6/13/2020

Bluetooth Speaker

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This is an independently funded project, designed to create a Bluetooth speaker. This project used skills in RF communication, circuit design, and PCB design. This Bluetooth speaker features a low pass filter designed to introduce static noise to the system to give the sound an "old fashioned" feel. This feature will be able to be turned on and off by the user. Additionally, another goal in this project is to avoid using components made in China. Instead American made components were used whenever one was available and it was economically feasible to do so.

Keywords: Audio Signals, Bluetooth, Electrical Engineering, KiCad, Mass Production, PCB

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Overview

There are 6 modules within this embedded system in order to make the speaker function as seen in Figure 1.

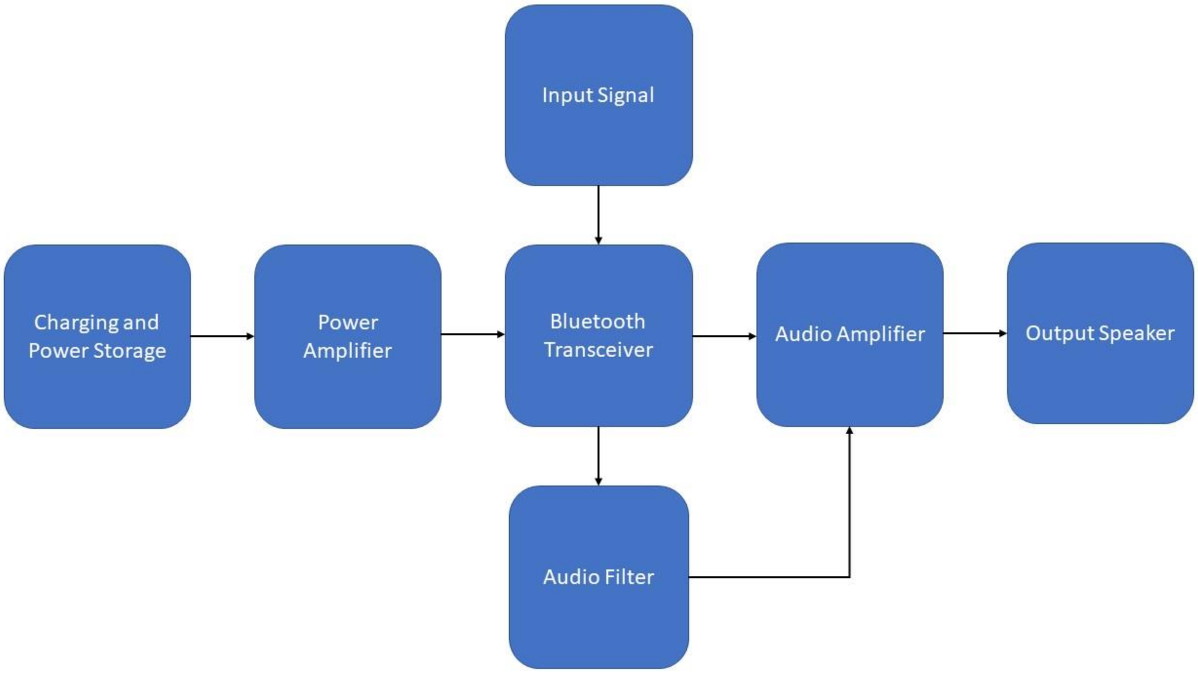


Figure 1 - Block Diagram of the System

The first block, Charging and Power Storage, will accept a USB input to charge the battery, as well as manage the output power from the battery. Within this system there are also 3 LED indicators. The first is a simple power indicator, to determine if the system is turned on or not. The second LED will turn on when the system is charging. Finally, the third LED will turn on when there is a low battery as determined when the voltage falls below a predefined reference.

The power amplifier block will take the 3.7-volt battery output and convert it to a 12-volt signal. The 12-volt signal is then brought back down to 5 volts using a voltage divider. There are two reasons why this design was settled on as opposed to a simple 5 volt step up conversion. The first is that the Bluetooth module can accept a range of 5 volts to 24 volts. Therefore a 12-volt input signal will provide more power for the receiver than a standard 5-volt signal will. The other reason is that there are many aesthetically pleasing LED based components such as back lit anti-vandal switch which commonly require 12 volts to properly function. Should I ever decide to use such components in the future it will make the system much easier to redesign.

The Bluetooth receiver module is pretty straight forward in this project, it just requires an input power and a connection to the board. In the future I would like to redesign it to use a PCB mounted transceiver IC.

The audio filter is a low pass filter designed to produce an "old fashioned" sound. It can be enabled or disabled by the user at will by using a simple rotary switch. If the filter is disabled then the signal will go straight to the audio amplifier.

The audio amplifier is a PAM8403 IC by Diodes Incorporated. This IC was chosen because it is capable of stereo output, and it a commonly used amplifier. Therefore, there are a plethora of example circuits to reference. Additionally, it is cheaper than the Texas Instruments equivalent. Even though this project will only use one speaker and therefore use mono output, the stereo capabilities are important because if I ever decide to create a stereo speaker setup, redesigning the output will be a trivial correction.

Charging and Power Storage

The device is powered starting with a micro-USB charging module. The USB input is connected to a type BQ24091 chip by Texas instruments as depicted in Figure 2. This chip allows the battery to be safely charged. Additionally, if the USB is plugged into a power source while the system is in use the system will draw power directly from the USB power source rather than the battery. The LED connected to pin 5 is the low battery indicator. This LED turns on when the voltage in the battery falls below the input voltage of the chip. The charging LED is connected to pin 8, and is turned on when the battery is charging. The resistor connected to pin 4 programs the current termination threshold of the chip; anywhere from 5% to 50% of the output current is an acceptable range. The 10KΩ thermistor is connected to the temperature sense pin. When the pin is pulled high battery, charging is enabled.

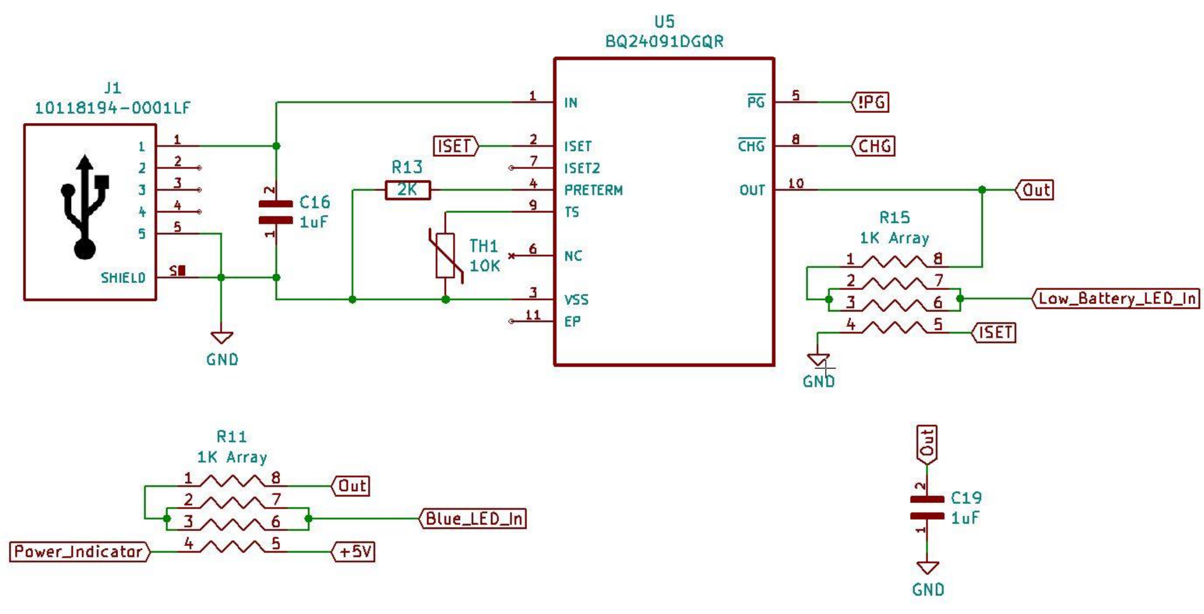


Figure 2 - BQ24091 and Associated Components

The battery is a 2Ah lithium ion battery which I was purchased from Sparkfun. This battery comes with a PH series JST connector built into the battery for ease of integration. The battery is protected by a BQ297xx chip by Texas Instruments. This chip is for current protection.

