting location, press footswitch, and again move transmitter up and down and verify that the digital pot outputs a voltage sweep between 0 V and 9 V
• Power supply can accurately supply 9 V output up to 50 mA with $\Delta V \pm 1\%$ and 3.3 V at 100 mA with $\Delta V \pm 1\%$ simultaneously	1. Disconnect all internal PCB power rails 2. Connect 9V external power supply 3. Connect ~180 Ohm resistor to 9 V output test point, and measure voltage across resistor, verifying it remains within 9 V ± 1% 4. Connect ~33 Ohm resistor to 3.3 V output test point, and measure voltage across resistor, verifying it remains within 3.3V ± 1% 5. With both loads connected, measure voltages across each load and verify they both still operate within specified range

Audio/Wah Circuit

Schematic:



Blocks: Input Filter Output Power

Figure 6: Wah Effect Schematic

Block Description:

The Power blocks represent the power to be supplied externally by the previously mentioned One Spot 9V DC wall adapter [13], as this adapter is already filtered and includes reverse-bias protection. Resistors connecting the power blocks to the other blocks aid in suppression oscillation.

The Input block contains a common-collector NPN buffer. To avoid higher-frequency signal loss, the input impedance consisting of R11 and R15 is orders of magnitude higher than the output impedance. The need for an input buffer is only a consideration if we do not implement a true bypass of the signal for the “off” mode, as is the case with the implementation of an analog mux for signal routing [4]. This prevents the wah circuit from loading the clean signal and cutting its tone.

The Filter block shows the layout for an active bandpass filter with a common-emitter amplifier. This filter is designed to boost a frequency range centering from roughly 450Hz to 2kHz, covering an acceptable range for a wah effect. The center of this range is to be controlled by a digital potentiometer (Digital_POT), which will connect to the Filter block at capacitor C3. The bandwidth of the boosted frequency range will also increase with frequency, meaning that the bandwidth will widen as the center frequency of the bandpass increases. This is to prevent intense resonance from the higher frequencies. Resistor R1 serves as the input impedance of 68kOhms.

Capacitor C1 serves as a bypass between the input stage and the filter stage. The biasing of both the NPN BJT and the inductor will be handled by R3 and R7, which form a voltage divider. The most essential component of this block is the 500 mH inductor, as altering this value significantly will certainly have an effect on the boosted frequency range. The tolerance of this value will be explored in the "Tolerance Analysis" section.

The Output block features a low output impedance common collector NPN BJT, similar to the input buffer. The BJT is biased to buffer the signal from the digital potentiometer and control the effect of the potentiometer position on the volume level of the output.

Requirements & Verifications:

• Circuit sweeps frequencies from lower-mid to upper-mid range (400Hz to 2.5kHz) with 15-20 dB amplification.	1. Connect input of wah circuit to external AC power supply 2. Connect output to oscilloscope 3. Create test program for microcontroller which sets the number of taps for the digital potentiometer to 0 or 1023 4. Perform a spectral analysis on the oscilloscope with the number of taps at maximum. Note the peak and -3dB range for the minimum frequency boost. 5. Perform a spectral analysis on the oscilloscope with the number of taps at zero. Note the peak and -3dB range.

• Filter voltage gain must be between 1dB to 19dB	1. Connect input of wah circuit to external AC power supply 2. Connect voltmeter to filter block input and ground 3. Connect output to oscilloscope 4. Create test program for microcontroller which sets the number of taps for the digital potentiometer to 0 or 1023 5. Measure output voltage for each potentiometer setting

Software

Diagrams:

