PERSISTANCE OF VISION MUSIC DISPLAY

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Abstract

The purpose of this project was to create a unique approach to music visualization in a manner that hasn't been done before. We used the concept of Persistence of Vision to create a music visualization display. This was accomplished by spinning an LED bar to a critical speed in which an optical illusion begins to form a "static" display. We used this concept to create a canvas where we can map the frequency spectrum of the music onto our "static" display. This project takes concepts from digital / analog signal processing, power electronics, control theory, and embedded systems and uses them create a visually stunning product.

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1. Introduction

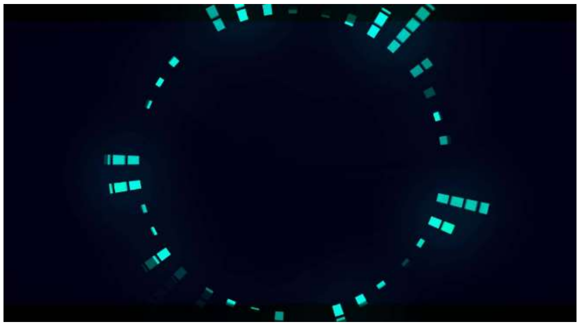

Figure 1. Circular music visualizer example.

Circular music visualizers, as shown in Figure 1 above, have recently become popular in the entertainment and music scene for their unique take on music visualization. Creating one is easy on a computer or an HD TV due to the high pixel count or large computation power. However, many light fixtures used by hobbyists / artists / entertainment companies use low resolution square dot pixel displays to visualize their music. This causes jagged edges on the frequency bins of a circular music display. Anti-aliasing filters can fix this issue but the result looks messy and unprofessional. Therefore, we set out to find a solution to this by displaying the visualization radially on a PoV display. We will be going over our goals, design process, verification of our design process, parts, labor, accomplishments, uncertainties, ethical considerations and finally we will conclude with a discussion of our future work with this project.

1.1 Goals

We had three personal goals that we wanted to achieve while devising this project. The first goal that we set out to accomplish was to have the ability to intake audio from any source that supported a 3.5mm aux cable. The reason behind this was that we wanted the system to be compatible with a wide range of users and applications. The second goal that we set out to accomplish was to provide a "plug and play" capability for the project. This means that the user would simply have to plug in their audio device and power the project via a power outlet and the project would function as intended with no further interactions. Having this feature is vital for both professionals and common consumers as it provides an ease of use for the user. Our third and final personal goal was to create something interesting and unique on a media that has not been explored before. It is important to keep in mind that unique, flashy and new products are what entertainment industries are looking for.

We also had technical goals that were necessary for our project to work in the way that it was intended to. In order to interact with all types of audio we decided we would have to make an audio interface that the user would have easy access to. We as the engineers would have to design a circuit to ensure that whatever audio was placed into our system would then be properly conditioned. Keeping in line with making things easier on the user, we decided that it would be necessary to build a power converter so that various subsystems would have the appropriate power provided to them without the inclusion of outside components. This would allow the system to have a single outlet cable. This in turn would allow the system to be more compact and simple for user interfacing. Lastly, we found it to be vital to maintain the PoV illusion during all points of operation. To ensure this condition was fulfilled we required that the motor should spin at a consistent speed.

1.2 Block Diagram

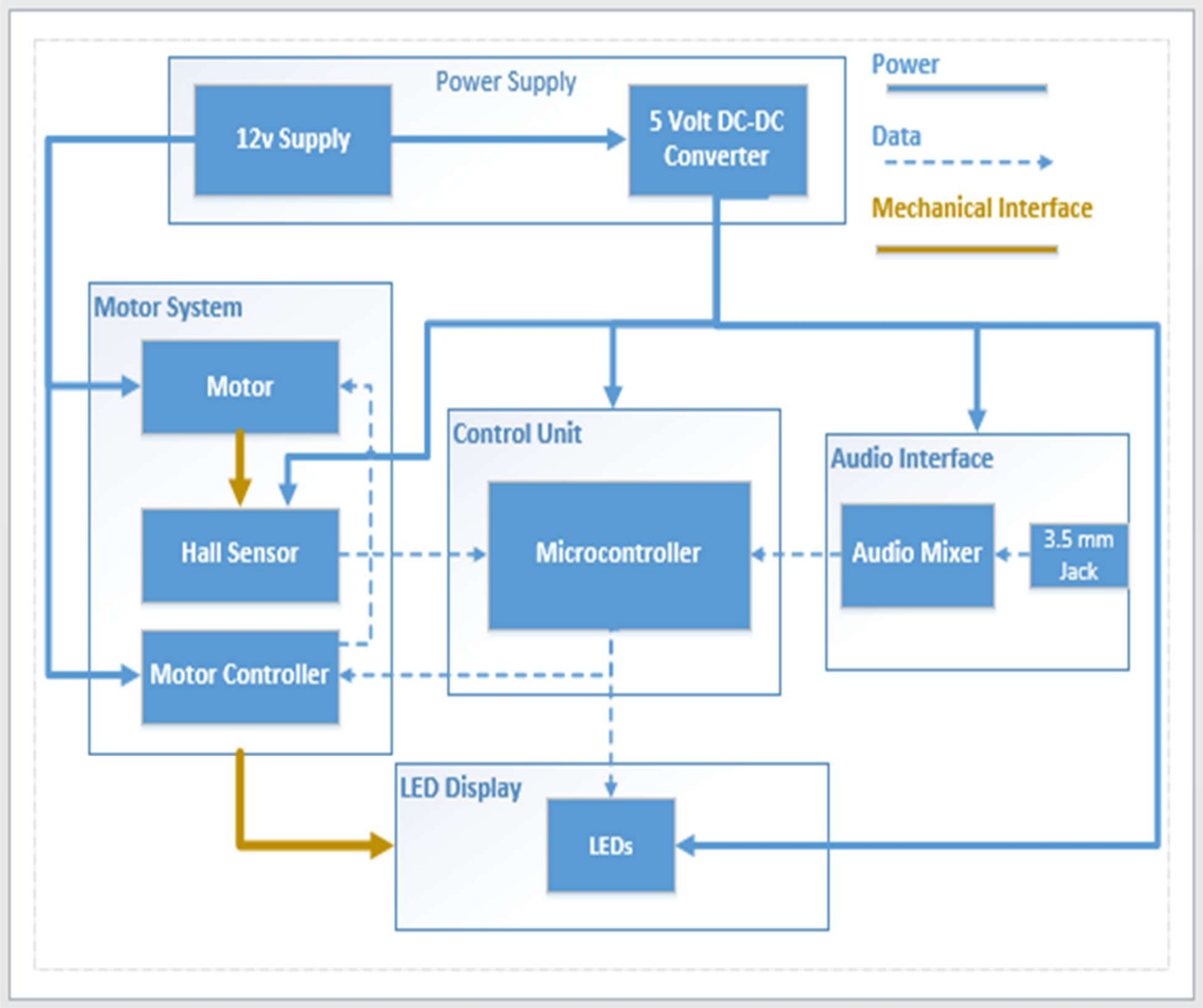

Figure 2. Block diagram of entire system.

