60-HERTZ ELECTROMAGNETIC FIELD DETECTOR/INTERFACE SYSTEM

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Abstract

We designed and built a 60-Hertz electromagnetic radiation (EM) detector and haptic interface system. The system consists of an antenna system, an amplifying filter, a microcontroller module, and a micro-transducer array. Together, these modules allow the user to detect 60-Hertz EM radiation at intensities ranging from 0.01uT to 10uT.

The antenna system picks up electromagnetic radiation through Faraday induction, and the rest of the system translates the intensity of the ambient 60-Hertz magnetic field at the sensor to an intensity of vibration on the skin of the user, subject to the limited resolution of the feedback array.

Although the design met all of the requirements, there are still improvements that can be made by making the communication between the sensor module and the feedback array wireless, incorporating a larger feedback array, and creating a smaller enclosure for the system.

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1. Introduction

1.1 Motivation

Ambient electromagnetic radiation can be a problem in many applications where electronic instrumentation is involved; the motivation for this project stemmed from such a problem. Electro-encephalogram (EEG) readings in particular can be adversely affected by the presence of ambient 60-Hertz (60-Hz) radiation; this frequency is omnipresent in the United States due to the national standards for electrical power generation and transmission.

The first aim of this project was to create a portable 60-Hz electromagnetic radiation detection device that could be easily used to pinpoint areas of high radiation density. The second part of this project was aimed at developing a haptic feedback system that utilized micro-transducers to deliver the field intensity information to the human body through its sense of touch. The applications of this project, however, extend far beyond locating hotspots for proper equipment placement; such a system could facilitate the three-dimensional mapping of static 60-Hz electromagnetic radiation fields in and around structures, which would make it possible to study the effects of such radiation on flora and fauna, for example. The haptic feedback system could also make it possible for human beings to experience a new “sense” through the existing sense of touch; the integration of these senses may open up new avenues of research in the field of neuroscience as well.

1.2 Goals

The main goals of this project were to create a 60-Hz radiation detection system using an inductive coil antenna as the sensing apparatus, and to create a haptic interface to deliver the field intensity information to a user. The system was designed and built in modules, which will be discussed in detail in the following sections.

The overall goal of the system was to be able to detect 60-Hertz electromagnetic radiation within an intensity range of 0.01uT to 10uT. This intensity range was determined after research into the typical magnetic field strengths of household appliances. Based on data from the Federal Office for Radiation Safety in Germany [5], it was determined that the lowest significant field strength for our application was 0.01uT; thus, this value was chosen to be the lower bound for our range of detectable intensities. The upper bound on the range was determined by considering the parameters of the module that was used for amplitude detection, specifically an Arduino microcontroller. The microcontroller can read analog voltages between 0 V and 5 V, with a resolution of around 5 mV. Thus, due to the fact that we aimed to have the gain of our system linear with respect to input intensity, the bottom of the detectable range would have to map to around 5mV, and the top of the range to 5V. Thus, our maximum detectable intensity was constrained to be around 10uT. However, due to the fact that intensities of 10uT are only reached within a foot of powerful electrical equipment such as vacuum cleaners (which would be obvious to a user), it was determined that 10uT was an acceptable maximum for detection. If the strength of the

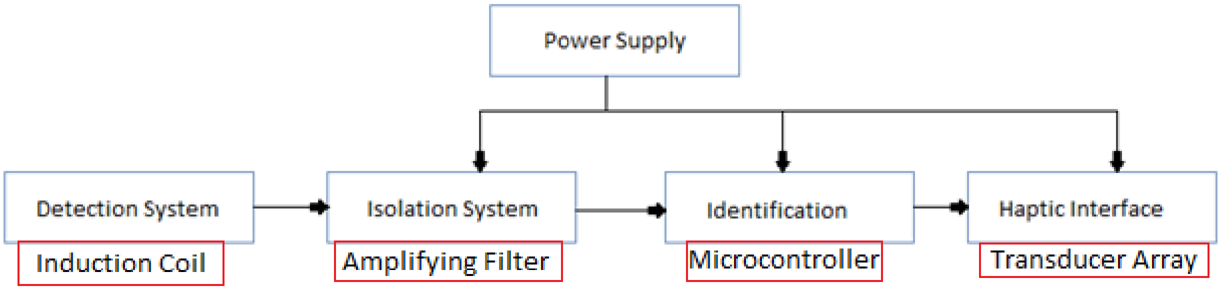

Figure 1: Block Diagram of System

field were greater than this limit, the system would indicate the fact that it had saturated. The final system that was built met these specifications.