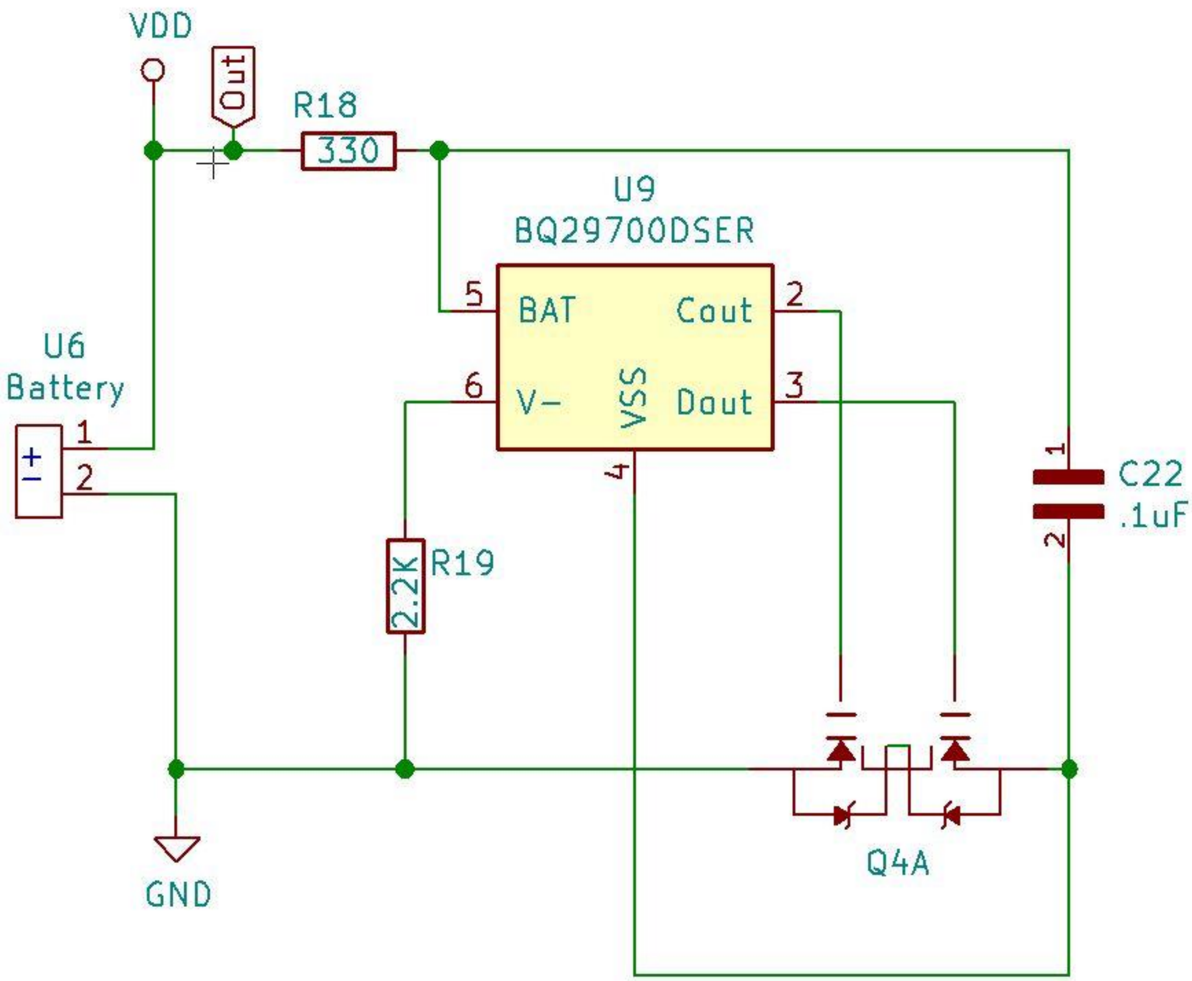


Figure 3 - Battery with Current Protection

Power Amplifier

The power amplifier uses an LTC3872 by Linear Technology. This chip is particularly convenient because it is by Linear Technology and built into LTSpice circuit simulation software. Because of this I didn't need to do any major circuit design, and instead was able to come to a finalized design by manipulating different values in the circuit as shown in the figure below. The resulting setup took an input of 3.7 volts and gave an output of 13 volts.

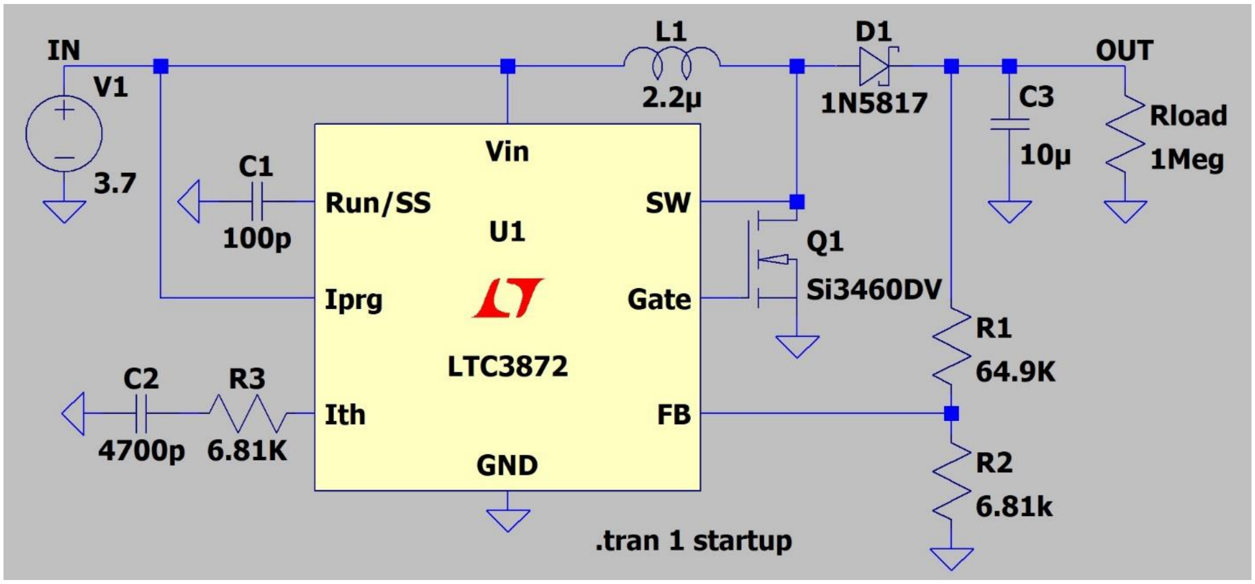


Figure 4 - LTC3872 Power Amplifier Circuit

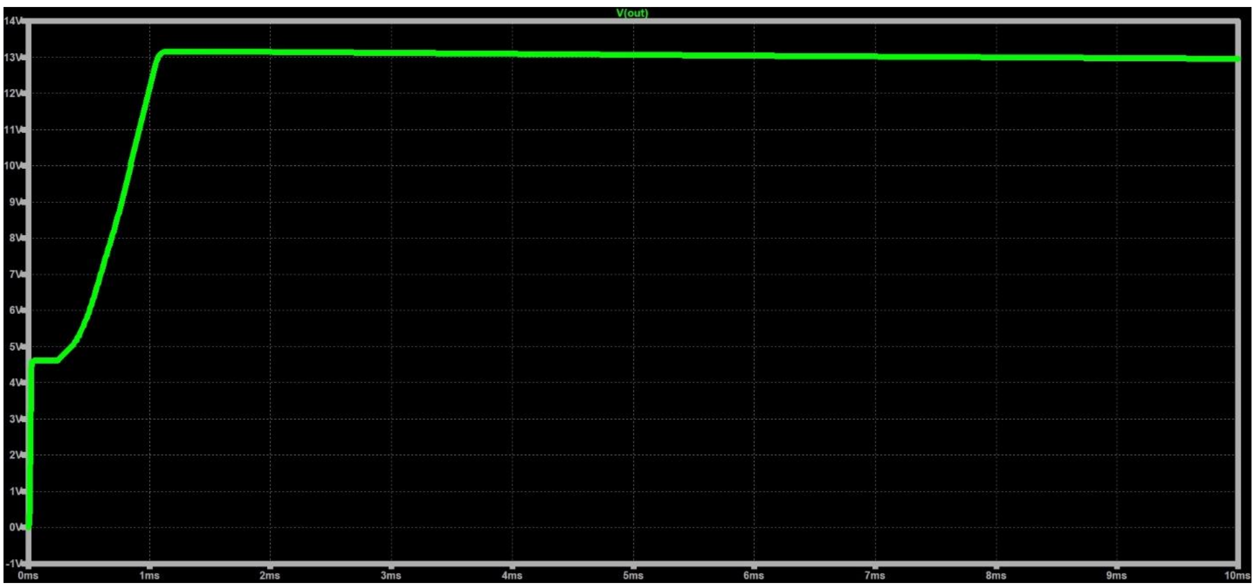


Figure 5 - The output signal from the LTC3872 circuit peaks at about 1 ms, and gradually declines afterwards. The final output is just under 13 volts.

In order to set proper rail voltages in the later op-amps in the audio filter the +5-volt node needs to be inverted to create a -5-volt power supply. This is accomplished with a TL7660 chip by Texas Instruments. This low-cost IC is very simple to use and just requires two 10µF electrolytic capacitors connected to it.

