ECE 445
Design Document
Spring 2020

Hip Hop Xpress: Double Dutch BoomBus Window Equalizer

Team 46
Anushrav Vatsa (avatsa2), Colin Sandstrom (colinls2), Ioan Draganov (idraga3)
Professor: Rakesh Kumar
TA: Jonathan Hoff (jehoff2)
24 February, 2020 (Mon)

Contents

1. Introduction

1.1 Problem and Solution Overview

Dr. William Patterson has been bringing the art and cultural experience of music to communities around the country with his Hip Hop Xpress project. The newest version of this project is the Double Dutch Boom Bus, which will be a repurposed school bus outfitted with all the equipment necessary to bring hip hop wherever it's needed. From the Hip Hop Xpress site, "[The Boom Bus] will be an internet-connected mobile classroom and sound studio, a means to collect oral histories, a cross-generational catalyst for music sharing and production, and a method to link communities across the state through music, dance, visual arts, and history"[1]. Dr. Patterson has reached out to us in the ECE department for assistance designing equipment to enhance the bus's interactivity and function.

We want to enhance the Boom Bus experience by integrating the windows as a part of the music-making process. We'll connect sensors to the windows that detect how far the windows have been moved, and use this data to control an audio mixer running on a microprocessor. The windows will serve a function similar to that of a slider on a mixing board, providing a visual of how effects are applied to an audio signal to the crowd outside of the bus. They can also provide an interactive experience to those on the bus, allowing them to work together with audio mixing, a process normally done individually. This project will try to address the most important aspect of Dr. Patterson's presentation, which is to pull more people, especially the younger generation, into the music experience. We believe the best way to do that is to let the audience be a part of the musical experience themselves.

1.2 Visual Aid

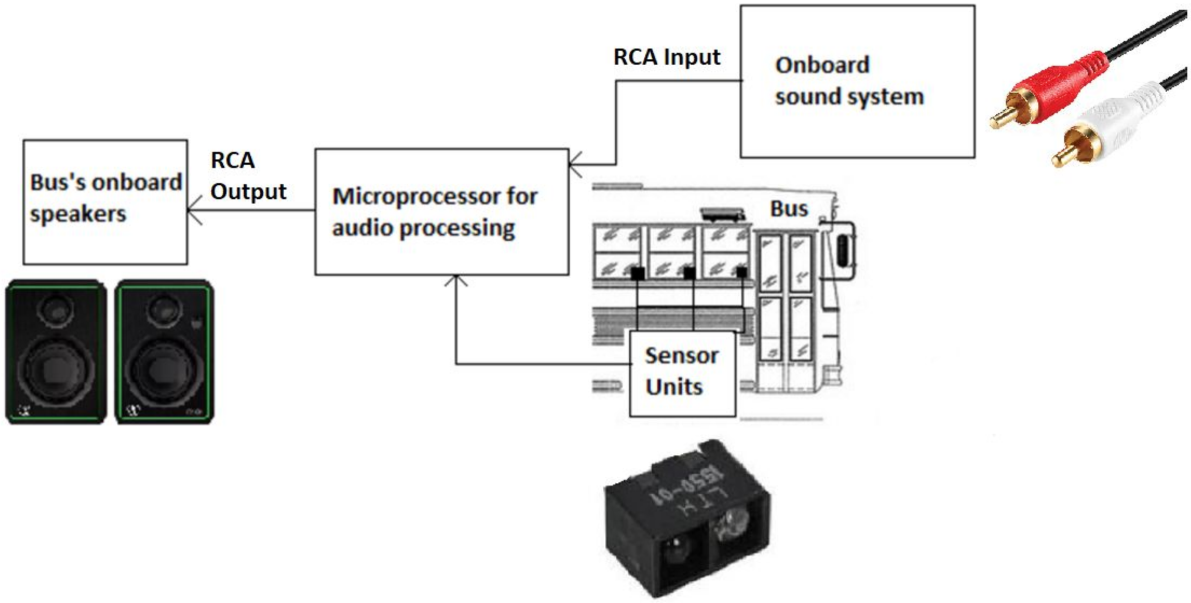

Figure 1. Physical design diagram

1.3 High Level Requirements

- The system must be able to convert the levels of the windows into five discrete values to control our audio system, leading to amplitude levels for each frequency band in our equalizer.
- The system must integrate with the onboard audio system of the Boom Bus.
    - The system will sit between the mixer and the amplifier and should be able to read analog stereo audio input (via RCA) and output analog stereo audio after processing (via RCA) to the main amplifier on the bus.
- The system must have real-time communication and processing systems to prevent any delays and async behavior since we are working with a music system. To be considered real-time, any delay we introduce must be less than 10 milliseconds.