1.3 Block Diagram Description

Our block diagram consists of 5 subsystems: a power supply, a motor system, a control unit, an audio interface, and an LED display. The entire system is powered by a single wall outlet 12V DC power supply that is also converted to create a 5V DC railing. The 12V rail provides power to the motor system exclusively while the 5V rail supplies power to the LED array, the microcontroller, and the audio interface. The motor system is controlled by the microcontroller in order to generate a constant speed. The motor is mechanically connected to an armature that the LEDs are attached to. A hall sensor is included in the motor subsystem as a means of determining when to display data onto the LEDs while also providing data to the microcontroller so that it can accurately control the motor speed. The microcontroller is the brain of the project as it takes in data from the hall sensor and the audio interface, processes it, and then provides the necessary output to the motor and the LED display.

2 Design

2.1 Power Supply

2.1.1 Description

The power supply will provide power to all other subsystems within the project. The entire subsystem consists of a 12V power supply that is also converted in order to create a 5V railing.

2.1.2 Design Choices

In regard to the 12V power supply itself, since we did not design it, there were no design choices to be made for it. We simply had to calculate an appropriate amount of power required for our project and then buy a power supply that met these requirements. The design in this subsystem comes from the DC-DC converter that is used in order to generate the 5V railing. Figure 3 shows the schematic for the converter circuit that was used in our project.

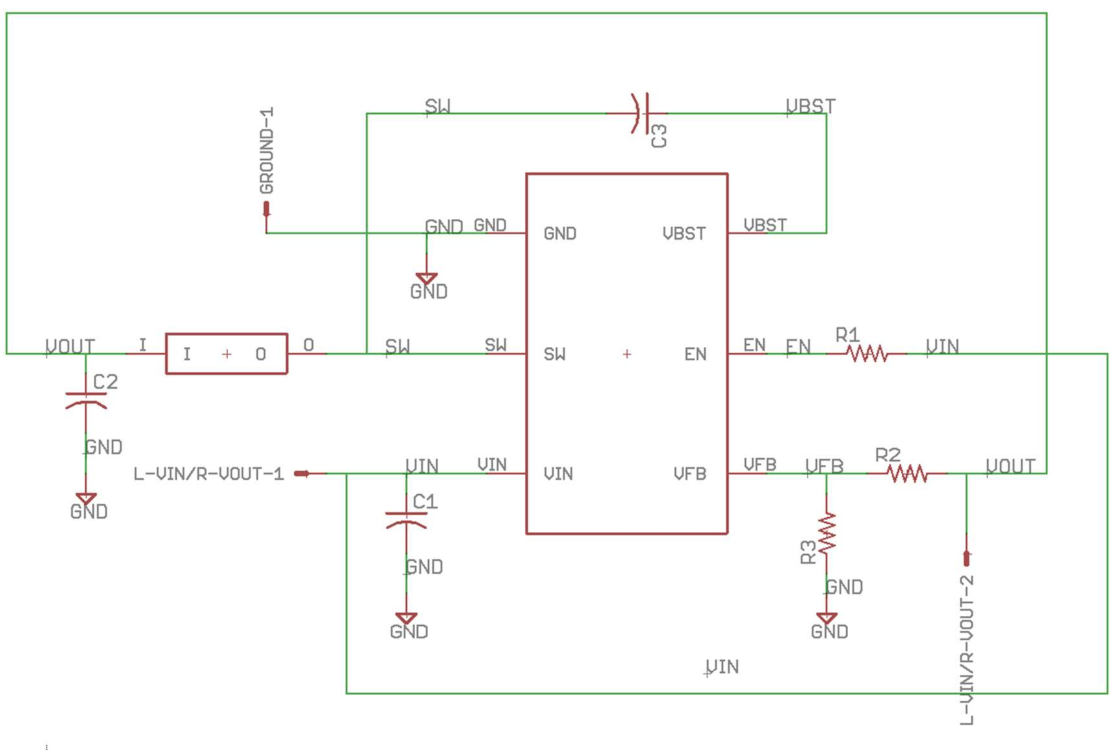

Figure 3. Schematic of converter circuit.

Going into further detail about the layout of this circuit, a general model of how the circuit should be constructed was provided from the data sheet for the converter chip [1]. The chip used for this circuit is the TPS563208. This chip was chosen based on how simple it was to implement, how much current it could output, and whether it was surface mount solderable. The passive components chosen for use in this circuit were picked based off information from the data sheet [1]. Extra thought was put into the choice of the inductor as it was required that it could handle at least 2.3A without saturating. This value for current required was determined from a rough calculation of maximum load from the subsystems powered by the 5V railing. The inductor chosen for use in this circuit is the SRP4012TA-3R3M [2]. Note that the component with the I and O ports is the inductor. We had to create custom pads for the inductor that we choose to use. C1 and C2 are the input and output coupling capacitors. Their main purpose is to serve as chokes for higher frequency noise and to keep ripple at a minimum. Noise should be eliminated at the input and output. R1 is used to reduce the current going into the enable gate so that it does not get damaged. R2 and R3 are used to create a reference voltage that the feedback network uses to stabilize the output to the desired output regardless of the input. C3 is used as a feedback between the VBST and the output while providing further high frequency filtering. The component values were chosen as such:

Table 1: Component values used for converter circuit

C1	22 µF
C2	44 µF
C3	0.1 µF
R1	10 kΩ
R2	10 kΩ
R3	47 kΩ
L	3.3 µH

C1 and C2 had to be significant in their values such that proper filtering occurred at the input and output of the converter. C2 was made twice as large as C1 because output capacitors typically have to be larger in values such that the output is properly filtered. C3 does not have to be significantly large as it simply provides a feedback between two parts of the chip. R1 doesn't need to be significantly large as 10 kΩ will limit any sort of input current down to a reasonable level. The values for R2 and R3 were chosen in accordance to an equation given in the data sheet for the converter chip. The equation is as such [1]:

$$V_{OUT} = 0.768\ x\ (1 + \frac{R1}{R2})$$

2.2 Audio Interface

2.2.1 Description

A lot of music involves utilizing the left and right channels to create a soundstage for the music. Because we only have one audio quality ADC on the micro, we created an audio mixer for the left and right channels. This consists of two op amp amplifiers. The ADC only works within a set range of voltages. To make sure our audio is sampled correctly we made a passive bias filter to set the correct DC bias.

2.2.2 Design Choices

The first stage is for the active mixer to combine the two signals. We chose the input and feedback resistors to provide unity gain on the output of the first stage. The second stage is used merely to recover the phase of the signal due to the first stage inversion. The second stage has a slight gain to compensate for any gain loss and to provide some voltage leeway for the output potentiometer. The reason for the output pot is to be able to tune the output voltage swing to one volt peak to peak for the bias filter. The following equation is used to calculate the amplifier gains:

$$V_{Out} = \frac{R_{feedback}}{R_{Input}} * V_{In}$$

We don’t have negative voltages from the power supply but the audio signal does. To compensate for this the op amps are referenced to a virtual ground. This puts our output signal on a 2.5V DC bias. We place an output filter to remove the bias before the potentiometer to ensure our signal is conditioned for the bias filter. Some extra resistors are added onto the virtual ground inputs to balance the impedance.