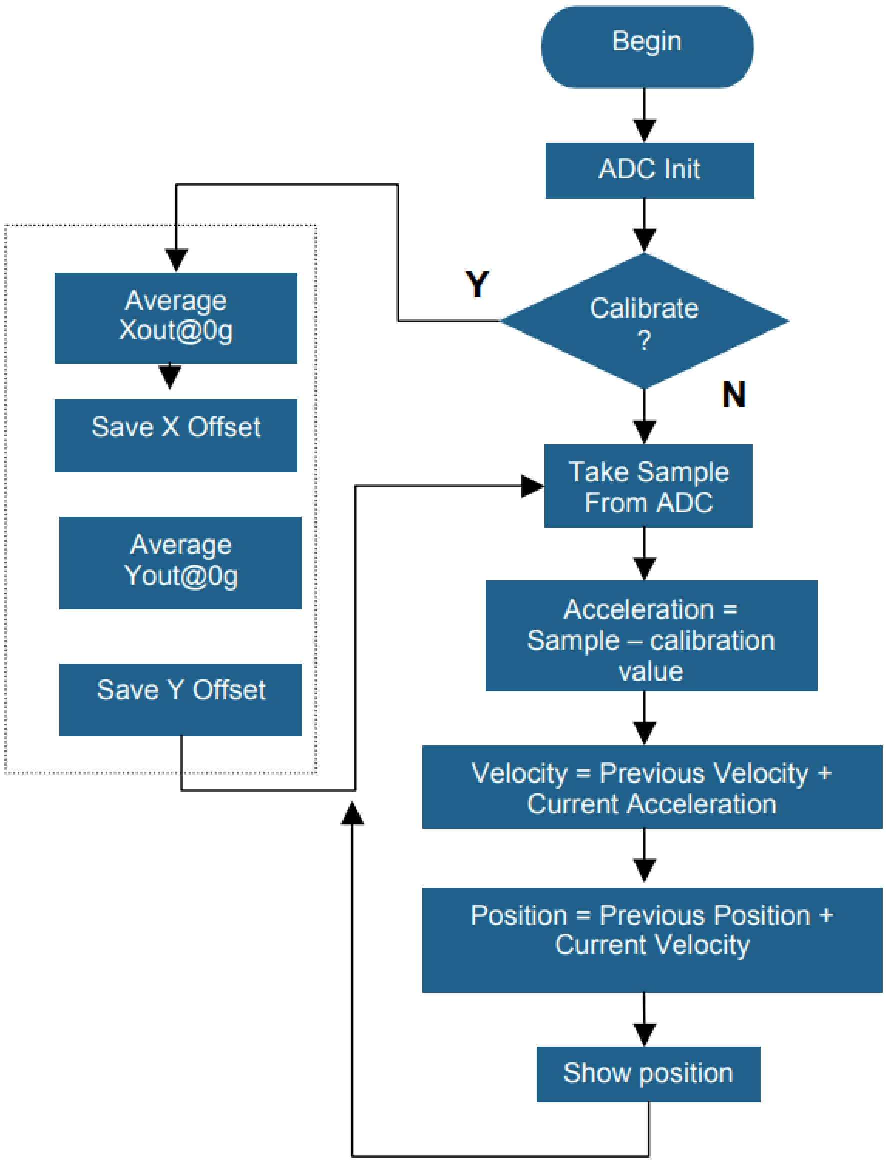


Figure 7: Sample accelerometer manipulation algorithm taken from NXP Semiconductor application note [22]

Algorithm Description:

Our goal with using an accelerometer is to convert the accelerometer data into positional data which can then be normalized to fit within a 10 bit range to control the digital potentiometer. We plan on using this using an algorithm and code from an NXP semiconductor application note on the subject [22]. Our implementation will look much like the flowchart seen above, however we will have two calibration points to set a start and end position, which will allow the generation of a finite range of values. This sweep can then be normalized so that any distance covered by the headstock can be used to control the full sweep of the digital potentiometer.