2. Design

2.1 Block Diagram

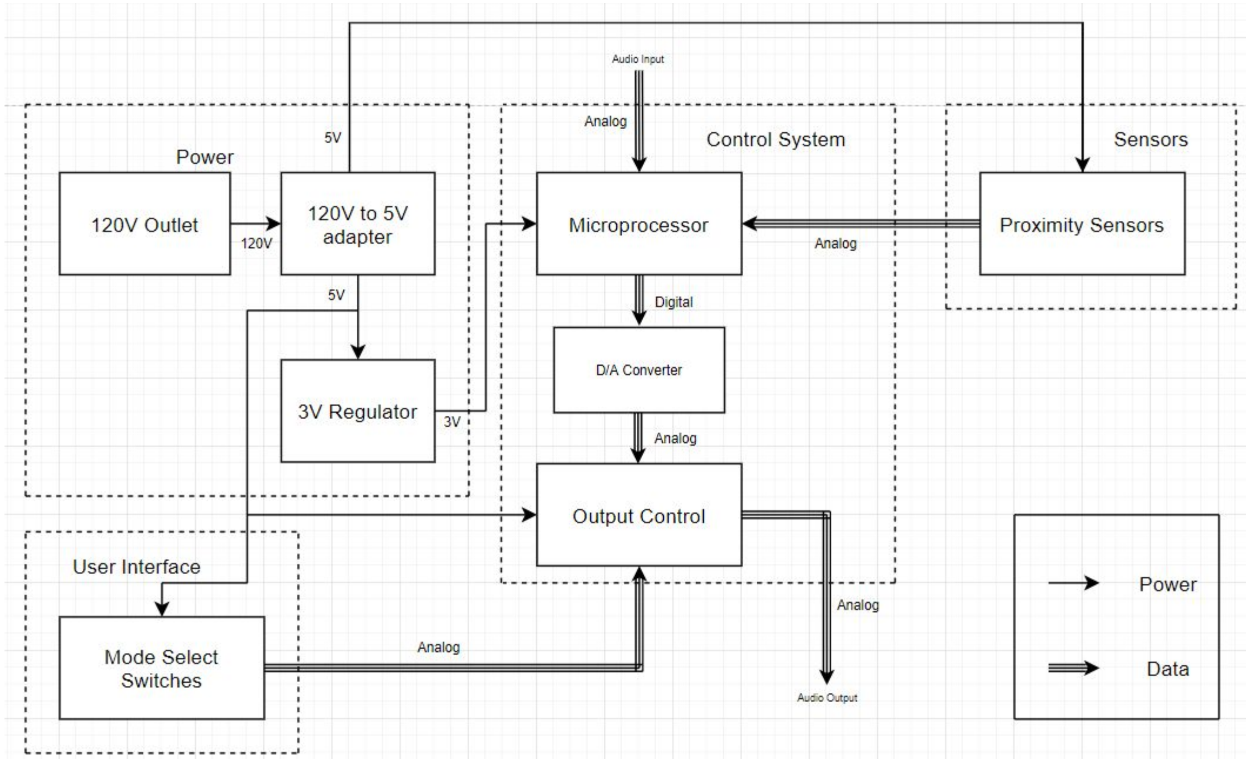

Figure 2. Block Diagram

In order to convert the window's height into levels on an equalizer, we've decided to hook up IR proximity sensors at the bottom of each window and wire them to the input of a microprocessor. The sensor block will convert the height of each window into analog voltage, which will be sent to the microprocessor. The microprocessor will use this data to set the coefficients on several band-pass filters, which are applied to the audio input. The user interface will consist of a power switch and a mode select switch to allow users to bypass our device if they don't want to use the equalizer. Finally, the power subsystem will provide power to each other system.