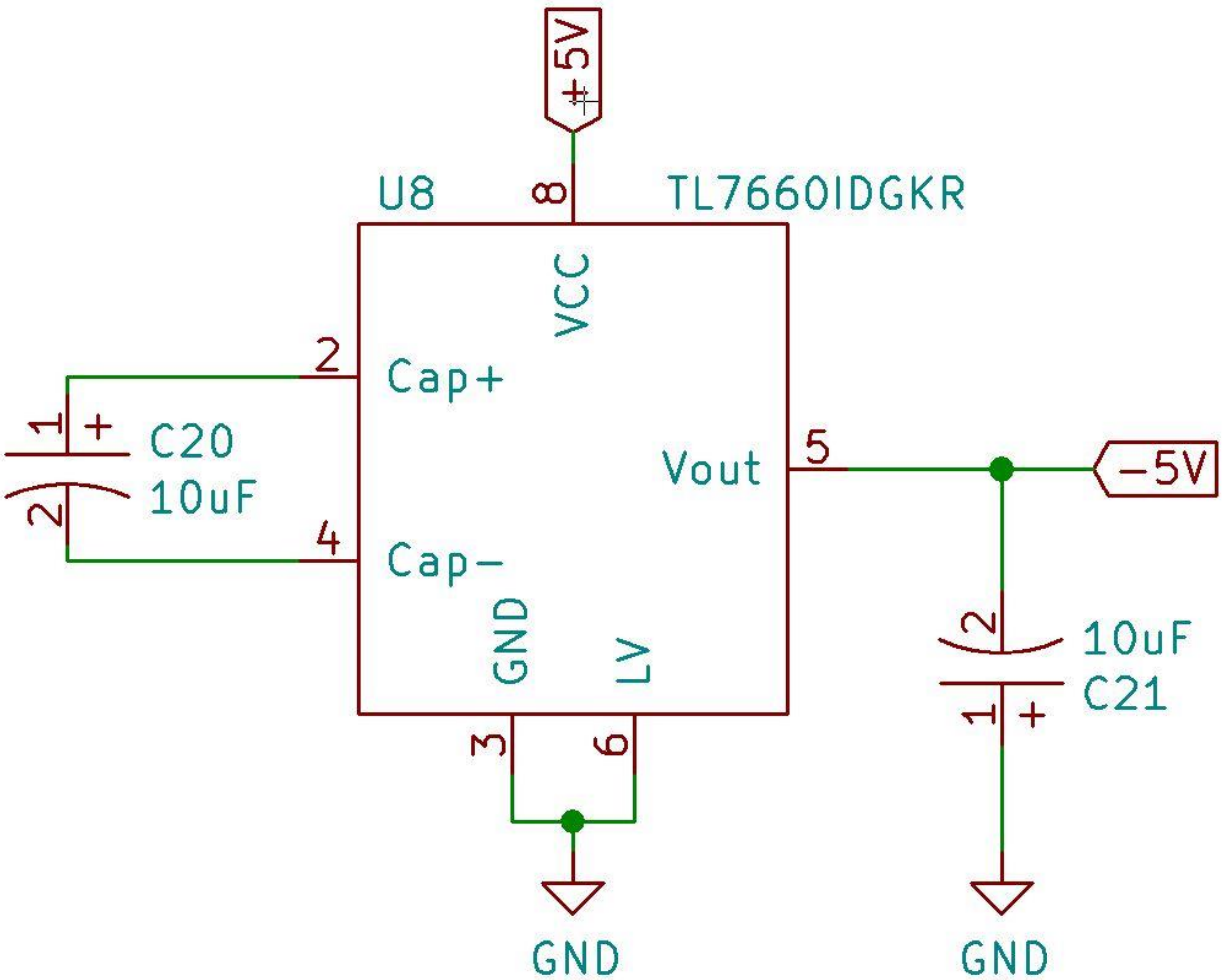


Figure 6 - Voltage Inverter

Selection of a Bluetooth Receiver

At the core of any Bluetooth enabled device, including Bluetooth speakers is the receiver. Bluetooth communication works by transmitting and receiving data between two devices using ultra high frequency radio communication. These radio waves range in between 300MHz and 3GHz in frequency. The wavelength is between 0.1 meters to 1 meter [1]. Broadly speaking there are two types of Bluetooth receivers to chose from. The first is a regular IC chip; these are more difficult to use but are cheaper and offer more fine control over the system. The second type is a transceiver module. Transceiver modules are easier to use and integrate into a project and have the advantage of not having to create a functional RF circuit. The downside to transceiver modules is that they do not offer the control that an IC does [2].

For this project I have decided to work with a Bluetooth transceiver by DROK which as of May 14th, 2020 is retailing for $12.69 on Amazon [3]. I selected this module over other cheaper modules that could be mounted directly on a PCB for a few reasons. The main reason is the ease of integration, as almost all transceiver modules require some form of programming using a streamlined hardware description language. One such example of this software is PSoC creator by Cypress, an American manufacturer of Bluetooth receivers and other similar devices [4]. Finally, all transceivers require a way to upload the written software onto the device. This typically requires expensive programmers [5]. Every chip needs to be programmed prior to being mounted onto the PCB, or else it will require some sort of ICSP output pins and associated circuitry in order to program.

The transceiver by DROK offers "plug and play" functionality; that is to say it requires no programming whatsoever, and is ready to be paired with a phone or other device. The other main reason why I chose the DROK transceiver is that it offers a convenient integration into the rest of the system. It has 3 output pins with a standard 2.54mm pitch, which makes it easy to design a PCB with header pins to receive the output from the Bluetooth module. It also offers mounting holes on the PCB which will make it easy to place securely in a case. This may seem like a minor benefit, but a surprising number of "plug and play" type transceivers do not offer this feature.

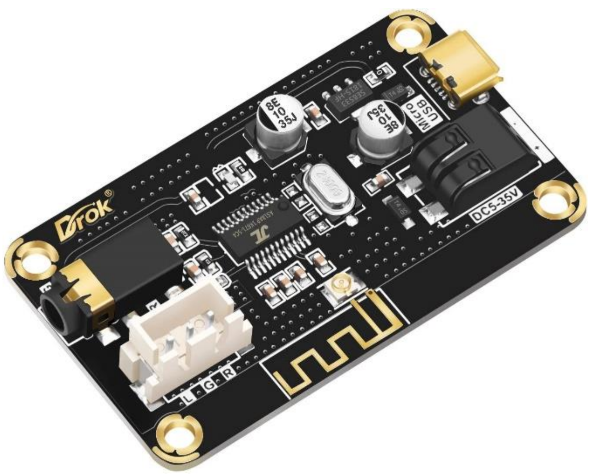


Figure 7 - DROK Bluetooth Transceiver Module

Audio Filter

The audio filter that was designed was a 2nd order low pass Chebyshev Type I Filter. This type of filter was selected for its bandpass ripple and sharp cutoff frequency, which will enable a grainy sound [6]. This filter was first modeled in MATLAB using the digital signal processing toolbox. Different values for a cutoff frequency and filter order were chosen to create a filter. Once this was done, a test song was played both with and without the filter in order to listen to what the filtered audio signal sounded like. Once I found a result that I was happy with I designed a matching filter. Chebyshev Type I filters are convenient because they have tables with values in which the filter can be designed and then applied to a generic Sallen–Key topology [6].

The MATLAB Code is as follows:

```matlab
%% Low pass filter sound testing
[y,Fs] = audioread('Call_Me_Call_Me.mp3'); % Test Song
time = 1:size(y(:,1)); % Create a time vector
```

```matlab
%% Create a filter
N = 2; % 2nd order filter
fc = 1693; % Cutoff frequency of 1693 Hz
wn = fc * 2 / Fs;
[b_low,a] = cheby1(N,1,wn,'low'); % low pass filter

figure(); % Create a new figure
freqz(b_low,1,512); % Frequency response
str = sprintf('Output 1 - Cutoff Frequency At %d Hz', fc);
title(str);
output = filtfilt(b_low,a,y); % Apply the filter
```

```matlab
%% Plot the resulting filtered signal
figure();
subplot(2,1,1);
plot(time,y);
axis tight;
xlim([1000000 1000500]);
title('Original Sound File');
ylabel('Amplitude');
xlabel('Time');

subplot(2,1,2);

plot(time,output);
axis tight;
xlim([1000000 1000500]);
title('Filtered Sound File');
ylabel('Amplitude');
xlabel('Time');
```

```matlab
%% Play the song
% sound(y,Fs); % Without Filtering
sound(output,Fs); % With Filtering
```