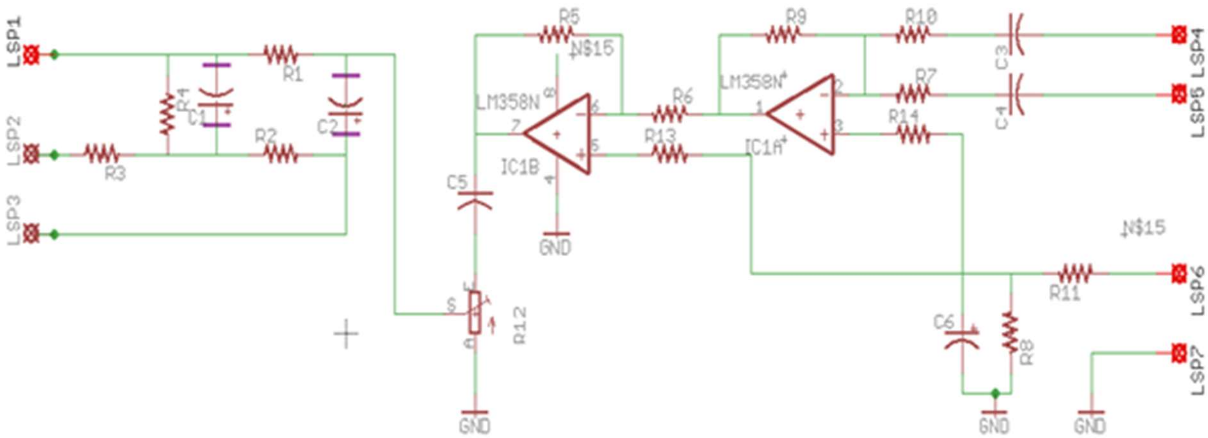

Figure 4: Audio interface circuit schematic

The ADC can only sample signals within a set range and frequency so extra signal conditioning is required to get it within the operating range. The 3.3V supply is divided to just over half a volt in order to keep the input signal just above ground level. The capacitors provide basic filtering to the signal to ensure that the ADC output doesn't alias.

2.3 Motor

2.3.1 Description

The motor system is in charge of spinning the LEDs to a target revolutions per minute, RPM, to generate the display. Component wise, there are three main parts: the motor, the motor controller, and the hall sensor. Producing the correct RPM is done with help from a magnet embedded within the LED armature that interacts with the hall sensor each time it passes over it. Design choices were made on the hall sensor and within the micro in order to output the correct signal for the motor controller. There was also a mechanical portion that was utilized in order for the motor system to work properly.

2.3.2 Design Choices

For the mechanical design, the motor is in a pulley-belt system with a ratio of 1:4 with the other end being the slip ring / LED armature shaft. This was done since the RPM range of the motor goes well beyond what we need for the project. Reducing the RPM would in tandem increase the torque done of the LED armature by the same pulley ratio.

Initially, the hall sensor did not properly function by itself. Testing showed that the output of the hall sensor's Vout did not match the range specified by the datasheet. Due to this, we designed a PCB layout to properly mount the hall sensor and its supplementary parts. These supplementary parts were a resistor and capacitors since the issue was a need for biasing for Vcc and Vout.

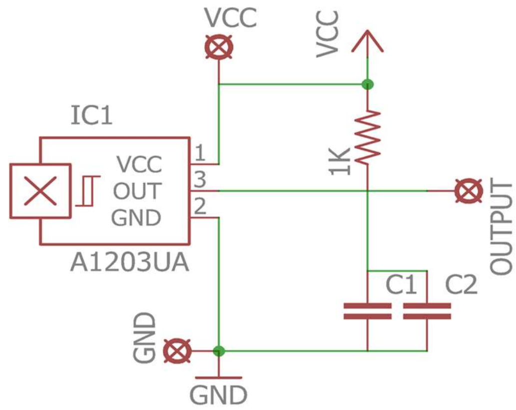

Figure 5. Hall sensor circuit schematic

Intentions to use a custom PCB for the motor controller were discussed and whether or not we had the time for it in the build phase of the project. To run the motor controller, the microcontroller sends out a constant pulse width modulation signal, a PWM, to generate a certain speed for the motor. We realized very quickly that there was a problem with the motor system as the RPM calculation based from hall sensor feedback clearly showed that the motor speed and RPM were unstable. At its worst the motor would sway in RPM with a delta of 30 RPM. To mitigate this, we used a proportional-integral, PI, controller to reduce the error of the system. The controller runs within the main loop of the microcontroller. It starts with an initial PWM value that changes with refreshed error calculations each time the hall sensor detects the passing of the magnet. Below are two equations that we implemented in code for the PI controller. In the first equation, the variables K_p and K_i represent the individual constants we fine-tuned to create a stable control system. The second equation represents the trapezoidal approach we used to generate the integration of error. I_k represents the integration, $error_k$ the current error, and T is the total time from the current error from the previously calculated error.

$$PWM = PWM + K_p(RPM_{desired} - RPM) + K_i \int (RPM_{desired} - RPM)$$

$$I_k = I_{k-1} + \frac{error_k + error_{k-1}}{2} * T$$

2.4 Microcontroller

2.4.1 Description

The microcontroller we decided to use was an ARM Cortex M0 processor based off the Teensy 3.2 dev board. We chose this specific model because the chip has fast MAC instructions which multiply and accumulate in the same clock cycle. This is ideal because we want to process the audio as quickly as possible to leave enough time for the motor control code and display code. One of the best reasons we chose the teensy implementation of this micro was the custom bootloader it uses. It allows for the use of Arduino code as well as C++ libraries.

2.4.2 Design Choices

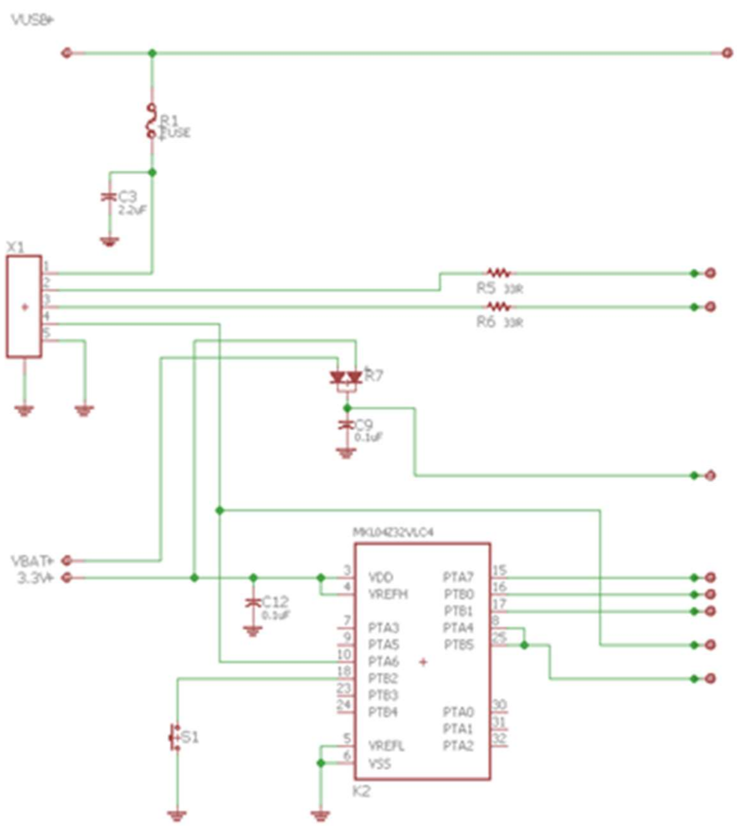

Figure 6. Boot loader schematic

We can program and debug the microcontroller through 8 pins using this bootloader chip. It acts as the programmer and as a host interface back to the computer. The original schematic came from the development board documentation but it has been modified for this design to be separate from the main microcontroller board [6]. We also removed some functionality that was not being utilized.