Tolerance Analysis

The success of this project relies heavily on being able to generate a good sweep of a digital potentiometer based on the output of an accelerometer. While ideally we are able to generate a continuous potentiometer sweep as with a mechanical pot, we have to approximate a continuous sweep using the steps of a digital potentiometer. The smallest difference in relative pitch that a human can detect is around 0.5% [3], which applied to a worst-case minimum value of our filter sweep range $f_L \approx 400Hz$ gives us the maximum frequency step we can allow to maintain audible continuity:

$$f_L * JND = 400 * 0.005 = 2Hz$$

To find the number of steps required to achieve this, we divide the total range of our filter sweep (with worst-case maximum value of $f_H \approx 2.4kHz$) by the maximum frequency step to get:

$$BW = f_H - f_L = 2.4k - 400 = 2kHz$$

$$N_{steps} = \frac{BW}{f_{step}} = \frac{2k}{2} = 1000 \approx 1024 = 2^{10}$$

Or 10 bits of resolution. This means we need to use a digital pot with 1024 taps and at least a 10 bit ADC. The built in ADC of the STM is 12 bits, so sampling resolution will not be an issue.

However, we must now verify that the accelerometer can output a wide enough voltage range to provide enough step resolution with the quantization of the ADC. Operating at 3.3 V with 12 bits of resolution, this works out to:

$$R = \frac{V_{DD}}{N_{samples}} = \frac{3.3}{2^{12}} = 0.806\frac{mV}{sample}$$

Our accelerometer has 3g sensitivity, with g being the acceleration of gravity, $g \approx 9.8\frac{m}{s}$. This is used to scale the per-g sensitivity of the accelerometer to achieve a wider output voltage swing for a given acceleration. Dividing the total sensitivity of the accelerometer by the resolution of our ADC gives us the maximum number of steps that can be generated by its output:

$$N_{steps} = \frac{n_g * S}{R}$$

Which, when rearranged, allows us to find the minimum sensitivity we can allow:

$$S_{min} = \frac{N_{steps} * R}{n_g}$$

Plugging in our values of $N_{steps} = 1024$ for the digital pot, $R = 0.806\frac{mV}{sample}$ for the resolution of our ADC, and $n_g = 3$ from the datasheet, we get:

$$S_{min} = \frac{1024 * 0.806}{3} = 275\frac{samples}{g}$$

According to the ADXL335 datasheet [21], the worst-case sensitivity listed is $270\frac{samples}{g}$ at 3 V, which means we should be able to achieve our “continuous” sweep.

In an effective wah pedal, a band pass filter is used to boost frequencies that shift with the control of a potentiometer. The resonant peak should shift from centering the lower-middle frequencies (roughly 350 hertz) to the upper-middle frequencies (roughly 2.2kHz), as indicated in pedal-manufacturer Dunlop’s own wah pedal frequency ranges [2]. Variations on which part of this range is covered are also demonstrated in Dunlop’s own pedal designs, so as long as the extremes of this range are not exceeded, issues with increased resonance at higher or lower frequencies will not be a concern. The inductor used is 560 mH with a 10% tolerance [23]. As the inductor value is essential in defining the boosted frequency range, we must explore if the range of inductor values will result in acceptable frequency ranges. To do this, the audio circuit was simulated using LTSpice, adjusting the inductor value to the extremes of the tolerance range (504-616mH) and adjusting the digital potentiometer (represented by digital_POT) to the extremes of the wiper (0-1).