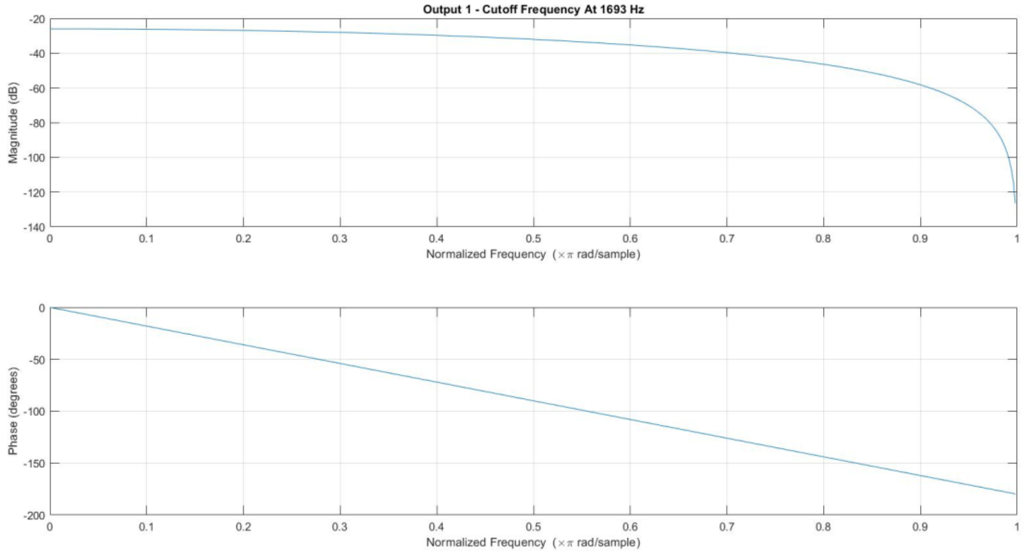



Figure 8 - Frequency response of the audio filter

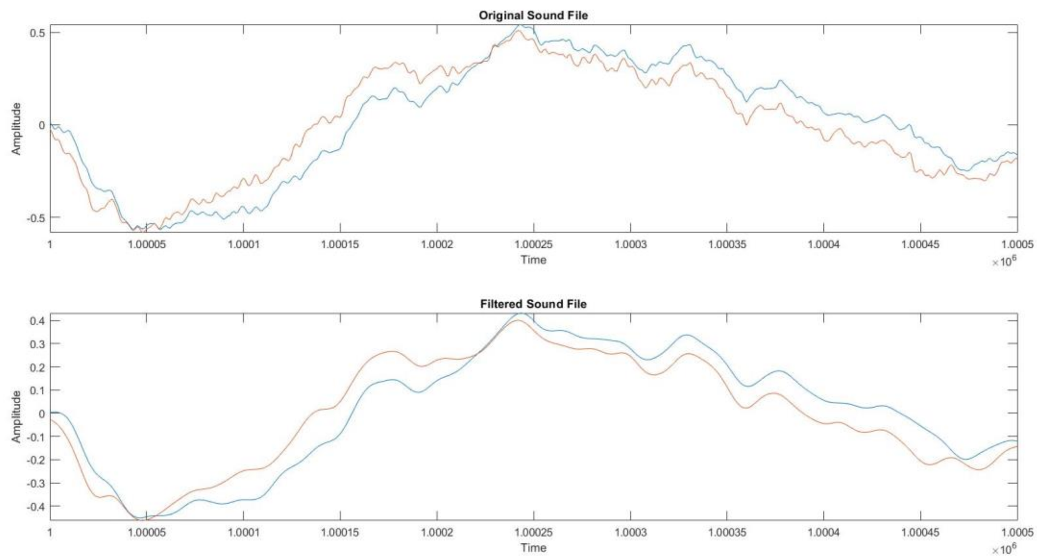


Figure 9 - original and filtered output signals

Once a filter order and an approximate cutoff frequency was decided upon, the filter was designed in LTSpice, and the frequency response was observed.

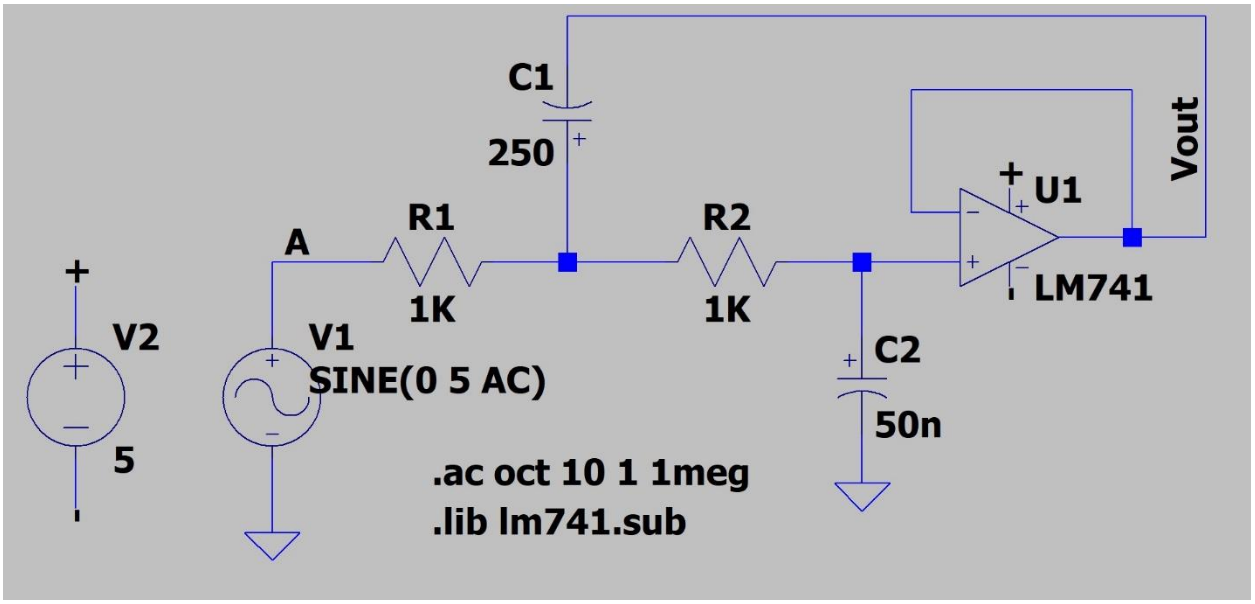


Figure 10 - Chebyshev Type I Low-Pass Filter

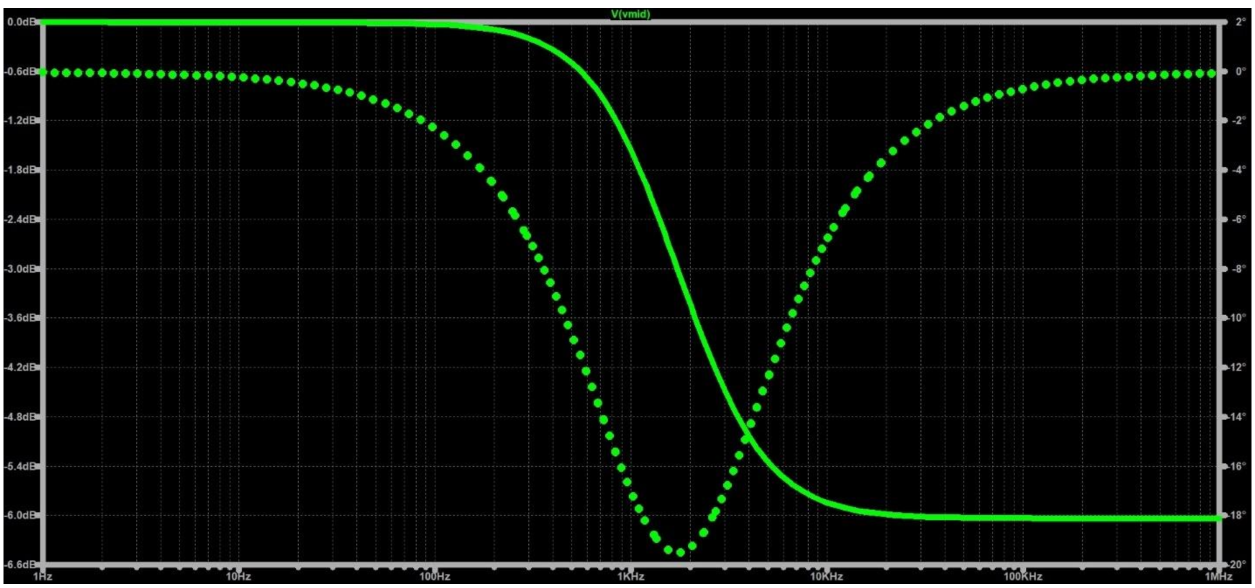


Figure 11 - Bode plot of the low pass filter with a cutoff frequency of 1693 Hz. The stopband region is only slightly attenuated at -6 dB, allowing the entire signal to pass through, but with audible distortion.

Filter Selection Logic

In order for the user to turn the audio filter on and off, some simple selection logic is needed. Two pairs of MOSFETs were used in conjunction with an analog switch. The MOSFETS control which switches are turned on and which are turned off. When the switch is turned on, one of the MOSFETs is used to deliver a high signal to the analog switch selector, while the other MOSFET is grounded to deliver a low signal to the other set of switches. An inverting gate is used to replicate the logic but with the opposite signals set to high and low. The left and right audio signals are sent to the analog switch, which then directs the signals either to the audio amplifier, or to the filter for processing prior to being sent to the audio amplifier.