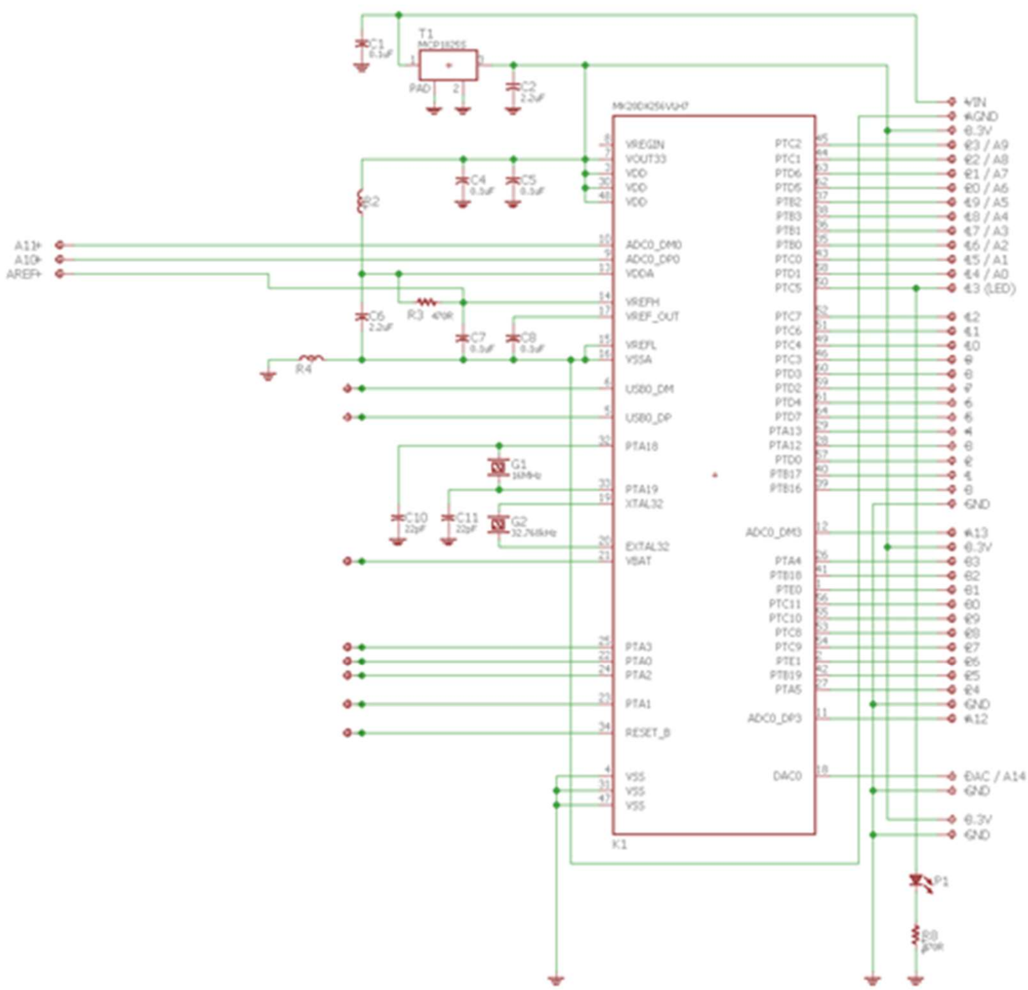

Figure 7. Microcontroller schematic

The original schematic for the microcontroller came from the development board documentation but it has been modified for this design [6]. The circuitry for the bootloader has been removed so the microcontroller can be used alone. We also removed some of the development board functionality as we did not need or use all the functionality. This is to create a cheaper product overall and to reduce the complexity of the PCB design as the development board has four layers. We also decided to add a secondary crystal for a real-time clock to make the timing calculations simpler.

2.5 LED Display

2.5.1 Description

Individually addressable RGB LEDs were used as they were easy to feed data into, could be cascaded, and offered a wide spectrum of colors. The LEDs were contained within an LED strip. Because this LED strip was purchased there is no design portion to go along with it. The LEDs needed to be able to refresh within 1.2 - 1.3ms. If they were not able to do this we would not be able to accurately display the frequency spectrum on our “static” display. We wanted 24 full revolutions per second (minimum speed that creates a persistence of vision) or 48 half revolutions per second and we wanted 16 frequency bins to be displayed within 1 half revolution so then the math followed as such for how fast the LEDs needed to refresh themselves:

$$T_{delay} = \frac{Refresh\ Rate}{FFT\ Bins} => T_{delay} = \frac{\left(\frac{1}{24}Hz\right)}{32} => T_{delay} = 1.3\ ms$$

3. Design Verification

3.1 Power Supply

3.1.1 Requirements & Verification

Ringing is a very common problem when designing power converters. Figure 8 shows the output voltage waveform for the converter zoomed in on the most extreme portion of the ringing. We tried to alleviate this ringing through several different methods. We increased our input and output capacitance, changed our chip, even remade our PCB so that our components were more closely spaced. None of these proved to be helpful in reducing the ringing in our signal. We choose our output voltage to be 4.38V such that this ringing would not cause any damage to any components in our system by exceeding 5V. Despite this ringing being very large, it is very short lived (8.200 ns) and did not cause any issues in our project overall, surprisingly.