2.2 Physical Design

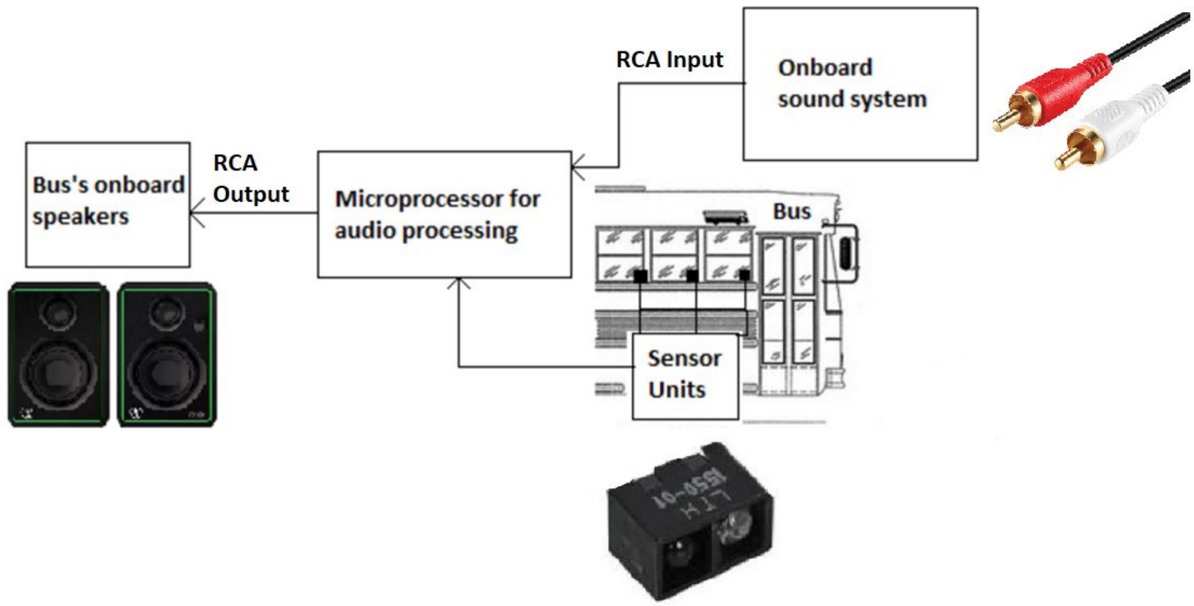

Figure 1. Physical design diagram (From Visual Aid section)