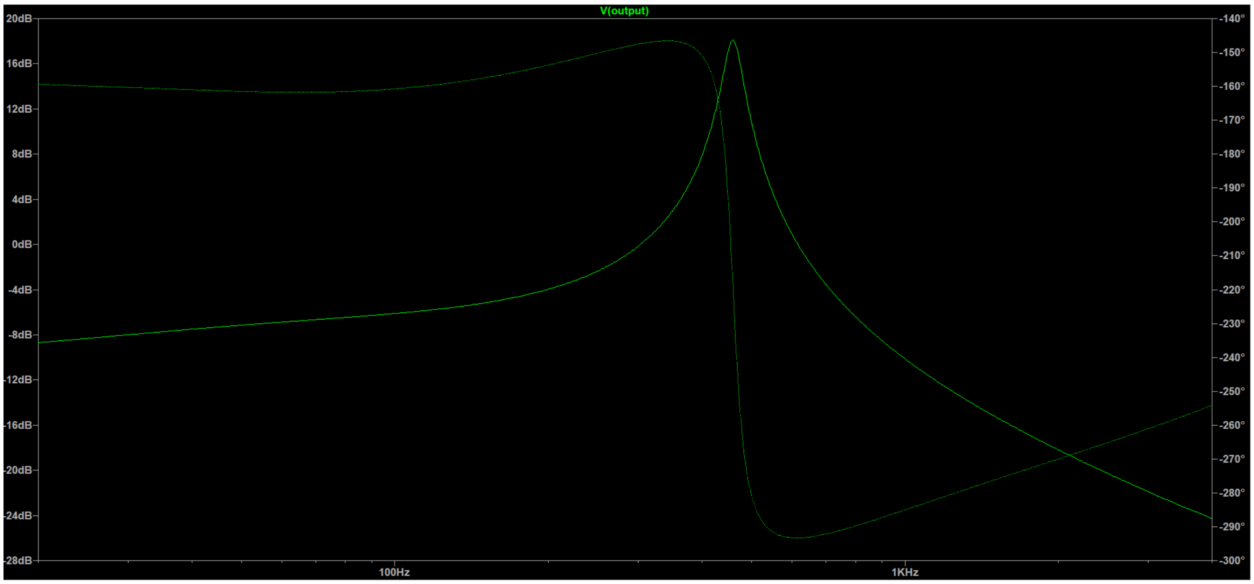


Figure 8: Boosted Frequencies - Inductance = 504mH, Wiper = 1

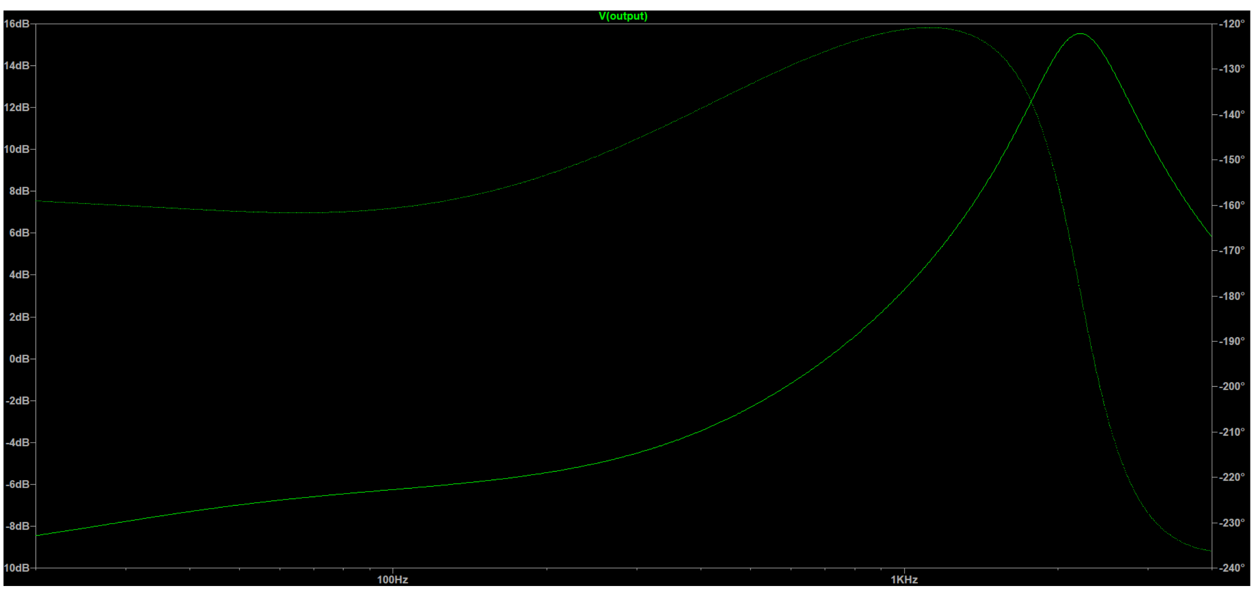


Figure 9: Boosted Frequencies - Inductance = 504mH, Wiper = 0

The above two charts show that at the low end of the inductor tolerance, the center of the boosted frequencies ranges from 460 Hz to 2.2 kHz.