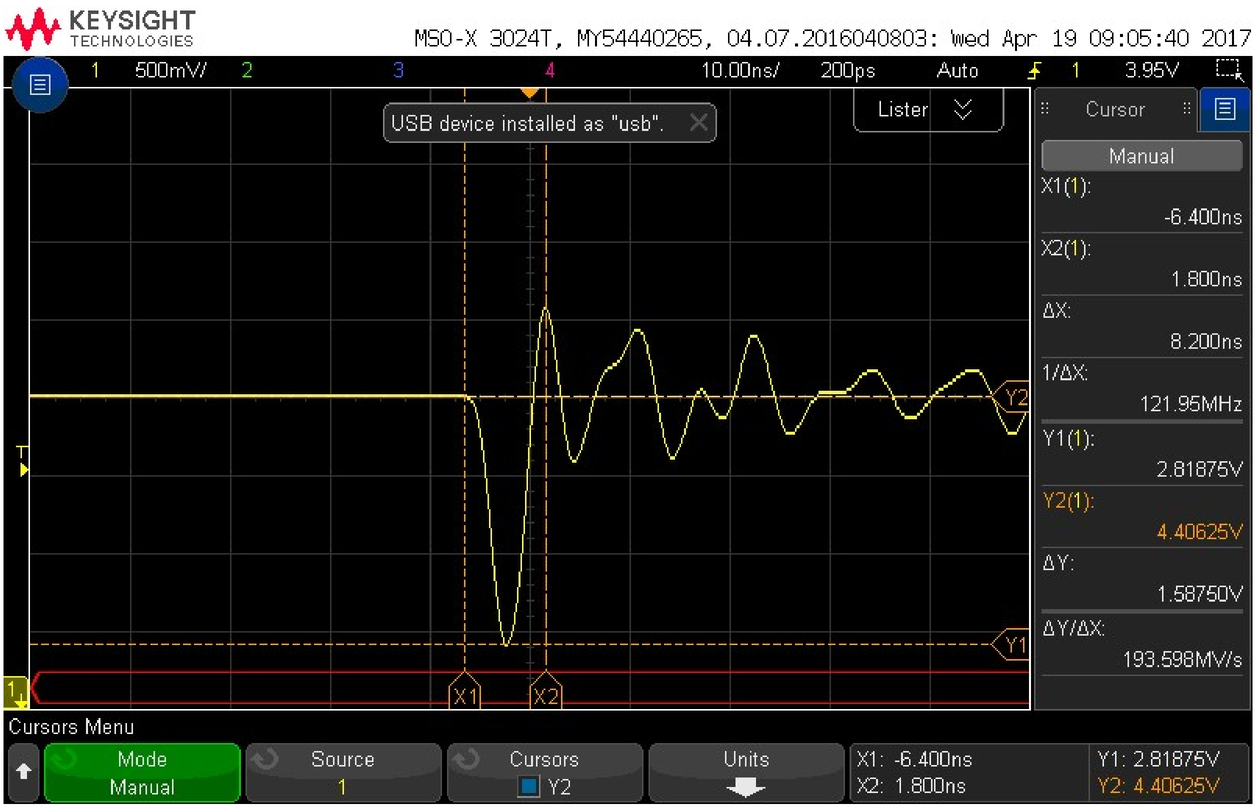

Figure 8. Ringing at output of converter waveform

Figure 9 below shows the ripple in our output. The large flucations on the left and right are the ringing previously discussed. The rising waveform within the cursors is the ripple. By observing the delta between the cursors and dividing it by the average of the two cursor values, it can be determined that our ripple is well within +/- 1% despite the ringing being much greater than it. To be more precise the ripple is 0.365%. This ringing is definitely not ideal and it makes the ripple insignificant. We would have liked to reduce it but we were unable to. We were informed by a ECE 469 TA that it was likely an artifact of the chip itself or the inductor that we chose to use.