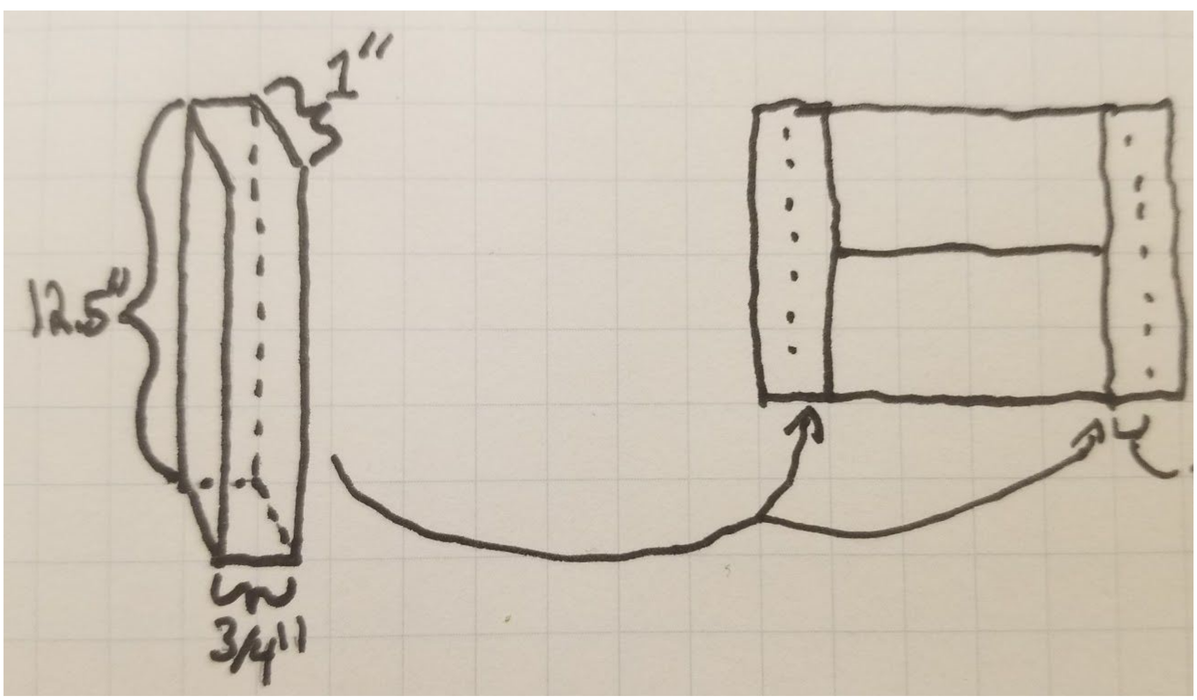

Figure 3. Physical diagram of space available for sensors

As seen in Figure 1, we will be mounting our sensors at the bottom corner of each window, in the rails that the windows slide up and down in. A drawing of the space available is provided in Figure 3. We will need to wire the sensor modules to the central unit through the outside of the bus - the architecture team working on the Boom Bus will drill holes to send the wires through as needed.

2.3 Subsystems

2.3.1 Control System

We will utilize the MSP430F5529**[2]** microprocessor from Texas Instruments, or equivalent. The MSP430F5529 has 14 analog input channels and built-in A/D Converter, so it has ample capacity to handle inputs from all the sensors and the sound system with excess channels in reserve, as we only require 10 analog input channels for our desired functionality. It has a max boot time of 3 milliseconds, and can operate at up to 25MHz, so it can process the analog signals from the input RCA cables in "real-time", in this case, we are treating real-time operation as operation with processing delay < 10ms. This line of microprocessors is considered "Ultra-Low-Power", and this particular microprocessor requires approximately 3V and less than 1mA to operate, so it can easily be integrated into the Boom Bus' with minimal impact on the Bus' regular functions.

Requirement	*Verification*
-Control system must be able to apply a digital 6 band filter with five levels controlled by sensors. *-Delay of the stereo audio must be less than 10 ms (for real time communication)* *- The MCU should be able to read analog inputs and, after processing, output analog signal to the audio out channel in stereo*	● *Generate input signal with function generator and connect input and output signals to oscilloscope. Demonstrate all five filter levels for each frequency band.* ● *Ensure that the distance between the same peak in the input and output signals is no more than 10 ms.* ● *Generate input signal with function generator and connect input and output signals to oscilloscope to demonstrate analog behavior of output given analog input.*

2.3.2 Sensors

This subsystem will sense how high the windows are and provide this data to the control subsystem. Optical sensors will be mounted at the bottom of the window to be able to tell when the windows are open or closed. School Bus windows are designed with ridges in the sides to fix the open window at specific intervals, the sensors only need to differentiate which interval the window is at rather than specific position at a given time.

We will be using IR emitters and photodiodes to create the distance sensing circuit. In order to convert the current output of the IR photodiode to a voltage to input to the microprocessor, we will simply connect a series resistor to ground and measure the voltage across it for input to the microprocessor. The specific values of resistors in the circuit will be fine-tuned later in development to provide the proper voltage to the microcontroller.