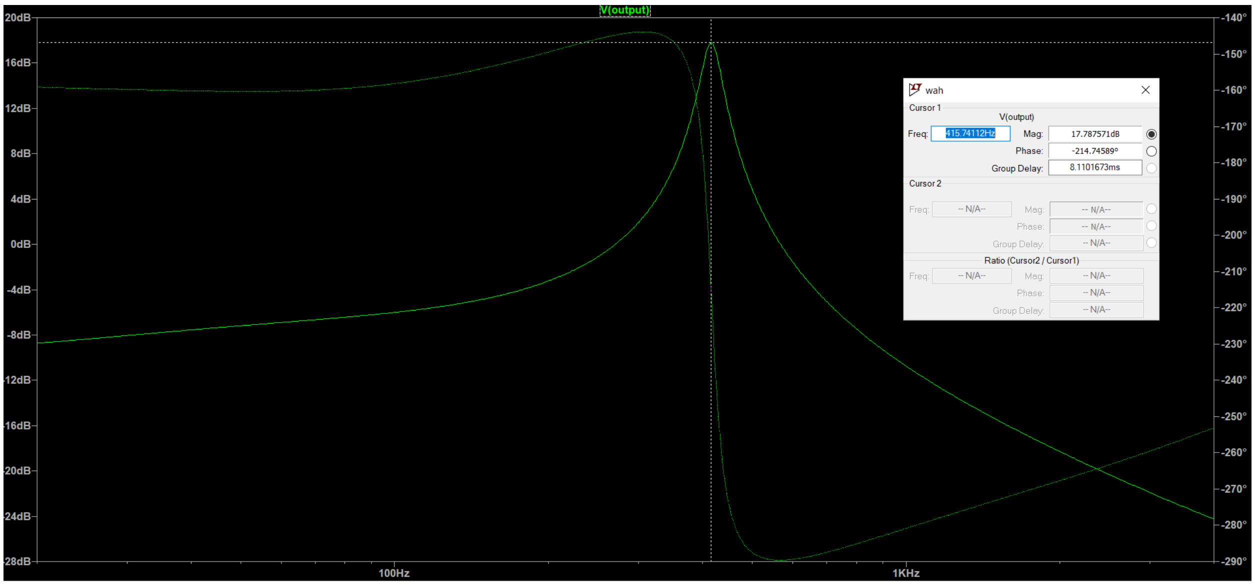


Figure 10: Boosted Frequencies - Inductance = 504mH, Wiper = 1

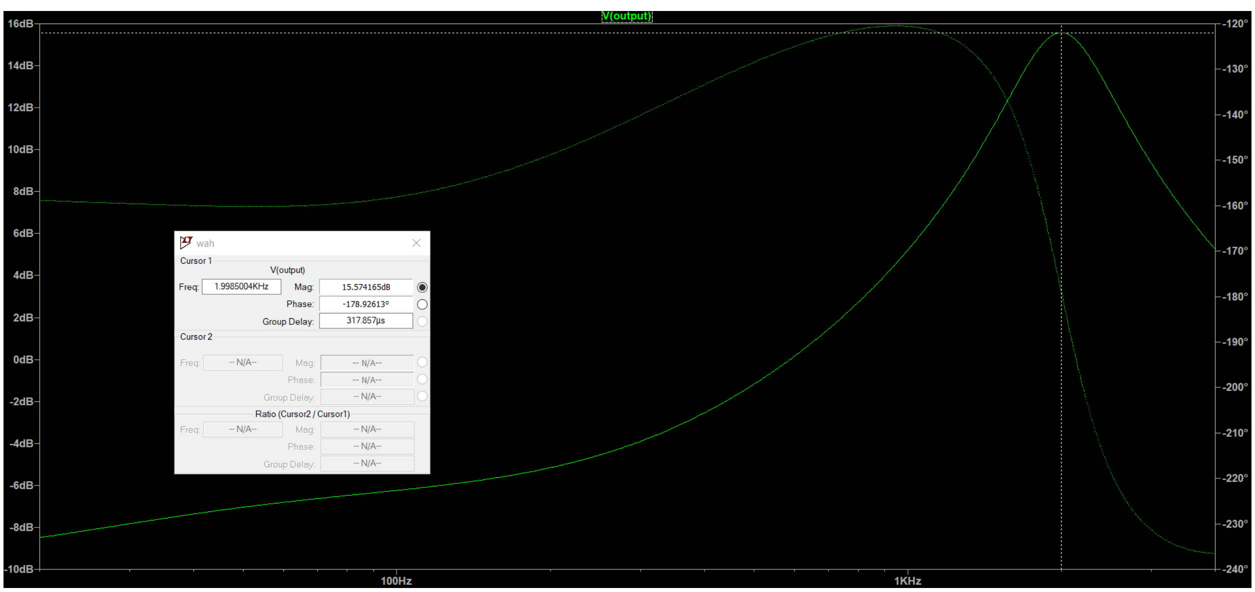


Figure 11: Boosted Frequencies - Inductance = 504mH, Wiper = 1

The above two charts show that at the low end of the inductor tolerance, the center of the boosted frequencies ranges from 415 Hz to 2.0 kHz. Both minimum and maximum tolerance values for the inductor create acceptable boosted frequency ranges, with the latter being preferable for having better low-mid frequency response.

Cost and Schedule

Cost Analysis

Labor:

Using the model provided to us from the course website, we estimate the cost of labor at $40/hr, 8 hours per week, for 16 weeks of class to be

$40/hr/person * 8 hr/wk * 16 wk * 3 people * 2.5 overhead = **$38,400**

Parts:

Name/Disc.	Manufacturer	Digikey Part #	Quantity	Cost
Transmitter MCUs	ST Microelectronics	497-19667-1-ND	2	$11.24
Receiver MCU	ST Microelectronics	497-17428-ND	1	$6.40
Accelerometer	Analog Devices	505-ADXL335BCPZ-ND	1	$8.36