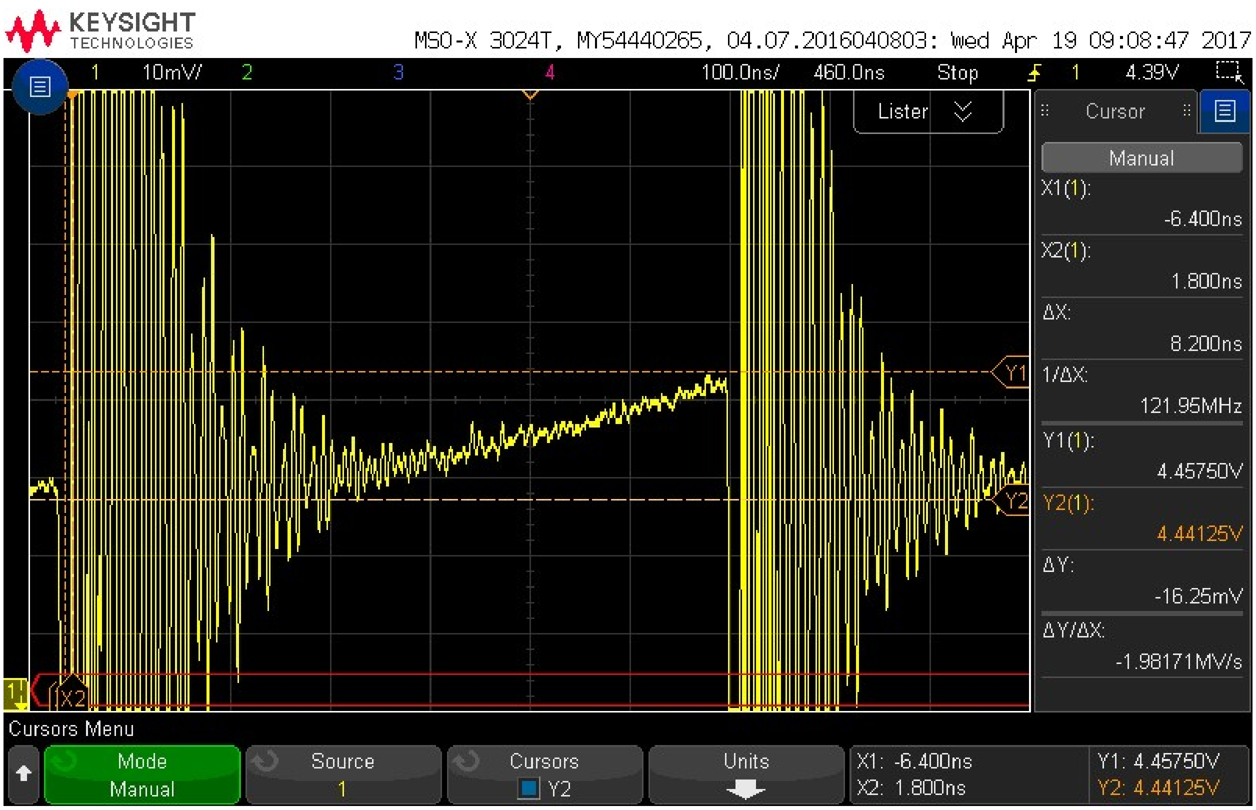

Figure 9. Ripple at output of converter waveform

3.2 Audio Interface

3.2.1 Requirements & Verification

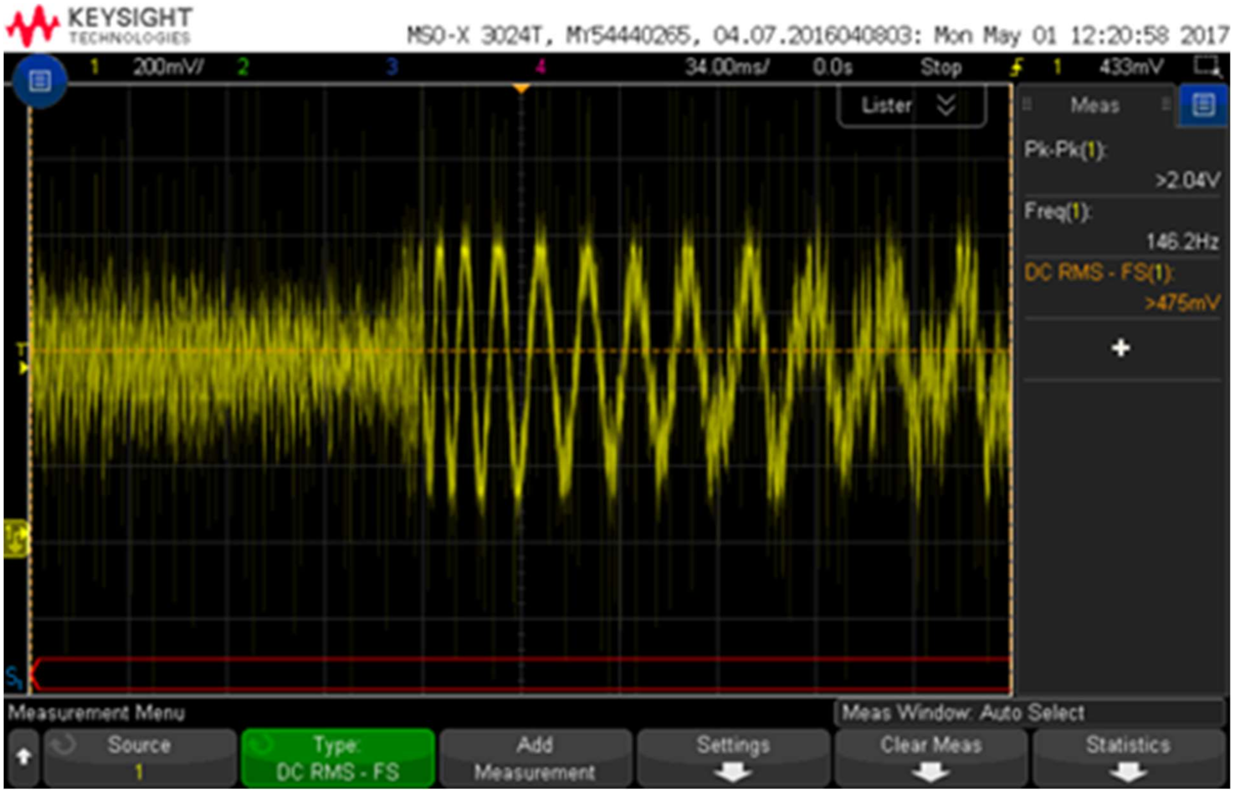

Figure 10. Audio interface output waveform

We had a requirement on the audio interface to maintain the 1V peak to peak voltage in order to match the input. We had measured the output audio at max input volume. We had expected some noise but we encountered noise that exceeded our 1V maximum. However, after further investigation we realized that this noise was not an issue for our project due to its very short lived lifetime. Our output signal minus the noise always stayed within the bounds of +/- 1V. Our other requirement was to set the DC bias to 450-550mV so the microcontroller's ADC could sample the audio. The ADC range is between 0V-1.6V so this was a necessity for our system to operate. Our measured DC RMS was 475 mV which was just on the lower limit of our requirement. This might have caused issues with displaying low volume audio but this did not cause any issues with the general operation of the project.

3.3 Motor

3.3.1 Requirements & Verification

Updates to the motor requirements were made once we realized that some requirements and verifications were invalid. For the demo, the requirement we placed on the motor system from the initial requirements was to have a steady state error within 1% of 720 RPM / 24 FPS. For the demo, we switched to 900 RPM / 30 FPS after we verified that the project worked with our verifications at 720 RPM. This design choice was done to give the user a more enjoyable experience. To verify this, feedback from the hall sensor was used. The figure below shows the waveform from the hall sensor when the system is at steady state running 30 FPS / 900 RPM. The hall sensor outputs a “high” when there is no interaction from the magnet. The short “low” signals that the magnet has passed over the hall sensor. When another low is reached, it means that the LED armature has done one full rotation. The highlighted section of $\frac{1}{\Delta X}$ reflects the FPS of the system. Since the display is generated from two blades, we double this value to achieve 30.12 FPS. From this value, we get a percent difference of 0.4% which is well within our margin of error. A similar result was seen with 24 FPS.

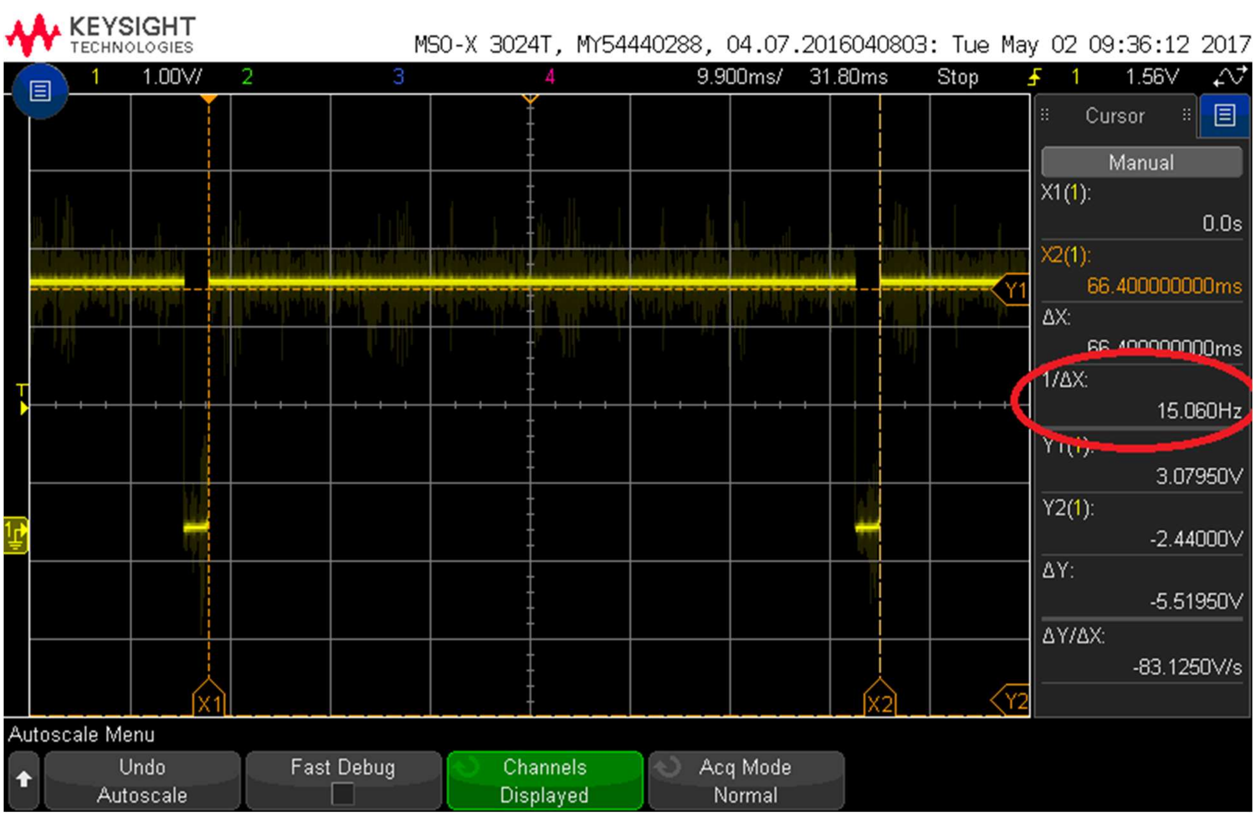

Figure 11. Hall sensor waveform

3.4 Microcontroller

3.5.1 Requirements & Verification

Our Microcontroller PCB unfortunately did not work during the time of the demo. We had tested our PCB for part placement, signal continuity, and power. We confirmed they all matched up on the schematic but we couldn't get it to work. We deduced that this was either an issue with our actual design or a faulty microcontroller / bootloader. The design could have been ruined when we modified the reference circuit by removing functionality. The ARM chip might have died due to humidity damage from being in open storage for an extended period of time. Either way, we did not have enough time or resources to develop a new board.