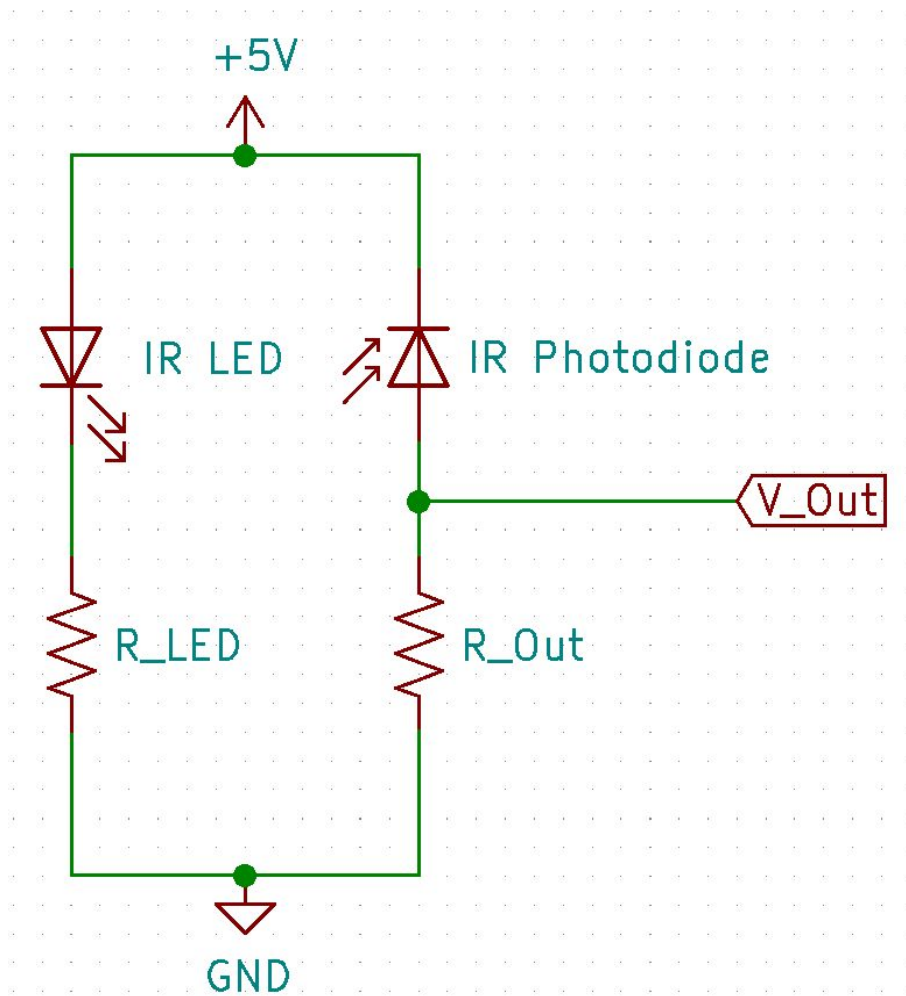

Figure 4. Sensor module circuit diagram

Requirement	*Verification*
-Sensors must be able to detect window height within 0.5cm of accuracy. *-Sensors must be able to resist snow and rain as they will be on the outside of the bus.*	● *Use the dummy window provided by the ECE machine shop to test different heights and ensure that the sensor module outputs the correct voltage for each height increment with 0.5cm margin of error.* ● *Test the sensor casing by splashing water from all directions and ensuring no water contacts wiring.*

2.3.3 User Interface

Our primary control unit will give the user some essential control over the system. This includes:

- *Basic power switch* - analog ON/OFF switch connecting circuit to power supply
- *Routing Control Switch* - analog routing switch feeding into 2:1 MUX to transmit the sound directly to the amplifier and bypass our system
- *Effects Control* - to allow for master volume control and other audio effects we can emulate on the MCU

Requirement	*Verification*
-Switches must shut off the other subsystems and route the audio straight to the output past the microprocessor when inactive. *-Power switch to allow master control for the whole system*	● *Hook up the system to an oscilloscope at input and output, show that the signal is passed directly to output when routing is inactive.* ● *Test the MCU's response to power termination and boot-up time to characterize how it handles I/O interrupts in those cases.*

2.3.4 Power

We will use a power adapter **[5]** to step down 120V supply from the wall output to reduce the voltage to 5V and 2A DC input for our system. We will also use a voltage adapter **[6]** to drive the microprocessor at ~3V, and to power the sensors mounted on the windows as well. We will use LM2940CT-5.0/LF01 manufactured by TI for this purpose.

Requirement	*Verification*
-System must be able to provide 3V and appropriate current for each separate block. *-Power adapter must be able to step down wall output of 120v to 5v*	● *Test the LM2940CT-5.0/LF01 voltage adapter in the lab to ensure exact and stable DC output and conversion from 5V to 3V.* ● *Test power adapter to get stable 5V and 2A output from the wall socket*

2.4 Tolerance Analysis

The most critical component of this project is the MCU. The MCU is responsible for processing the analog audio input and analog sensor input to produce a filtered analog audio output in real-time. In order to achieve that, the MCU must have sufficient analog input channels, and a high enough operating frequency to accomplish that with a delay less than 10ms.