Analog Mux	Vishay Siliconix	DG636EEQ-T1-GE4CT-ND	1	$1.54
Digital Pot	Analog Devices	505-AD5231BRUZ100-RL7CT-ND	1	$6.61
Level Shifter	Texas Instruments	296-12163-1-ND	1	$0.61
Boost Converter	Texas Instruments	296-41854-1-ND	2	$2.44

3.3V-3.3V LDO	Diodes Incorporated	AP2112K-3.3TRG1DITR-ND	2	$0.70
9V-3.3V LDO	Diodes Incorporated	AZ1117IH-3.3TRG1DICT-ND	1	$0.38
Battery	Panasonic	P189-ND	2	$0.88
Battery Holder	MPD	BU2032-1-HD-G-ND	2	$2.46
Transistors	OnSemi	BC846BLT1GOSCT-ND	3	$0.42
Large Inductor	Allied Components	3475-ASPC80-564K-RC-ND	1	$4.25
Mechanical Pot (Testing)	TT Electronics	987-1723-ND	1	$1.55
Assorted SMD passives resistors/ capacitors/ inductors/ LEDs	Various	Various	~100	~$20
5 Pin Connector	Sullins Connector Solutions	S6103-ND	7	$3.36
3 Pin Connector	Sullins Connector Solutions	S7036-ND	9	$3.33
Buttons	CW Industries	CW181-ND	7	$11.48
Audio Jacks	Neutrik	Not On Digikey	4	$6.36
Footswitch	N/A	Not On Digikey	1	$2.55
Enclosures	3D Print	N/A	3	~$5
				$99.92