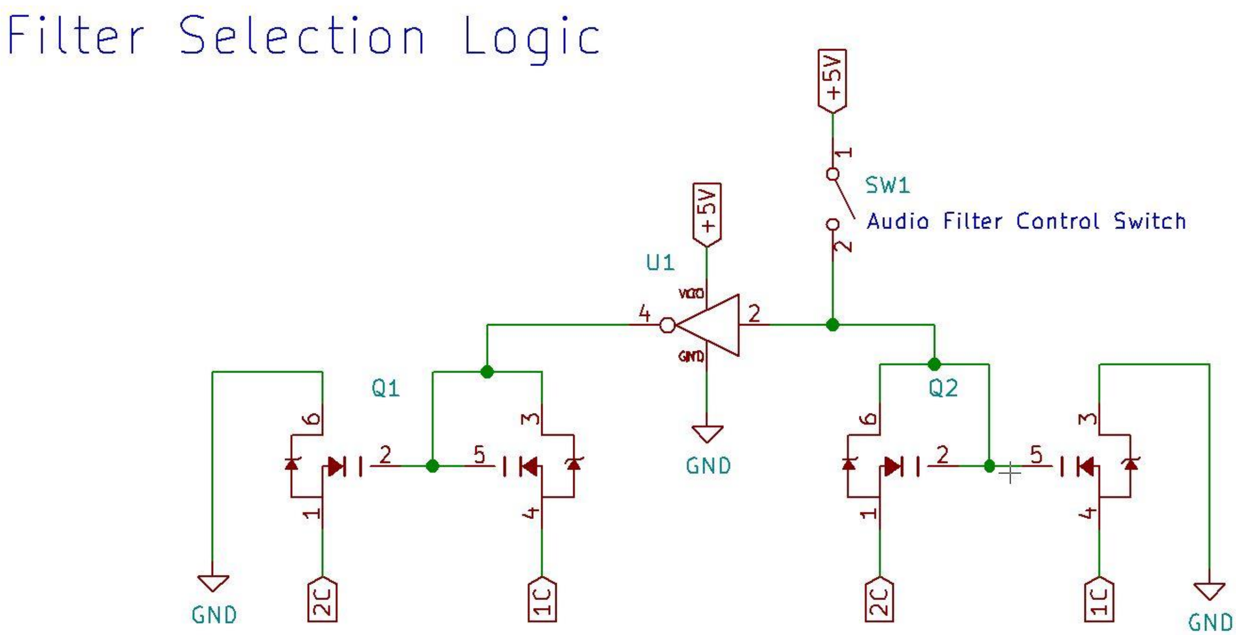


Figure 12 - Filter selection logic

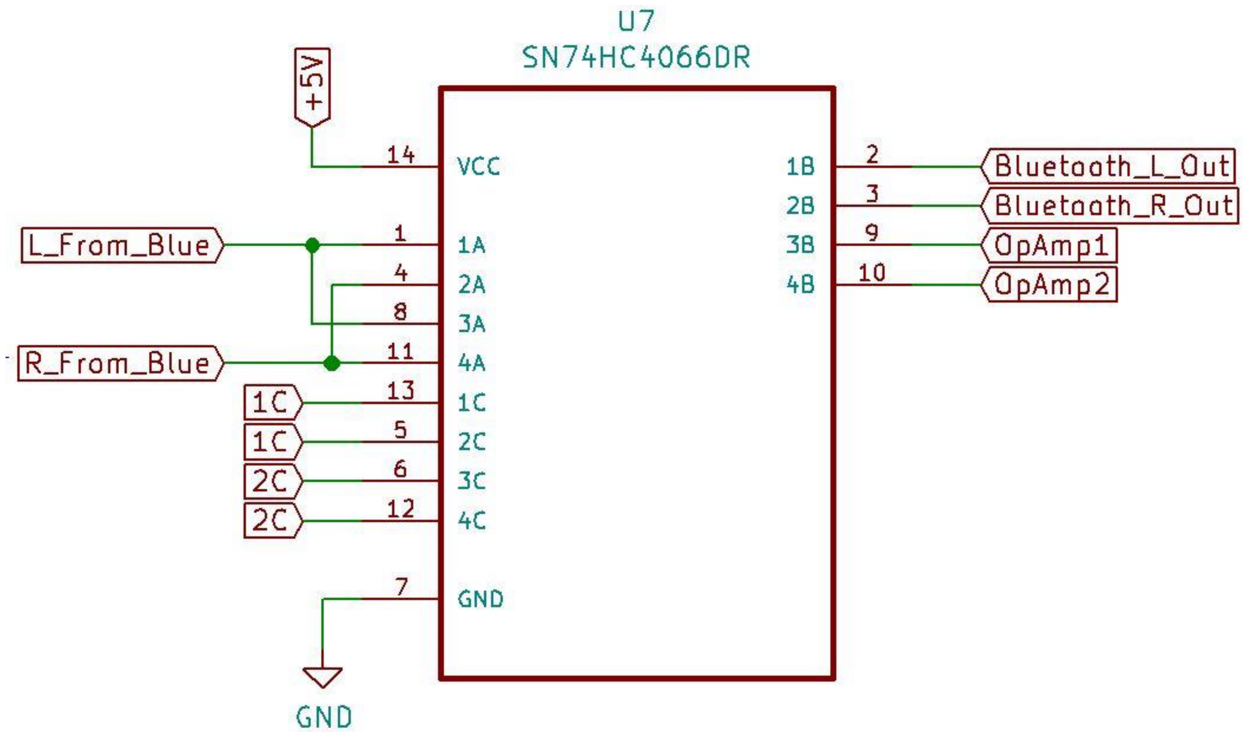


Figure 13 - Analog Switch

Audio Amplifier

A PAM8403 by Diodes Incorporated was selected for the audio amplifier. The circuit was designed predominately using the circuit suggested in the datasheet, however a 50KΩ logarithmic potentiometer was used to adjust the amplitude of the input signal, and therefore the resulting volume. Since only one speaker is to be used in this project, the left and right output terminals were tied together. If I decide to redesign this system in the future, it will be a trivial matter to add a second speaker by simply unwiring the two outputs and then connecting another speaker.

The speaker chosen for this system was an SP-4029-1 by Soberton Inc. This speaker was choses for its low cost, ability to reproduce audio signals across the entire range of human hearing (20 Hz to 20 KHz [7]), pre-attached JST connector, and mounting holes.

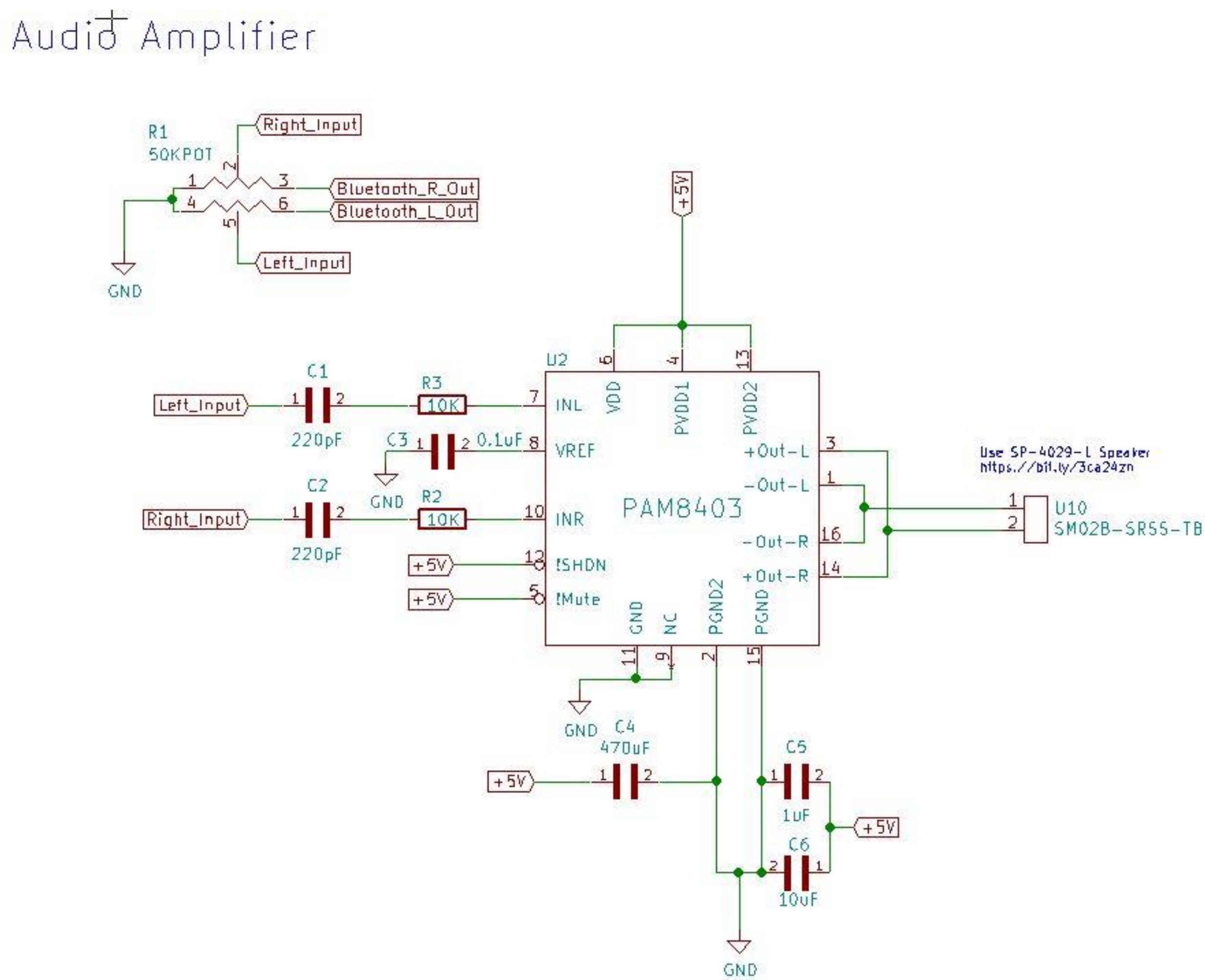


Figure 14 - PAM8403 amplifier with 50KΩ potentiometer

PCB Design

Once the design was finalized, a PCB was designed using KiCad. The PCB was designed in such a way that the USB port is in the back of the speaker, while the potentiometer is in the front. A separate board for the three indicator LEDs was created as well so that they could be placed in the front panel of the speaker.

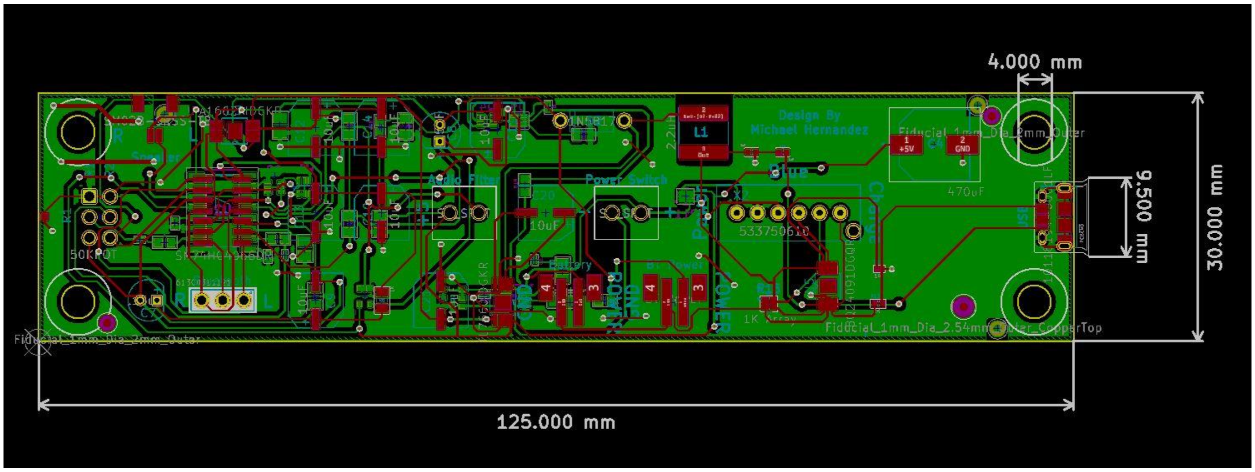


Figure 15 - The main PCB that was designed was 125 x 30 mm with 4 mm mounting holes