To that end, we intend to use a MSP430F5529 chip as our microprocessor. The MSP430F5529 is designed with 14 analog input pins with a built in D/A converter which allows it to accept 2 analog audio inputs from the stereo RCA cables and 6 analog sensor inputs. Since the MCU is powered with V_{cc}=3V±10%, and the RCA inputs can have varying voltages depending on the sound system, it will be necessary to connect the inputs to op-amps with |gain| < 1. The built-in A/D converter in the MCU has 12-bits of precision, which is an industry standard for audio. We can scale down our input voltage with an op-amp with a small gain so that we do not have inputs of greater than 3V to our microprocessor. We do not expect signals much larger than 10V at any given time, so that will provide ample leeway for our operations.

In order to compensate for the early decrease in voltage, we will also have to connect our output analog signal to an op-amp to counteract the previous adjustment. The gain of this op-amp should be the inverse of the input op-amp's gain. Amplifying the output signal may also amplify the noise in the signal to audible levels, resulting in a tradeoff between input range and sound quality that is common in many amplifiers. If our device runs in a limited mode of operation, it will be able to produce higher quality sounds, but if it operates on a broader spectrum of sounds, then the resulting sound quality may decrease.

Once the operating voltages are refined, we have to consider the sampling rate of the A/D converter to obtain operable digital inputs that the MCU can filter internally. Since the focus on this project is sound waves, our analog audio inputs will have expected frequencies ranging between 20Hz and 20kHz. In order to avoid aliasing in the digital signal, the ADC has to sample the inputs at a frequency ≥ Nyquist = 40kHz. By design, the MCU's ADC has a max clock frequency of 5MHz, typical clock frequency of 4.8MHz, and minimum clock frequency of 0.45MHz = 450kHz >> Nyquist = 40kHz, so the sound can be converted without distortion.

In addition, to achieve our goal of processing the signals in real-time, we need to ensure that our filtering takes less than 10ms to accomplish. The system clock of the MCU has a maximum frequency of 25MHz, and a typical operation frequency of 8MHz. The filter needs to be applied with a frequency greater than 1 filter per 10ms, so $f_{operation} \geq 100$Hz. 8MHz/100Hz = 80,000, so the MCU can complete a maximum of 80,000 operations per filter application and still stay within the constraints of real-time operation.

Our filter design will use FIR filters to achieve linear phase in the output. These FIR filters will be convolved with the windowed inputs of 100 samples, after taking the short time fourier transform (STFT) of each windowed input. These STFTs will be multiplied by the FFT (fast fourier transform) of the filter that will be computed in advance by our system. Our filter should be applied to at least 128-256 samples per frame in order to achieve a sound design. The Nlog(N) runtime of the FFT algorithm used for convolution will ensure that we can achieve these specifications.

For every frame we need to be able to perform the STFT using FFT algorithm, perform N (frame size) multiplies, then take the reverse fourier transform using the FFT algorithm to achieve our output. Based on the above parameters we have the following total number of operations per frame based on the frame size for the whole filtering process:

Frame Size	Number of Operations per Frame
4	176
32	2560
64	5888
128	12,312
256	29,696

As shown in the above calculations, we can easily achieve real time filtering with 256 samples per frame without pushing our MCU's processing ability. This will leave enough room for overhead from other processes like data handling and error detection in our system while meeting our strict real time processing requirement.

3. Cost and Schedule

3.1 Cost Analysis

Part	Part #	Quantity	Cost
Microprocessor	MSP430F5529IPN	1	$7.65
IR Emitter/Receivers	Gikfun EK8443	10 pairs	$5.78
Various basic circuit elements (resistors, wires, etc.)	N/A	Irrelevant	<$1.00
Power Adapter (120V - 5V AC to DC convertor)	B00JRNQUM8	1	$10.57
Voltage regulator (5V - 3V)	Texas Instruments LM2940CT-5.0/F0 1	1	$1.49
DAC and Amp	PCM1789	1	$1.75
PCB Estimate	N/A	1	$30.00
Total for parts	N/A	N/A	$58.24
Labor estimate	N/A	3 partners, 10 hours per week for 15 weeks = 450 manhours	$50.00/hour for 450 hours = $22,500 For exec's salary: 22,500 * 2.5 = $56,250
Total	N/A	N/A	$56,308.24

3.2 Schedule

Week	**Anushrav's Responsibilities**
2/24	Compile Parts list and create start prototyping circuit design
3/2	Evaluate circuit design and start working on PCB layout
3/9	Finalize PCB layout and place PCB order
3/16	Spring Break
3/23	Start assembling PCB components and soldering
3/30	Initial full system testing
4/6	Consider any redesigns, field testing on the bus
4/13	Final integration and debugging