Total Cost = **$38,500**

Schedule

Week of…	Overall Goals	Julian	Chris	Luna
9/25	-Finish Schematics -Finish Design Document	-Finish digital hardware schematics -Write Design Document	-Choose algorithm for processing accelerometer data -Write Design Document	-Finish analog hardware schematics -Write Design Document
10/2	-Finish PCB layouts -Order parts	-Finish digital hardware PCB layout -Order respective parts	-Order MCU dev boards -Begin preliminary programming	-Finish analog hardware PCB layout -Order respective parts
10/9	-Order PCBs	-Find enclosures/ remaining parts	-Develop programs for accelerometer and button data	-Find enclosures/ remaining parts
10/16	-Assemble PCBs and begin testing	-Assemble and test digital hardware PCBs	-Develop programs for accelerometer and button data	-Assemble and test analog hardware PCBs
10/23	-Continue testing individual boards -Order Rev 2 PCBs if applicable	-Continue to debug PCB -Order more parts/ board revisions if necessary	-Load programs onto PCBs -Refine algorithms	-Continue to debug PCBs -Order more parts/ board revisions if necessary
10/30	-Test integrated system functionality	-Continue to debug hardware PCBs -Refine physical interfaces of devices	-Test wireless data transmission integrity -Test and refine algorithms	-Continue to debug hardware PCBs -Refine physical interfaces of devices
11/6	Flex week/ continued testing	-Continue to debug hardware PCBs -Refine physical interfaces of devices	-Test wireless data transmission integrity -Test and refine algorithms	-Continue to debug hardware PCBs -Refine physical interfaces of devices

11/13	Flex week/ Mock demo	-Work on mock demo and final presentation	-Work on mock demo and final presentation	-Work on mock demo and final presentation
11/20	Thanksgiving!	Sleep	Eat	Sleep Again
11/27	Final Demo	-Work on final demo and presentation	-Work on final demo and presentation	-Work on final demo and presentation
12/4	Final Presentation	-Work on final presentation	-Work on final presentation	-Work on final presentation

Ethics and Safety

In keeping with ethical guidelines outlined by IEEE [1], consideration for the safety of the end user is our highest priority. We have made design choices when possible to minimize any risk involved in the operation of our project. For powering our subsystems, we chose to use standardized and regulated power supplies, be it our voice of 9V wall supply [13] or our choice to use coin cells instead of dealing with the risk inherent with a rechargeable Li-Ion battery supply. Ethically, as far as the environment is concerned, a rechargeable power supply solution would be advisable in the future, but given our very limited development time we felt it safest to use a power source that is readily available and minimizes risk. Our choice of RF modules are also in compliance with FCC regulations on ISM band devices [12]. Finally, we will ensure the quality of our designs through seeking criticism and advice not only through mandatory design reviews, but by seeking the guidance and advice of others with experience in the scope of our project.

Citations

[1] IEEE, "IEEE Code of Ethics," *ieee.org*, 2020. https://www.ieee.org/about/corporate/governance/p7-8.html

[2] "RANGE OF EXPRESSION: FIND YOUR CRY BABY® WAH - Lifestyle - Dunlop," Oct. 08, 2021. https://lifestyle.jimdunlop.com/find-your-cry-baby-wah/ (accessed Sep. 26, 2023).

[3] "Critical Bandwidths and Just-Noticeable Differences," *www.phys.uconn.edu*. https://www.phys.uconn.edu/~gibson/Notes/Section7_2/Sec7_2.htm#:~:text=Between%20these%20two%20mechanisms%2C%20the (accessed Sep. 29, 2023).

[4] "The Technology of Wah Pedals," *www.geofex.com*. http://www.geofex.com/article_folders/wahpedl/wahped.htm

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