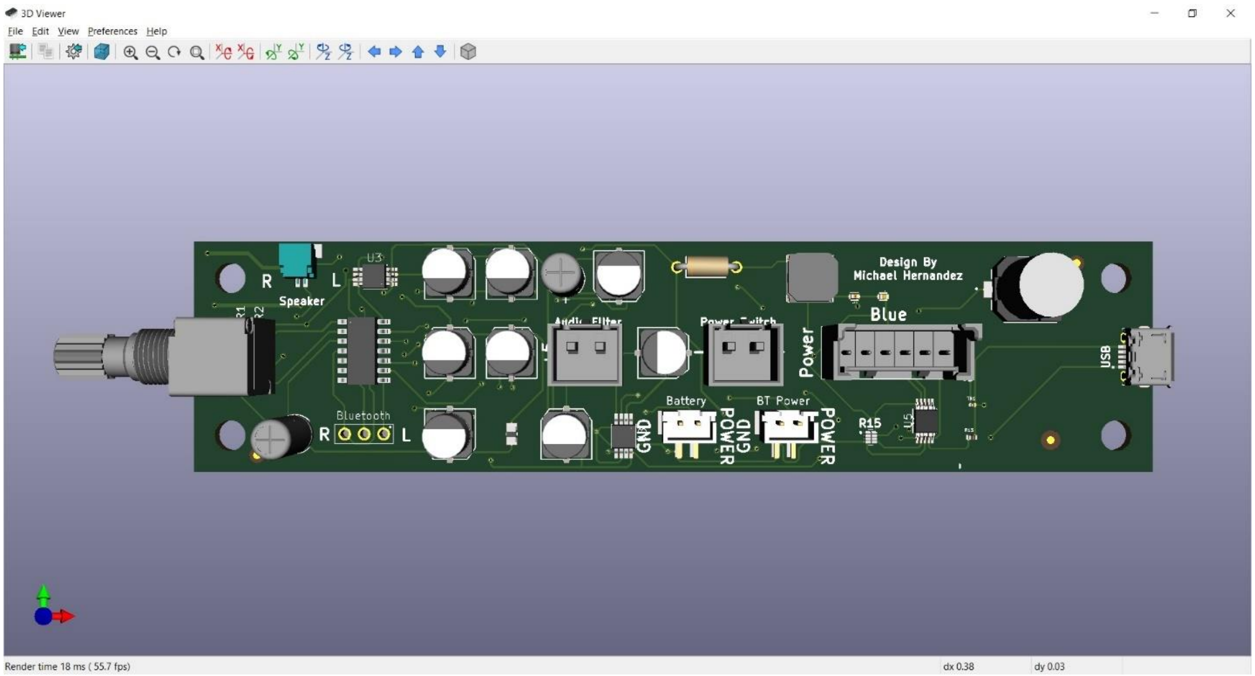


Figure 16 - Top view of the PCB

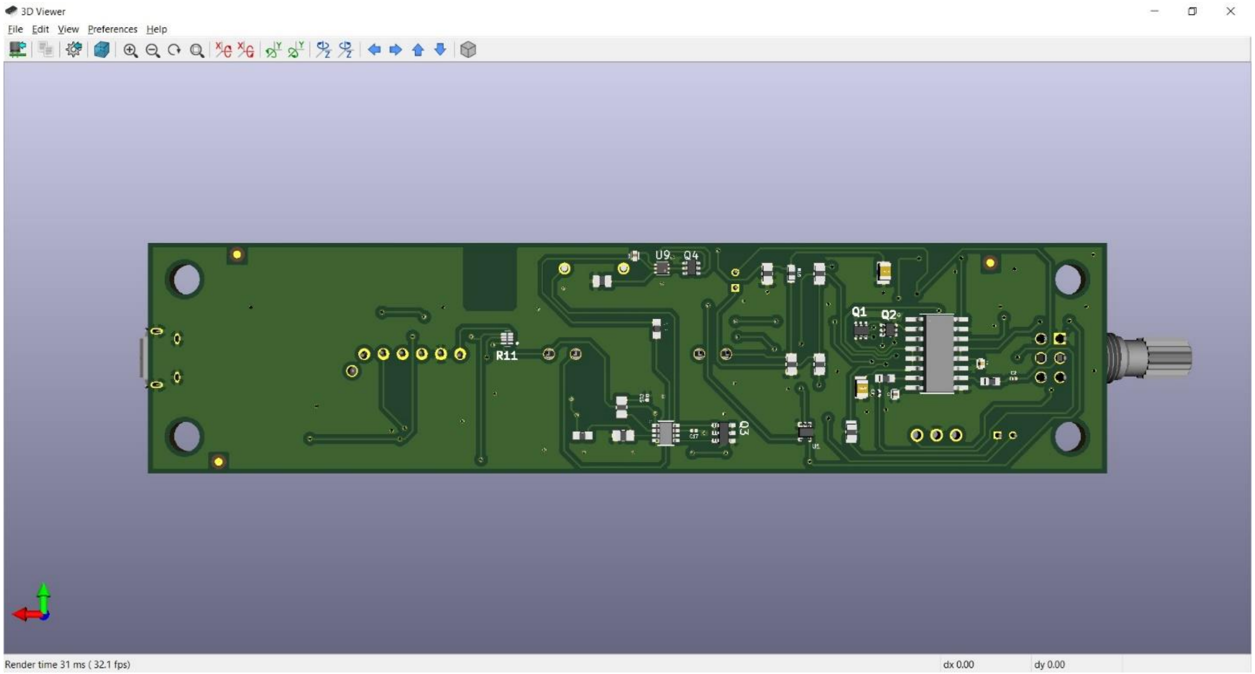


Figure 17 - Bottom view of the PCB, the ground plane is clearly visible

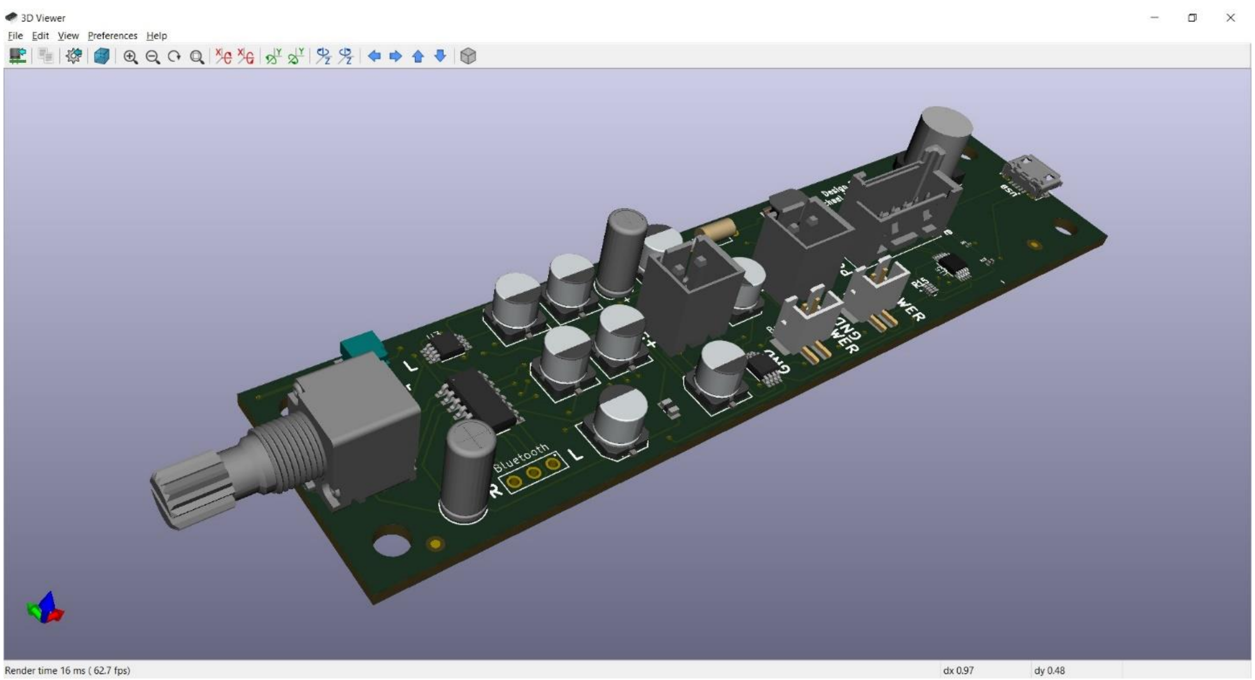


Figure 18 - Angled view from the top, note the protruding potentiometer which will be used as the volume control