Week	**Colin's Responsibilities**
2/24	Bus measurements, initial characterization of sensors
3/2	Bias sensor module with appropriate resistances for maximum/minimum voltage outputs
3/9	Fine-tune sensor circuit for specific levels of the windows, work with machine shop to design casings for sensors
3/16	Spring Break
3/23	Test sensor circuit in field conditions (long wires, mounting in window space)
3/30	Initial full system testing
4/6	Consider any redesigns, field testing on the bus
4/13	Final integration and debugging

Week	**Ioan's Responsibilities**
2/24	Research Microprocessor
3/2	Start writing code to accept sensor and audio inputs
3/9	Program Microprocessor to apply filter to audio
3/16	Spring Break
3/23	Debug and expand functionality
3/30	Initial full system testing
4/6	Consider any redesigns, field testing on the bus
4/13	Final integration and debugging

4. Discussion of Ethics and Safety

4.1 Ethical and Safety Concerns

When developing any electrical device, an engineer must consider the risk of electric shock to users and anyone coming into contact with the electronics. Our device is also to be mounted on a bus, which raises the additional concerns of weatherproofing the device and allowing passengers to escape in the event of an emergency. One more concern is that, when working with audio, there is a potential to cause hearing damage if the intensity of sound is too high.

4.2 Project Countermeasures

Our device will use voltages and currents that are small enough to not cause harm to humans, and we will have all of our wiring and hardware enclosed in plastic housing to ensure the safety of both humans and our circuitry. All electrical components will not be visible to the end user, so the risk of electric shock is averted.

To address the concerns regarding the emergency exits, we will not install any components on the windows that are designated as emergency exits so that passengers are not impaired in their ability to escape in the event of an emergency. If we were to mount any equipment that could get in the way of a passenger in an emergency, this would be a clear violation of IEEE Codes 1 and 9, to "hold paramount the safety of the public" and to "avoid injuring others" **[4]**. We need to avoid a situation where a person is harmed, even indirectly, because our installation got in their way when they needed to escape the bus.

In addition, any sensors and other equipment that we mount outside of the bus will need to be protected from any inclement weather. We believe that IP44 standards **[5]** are sufficient to protect our devices from any rain or wind that we can expect to encounter while on the road.

Finally, in order to address the concern of hearing damage, we will use a voltage regulator at the input of our device to ensure that the audio stream we output is not loud enough to cause hearing damage when plugged into a conventional speaker. There is, of course, the risk that someone could plug our output into an amplifier and then into a speaker, leading to loud enough sound to damage eardrums. We believe that the risk of an end user amplifying the audio with an external system will always be a risk, regardless of how we set up our system. To this end, we will regulate our output to not cause hearing damage under normal circumstances, but cannot control for end user behavior when connecting to other systems.

5. References

[1] "About". Publish Illinois Edu. https://publish.illinois.edu/hiphopxpress/ (accessed February 13, 2020)

[2] Texas Instruments. "MSP430F552x, MSP430F551x Mixed-Signal Microcontrollers". SLAS590N datasheet, March 2009 [Revised September 2018].

[3] "IEEE Code of Ethics". IEEE. https://www.ieee.org/about/corporate/governance/p7-8.html (accessed February 13, 2020).

[4] "IEC 60529". CVG Strategy. https://cvgstrategy.com/iec-60529/ (accessed February 24, 2020)

[5] "5V DC 2.0A Wall Adapter AC Power Supply 5V DC 2A 3.5mm/1.3mm Class 2 Transformer". Amazon. https://www.amazon.com/Adapter-Power-Supply-3-5mm-Transformer/dp/B00JRNQUM8

[6] "LM2940CT-5.0/LF01". Mouser Electronics. https://www.mouser.com/ProductDetail/Texas-Instruments/LM2940CT-50-LF01?qs=X1J7HmVL2ZGdHkE6VXLwfA%3D%3D&gclid=CjwKCAiAhc7yBRAdEiwAplGxX15pBYHakKe9dXwIhdEck9EVmO1SNGg9gH4Tazt5hB8Z7I-Od474sxoC5IYQAvD_BwE (accessed February 26, 2020)