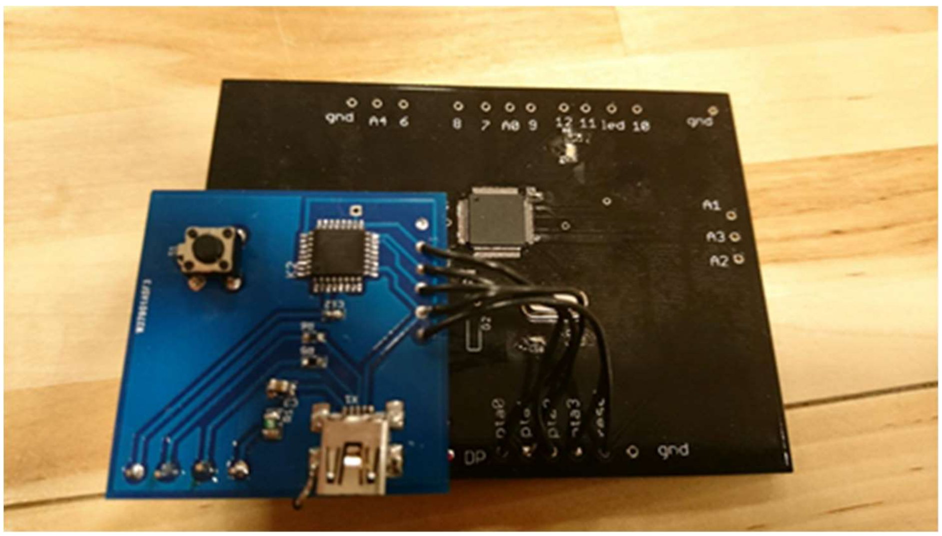

Figure 12. Bootloader and Microcontroller PCB

4. Costs

4.1 Parts

Table 2: Parts Costs

Part	Manufacturer	Retail Cost ($)	Bulk Purchase Cost ($)	Actual Cost ($)
Adafruit DotStar Digital LED Strip - Black 144 LED/m - One Meter	Adafruit	$74.95	$74.95	$74.95
6ft 80W Aluminum Alloy LED Power Supply 12 Volt DC Output	Intocircuit	$31.99	$31.99	$31.99
TI 4.5V to 17V Input, 3A Output, Synchronous SWIFT Step-Down Converter (TPS563208)	Texas Instruments	$1.34	$1.34	$1.34
TrackStar 1/18th Scale 14T Brushless power System (4300kv)	TrackStar	$37.99	$37.99	$37.99
Adafruit 6 wire Slip Ring	Adafruit	$14.95	$14.95	$14.95
Unipolar Hall sensor - low sensitivity (US5881)	Allegro	$2.00	$2.00	$2.00
ARM cortex M3 microcontroller + Programmer	PRTJ	$9.99	$9.99	$9.99
SRP4012TA-3R3M - 3.3 µH Inductor	Bourns	$1.16	$1.16	$1.16
Total		**$174.37**	**$174.37**	**$174.37**

Note: This total does not include the enclosure and armature that were made for us at no cost.

4.2 Labor

Labor Total: $3 * \frac{\$40}{hour} * 10\ hours\ a\ week * 16\ weeks * 2.5 = \$48{,}000$

5. Conclusion

5.1 Accomplishments

We felt like we learned and accomplished a lot throughout this project. We got to demonstrate our knowledge in order to create a project and we feel that this is an achievement. In addition, we found that our project brought a smile to everyone who saw it. This was ultimately our biggest achievement and what brought us the most amount of pride and joy.

5.2 Uncertainties

We had a few things that we did not consider while developing this project. The program would end up crashing if we attempted to make a program delay less than 1 millisecond. We had a few theories on why this was occurring but we could not pinpoint a fix. This limited our options for adding detailed frequency information and if given the time we would have consulted someone with embedded systems experience. We were also unsure of how to fully alleviate our ringing situation in our DC-DC converter.

5.3 Ethical considerations

After completing the demo and the rereading the IEEE Code of Ethics, there are indeed some ethics codes that we need to address.

#1 of the IEEE Code of Ethics states: "To accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment" [3]. Our current implementation of the LED display had visible amounts of strobing. For the demo, we warned everyone in the room of the problem before powering the project. For commercial use, a mitigation of this problem will be discussed in the next section. In addition to this is the sheer speed of the spinning armature. Since the armature is spinning so fast, we ensured that the plug and play functionality of the project gave users no access to the spinning armature and other components without being forced to unfasten the enclosure. Finally, we will administer a warning to users on how to safely interact with the power supply. Another warning will be issued for users that may find the noise produced by the motor system too loud, however, adjustments will be made to the commercial product to mitigate this.

#7 of the IEEE Code of Ethics states: "To seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others" [3]. The important portion to take from this is that we should properly credit the contributions of others. Persistence of

Vision screens have been done by many people around the world. Due to this, we acknowledge that this is not the concept of Persistence of Vision itself that makes our project unique but the applications in which we are using Persistence of Vision.

#9 of the IEEE Code of Ethics states: "To avoid injuring others, their property, reputation, or employment by false or malicious action" [3]. This is a crucial point of consideration in our final product. As discussed previously, our product has the potential to cause physical harm to others. Therefore, we are very careful to try and foresee problems with our product and create preventative measures for the user. An example of this was the previously mentioned enclosure that safeguards our project. This concept is similar to how the department of labor requires safeguarding for rotating parts [4]. Once again, another thing to take into consideration is proper housing of the power supply as it is plugged into a wall outlet and therefore could cause significant harm to others if improper contact is made. One final important factor when considering safety is to ensure that the power supply that we choose meets the appropriate safety standards and has the necessary safety marks [5].

5.4 Future work

As mentioned in the last section, the noise level of the project was louder than we ideally wanted. When properly enclosed, the project is more bearable, however we would definitely start making changes to reduce noise further. Sound dampening foam will definitely be added around the sides and on the top plate around the display. Since we would ideally like to make every electrical component custom, we would remove the store-bought motor controller and implement a BLDC motor controller. This will be added onto a single PCB that houses all of our electronics. This would allow for lower cost for the user and also to us. Fine tuning of the PI controller would eventually turn into implementing a PID controller. This will create a smoother climb to the target RPM instead of the current implementation that has a fairly high overshoot since there is no dampening being done on the motor output. While this is a very small issue that will likely be overlooked by the user, we find it important to give the best possible experience for the user and make sure everything we implement is finely tuned. We would also work to reduce the ringing in our converter circuit. One last feature that we would fix would be to add another hall sensor or another magnet to the system in order to prevent downtime in the LED display which manifests itself as an irritating strobing effect.

References

[1] TI(2015).TPS56320x 4.5-V to 17-V Input, 3-A Synchronous Step-Down Voltage Regulator in SOT-23. [Online].Available:http://www.ti.com/lit/ds/symlink/tps563208.pdf [Accessed: 23-Feb-2017].