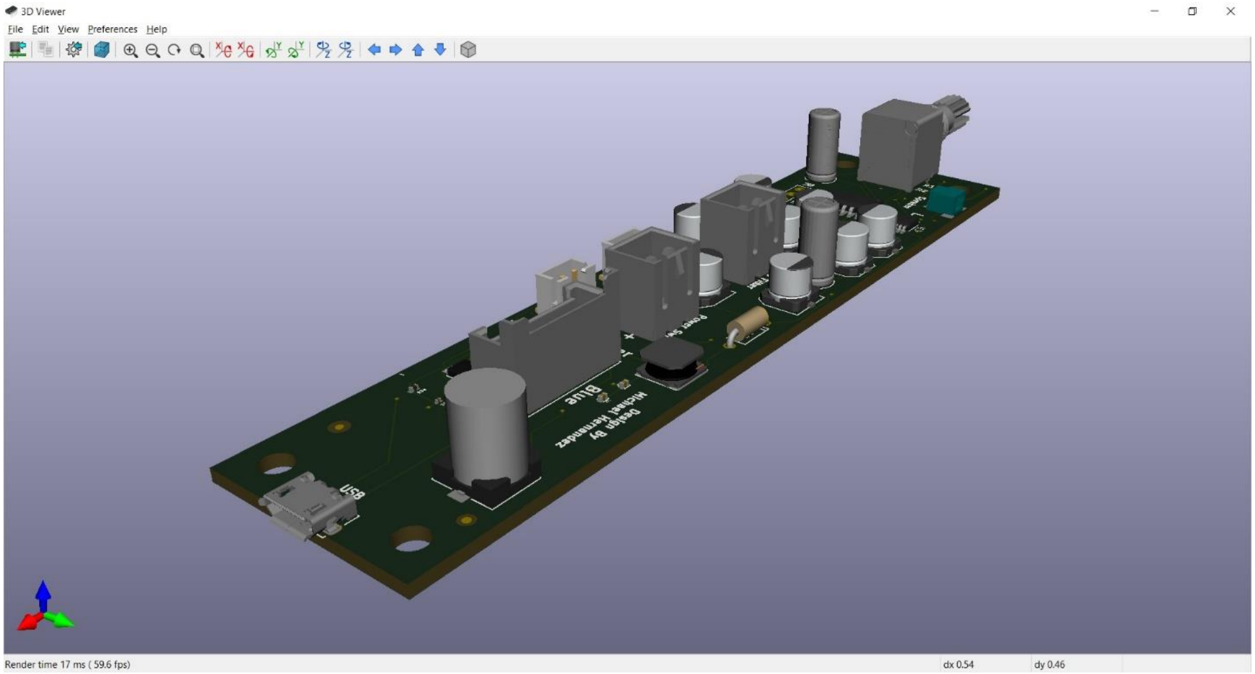


Figure 19 - Another angled view, this time the USB port is visible

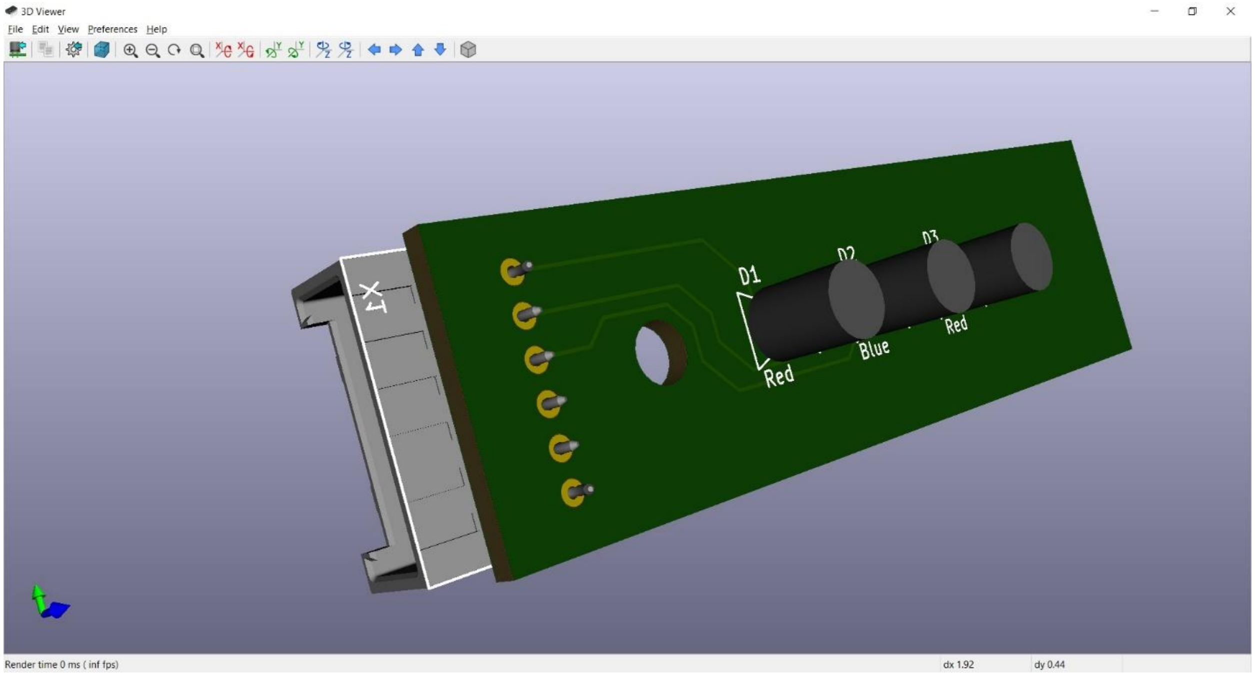
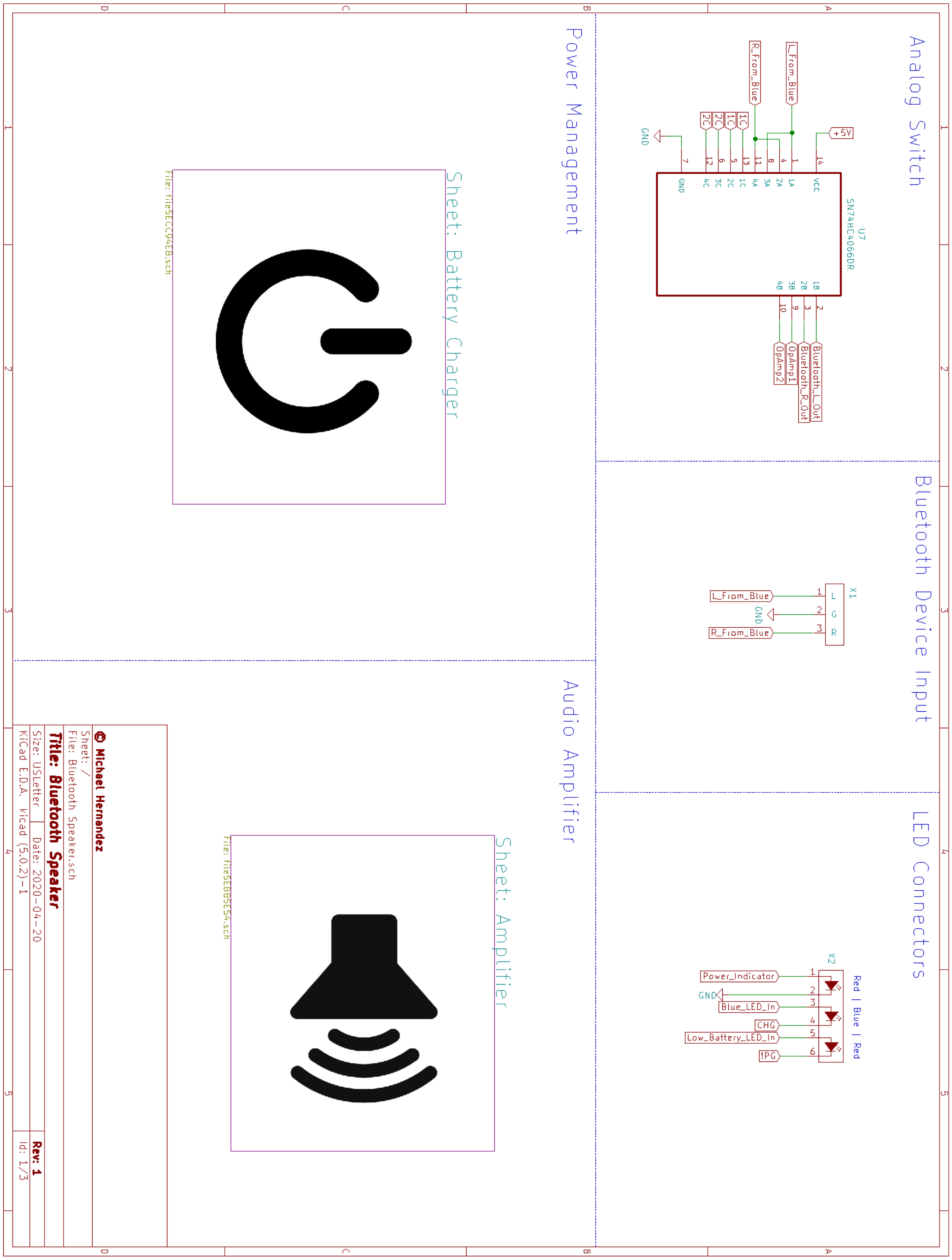


Figure 20 - The separate board containing the LED's. The board has a right-angle Molex connector which will be used to run wires between the LED board and the main board.

Schematics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Bluetooth Device Input
Audio Amplifier
Sheet: Amplifier
LED Connectors
SN74HC4066DR
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R_From_Blue
Bluetooth_L_Out
Bluetooth_R_Out
OpAmp1
OpAmp2
Power_Indicator
Blue_LED_In
CHG
Low_Battery_LED_In
Red | Blue | Red
© Michael Hernandez
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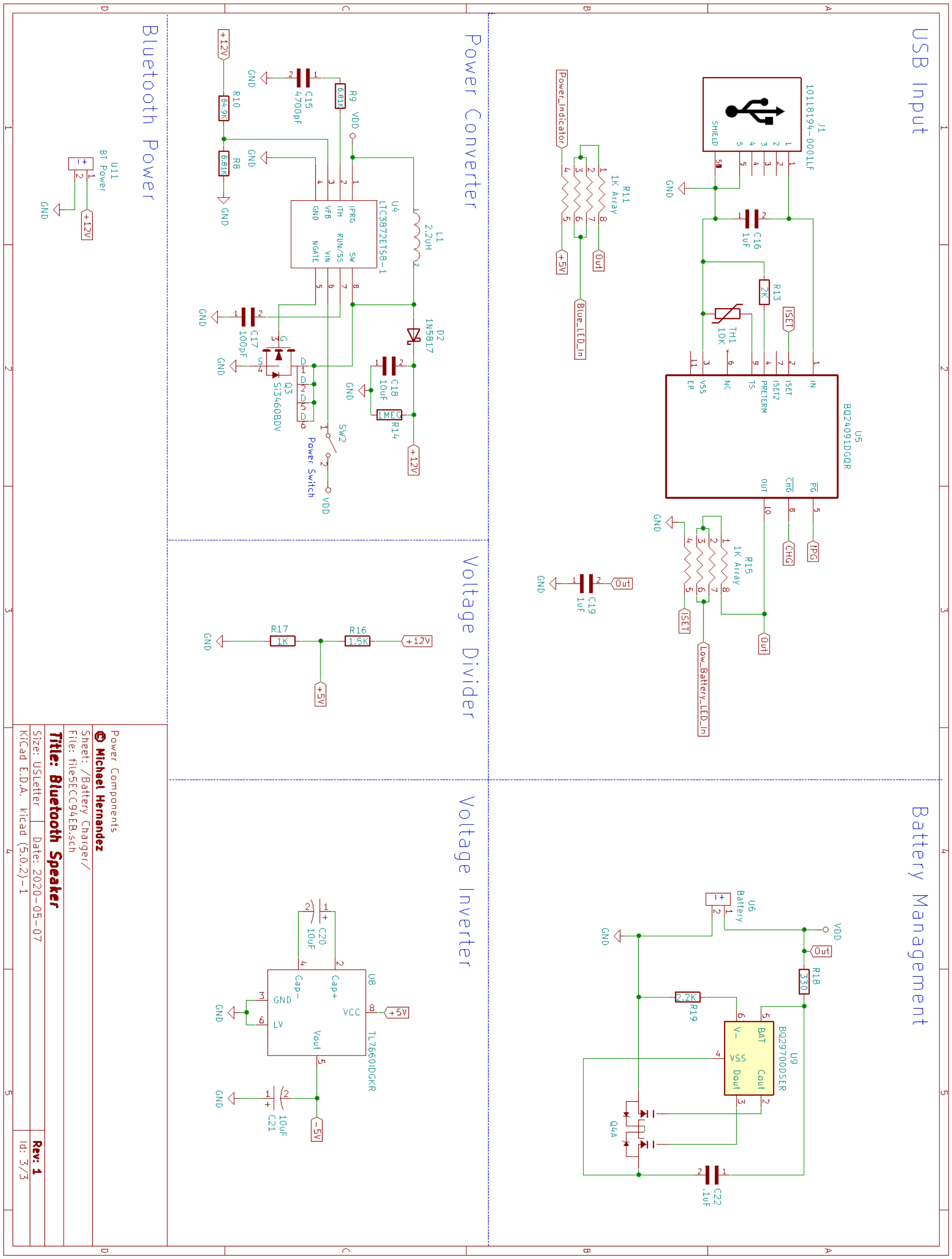
Rev: 1
KiCad E.D.A. kicad (5.0.2)-1
Id: 1/3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Voltage Divider
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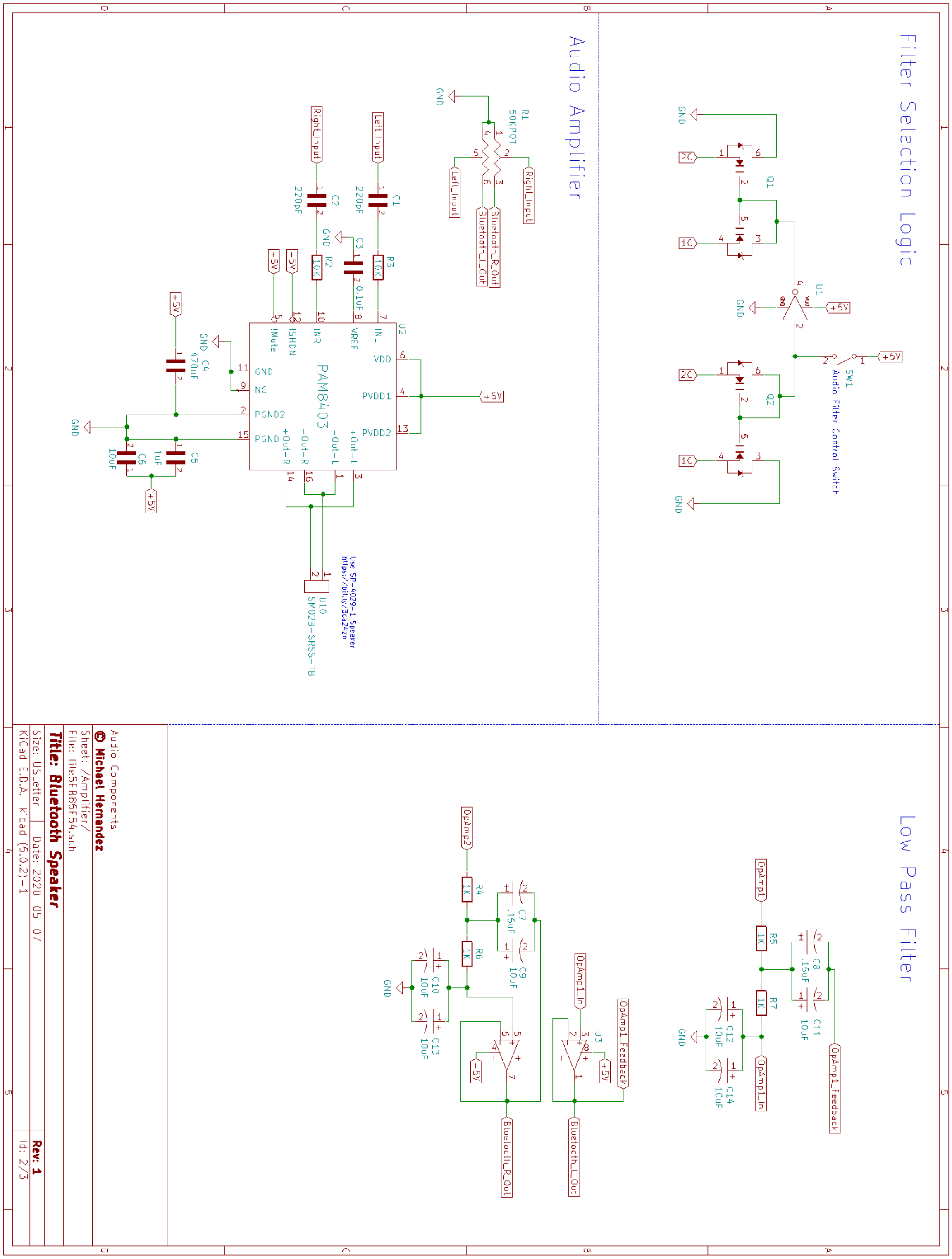
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Audio Amplifier
Low Pass Filter
PAM8403
Audio Filter Control Switch
Audio Components
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Size: USLetter
Date: 2020-05-07
KiCad E.D.A. kicad (5.0.2)-1
Rev: 1
Id: 2/3

Bill of Materials

[The Bill of Materials has been intentionally omitted from this report]

The total cost for producing one unit, *excluding* the costs of labor, an exterior case, packaging, instruction manuals, minor parts such as wires and screws, and shipping is approximately $77.95. The cost of this unit can come substantially if it is mass produced. The most obvious ways to reduce cost would be to reduce costs in the following areas: battery, Bluetooth module, speaker, and possibly eliminating board connectors in favor of soldering wires directly onto the PCB.

Due to the economics behind purchasing in volume, the cost to produce 100 PCBs can be brought down by $11.32 per speaker for a total of $66.73 per speaker. The total startup cost for producing 100 speakers would be $6,662.65. Again, this cost excludes labor costs for having the boards assembled, so it would likely be about $1,000 beyond the cost of the speakers to have them assembled.

[The Bill of Materials has been intentionally omitted from this report]

References

[1] Wikipedia, "Ultra High Frequency," [Online]. Available: https://en.wikipedia.org/wiki/Ultra_high_frequency.

[2] Tektronix, "Internet of Things: How to Select a Bluetooth Module," [Online]. Available: https://www.tek.com/document/application-note/.

[3] Amazon, "Bluetooth Board, DROK Audio Receiver Bluetooth Module DC 5V-24V Portable Wireless Electronics Stereo Music Receive Circuit Chip with Micro USB Port for Headphone Speaker Home Sound System DIY," DROK, [Online]. Available: https://smile.amazon.com/gp/product/B07P94Z9XR/ref=ppx_yo_dt_b_asin_title_o03_s00?ie=UTF8&psc=1. [Accessed 14 May 2020].

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[7] K. Saladin, "Hearing and Equilibrium," in *Anatomy & Physiology: The Unity of Form and Function*, New York, McGraw Hill, 2012, p. 596.