[2] Bourns (2017). SRP4012TA Series – Shielded Power Inductors. [Online]. Avaliable:http://www.mouser.com/ds/2/54/Bourns_SRP4012TA_datasheet-368538.pdf [Accessed: 27-Mar-2017]

[3] IEEE (2017). IEEE Code of Ethics. [Online].Available:http://www.ieee.org/about/corporate/governance/p7-8.html [Accessed: 1- Feb-2017].

[4] OSHA (2017).General requirements for all machines. [Online].Available:https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=standards&p_id=9836 [Accessed: 1-Feb-2017].

[5] CUI(2017).Power Supply Safety Standards, Agencies and Marks. [Online].Available:http://www.cui.com/catalog/resource/power-supply-safety-standards-agencies-and-marks.pdf [Accessed: 1-Feb-2017].

[6] PJRC (2017). Teensy. [Online]. Available: https://www.pjrc.com/teensy/schematic.html [Accessed: 27-March-2017].

Appendix A - Requirement and Verification Table

Table 3: System Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
Power Converter		
1. Must be able to handle 2.7 - 3A. 2. Can convert 12V to 5V effectively while keeping resulting voltage ripple below +/- 1%.	1. Verification a. Use power resistors to create a load situation and see if chip operates correctly / doesn't break. b. Measure resulting voltage and amperage with power meter and record values observed and load situation used. 2. Verification a. Create 2 converter circuits that are low amperage and measure load voltages with oscilloscope and measure voltage ripple for each situation. b. Save image of resulting voltage ripple waveforms.	Y
Motor + Control		
3. Must be able to spin consistently at the target of 720 +/- 1% RPM in order to achieve 24 FPS using two blades.	3. Verification a. Create a test environment with the motor and working hall effect sensor mounted onto a test PCB. b. Measure the RPM from the data of the hall sensor and record the results.	Y
Audio Interface		
4. The output signal from the filtered op amp stages must swing between 1V p-p 5. The output signal must have a DC bias of 450-550 mV	4. Verification a. Probe circuit after the output capacitor and measure max peak to peek voltage after running audio at max volume for 5 minutes b. If the peak to peak voltage exceeds 1V then adjust the	Y

	potentiometer until the desired range is met. 5. Verification a. Probe circuit at the output pin and measure the DC bias on an Oscilloscope	

Appendix B - PCBs

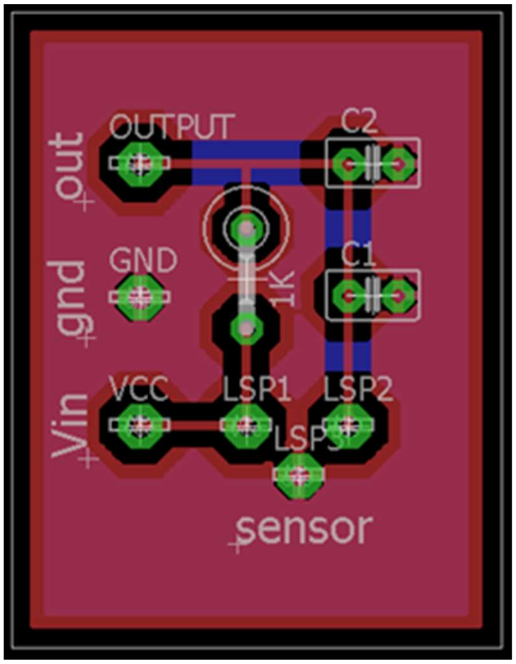

Figure 13. Hall sensor PCB

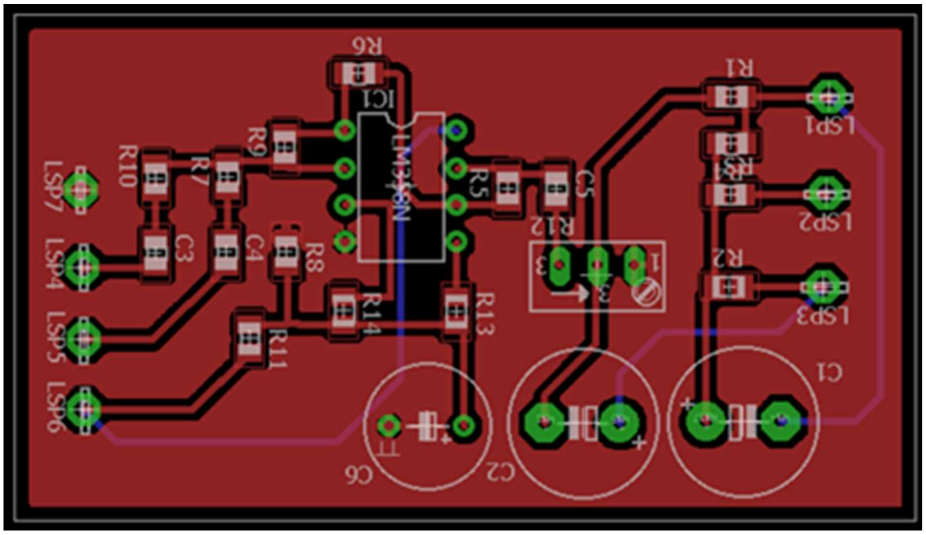

Figure 14. Audio interface PCB

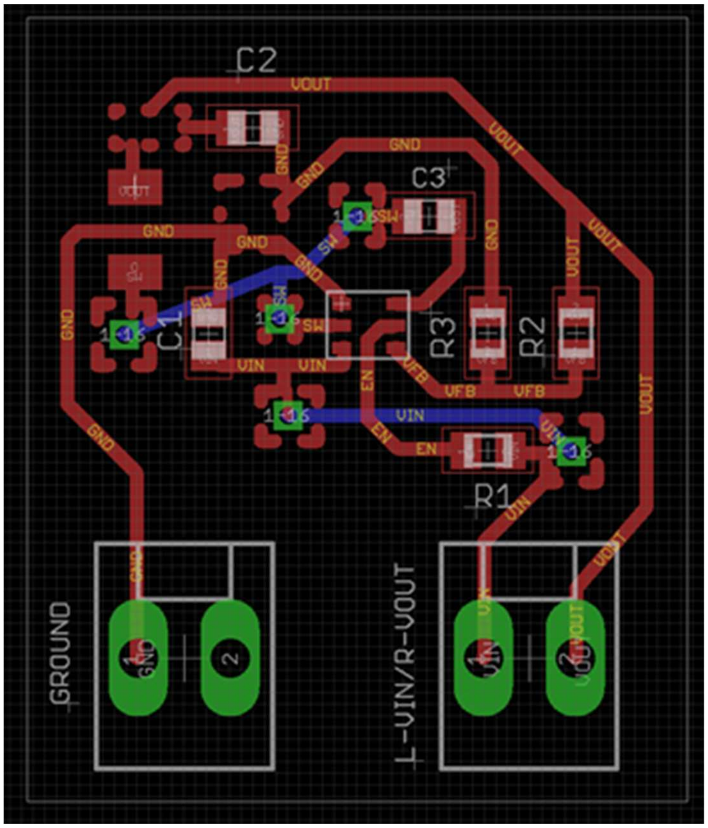

Figure 15. Power converter PCB