1.3 Modules

The system comprises of five modules, each with its own specific function. Figure 1 shows a block diagram of the modular system and the interconnections between modules. Detailed requirements and verification procedures for each module can be found in Appendix A, and are discussed further in depth in Section 2. The modules implemented in the system are:

1.3.1 Detection Module

The detection module needed to convert the strength of the ambient 60-Hertz electromagnetic field into a proportional analog voltage, which would feed into the isolation module. This module needed to be able to pick up all polarizations of the ambient field, and would incorporate 3 distinct antennas, each of which would feed into the isolation module separately.

1.3.2 Isolation Module

The isolation module needed to band-pass filter the input signals around 60-Hertz, and amplify the signal so that range of intensities detectable by the system (0.01uT to 10uT) would map to the correct range of voltages on the identification module (5mV to 5V). The isolation module needed to implement 3 identical amplification/filtering channels, one for each polarization input from the detection module.

1.3.3 Identification Module

The identification module needed to successfully identify the amplitude of each channel output from the isolation module; each input to this module was expected to be a sinusoid oscillating at 60-Hertz. The module needed to be able to calculate a vector sum of all of the amplitudes to identify the total intensity. The module needed to communicate with the haptic interface module to convey the intensity information.

1.3.4 Haptic Interface Module

The haptic interface module needed to communicate the intensity information conveyed by the identification module to the user through vibration; the stronger the intensity of the ambient field, the stronger the vibrational feedback to the user needed to be.

1.3.5 Power Supply Module

The power supply module needed to provide power to the operational amplifiers in the isolation module, the microcontroller in the identification module, and the micro-transducers in the haptic interface module. The final implementation of the power supply module incorporated 4 AA batteries (6V), 1 9V battery, and 1 AA battery (1.5V), for each of the above, respectively.

2 Design

2.1 Detection Module Design

The purpose of the detection module was to identify the strength of 60-Hertz electromagnetic radiation. The first design ideas for this module incorporated traditional antennas, but after initial research, it was realized that any antenna meant to transmit or receive 60-Hertz radiation would have to be unimaginably long, due to the extremely long wavelength of the frequency of interest. It was decided to use coils to pick up the radiation through Faraday induction instead. The system also needed to be able to detect all polarizations of the ambient field; thus, it was decided that the detection module would consist of 3 orthogonally oriented coils, as shown in Figure 2.

The use of induction coils brought with it many design choices, many of which included tradeoffs between size or cost and effectiveness. The first decision was a fairly straightforward one; it was decided that each coil would incorporate a ferrite core. The increased permeability that followed boosted the responsiveness of each coil. However, the permeability of the core depends strongly on its geometry, and the second design choice hinged around this property. The effective permeability of the core is given by the following sets of equations

$$N = demagnatization\ factor = \frac{d_c}{l_c}\left(\ln\left(\frac{2l_c}{d_c}\right) - 1\right) \tag*{(1) [3]}$$

$$\mu_{app} = apparent\ permeability\ (at\ center) = \frac{\mu_r}{1 + N\mu_r} \tag*{(2) [3]}$$

$$\mu(x) = \mu_{app}\left(1 + 0.106\left(\frac{2|x|}{l_c}\right) - 0.988\left(\frac{2|x|}{l_c}\right)^2\right) \tag*{(3) [2]}$$

$$\mu_{eff} =< \mu(x) > \tag*{(4) [2]}$$

where μ_r is the initial relative permeability, d_c is the diameter of the core, and l_c is the length of the core.

There were two possible cores that we could utilize, both with the same diameter (0.375 inches); the first was 2.5 inches long, which led to an effective permeability of around 20, and the second was 5.5 inches long, for which the effective permeability would have been around 50. Due to the fact that a major feature of our design was compactness, it was decided that the design would utilize the 2.5 inch long cores, which resulted in each coil being 2.5 inches long.

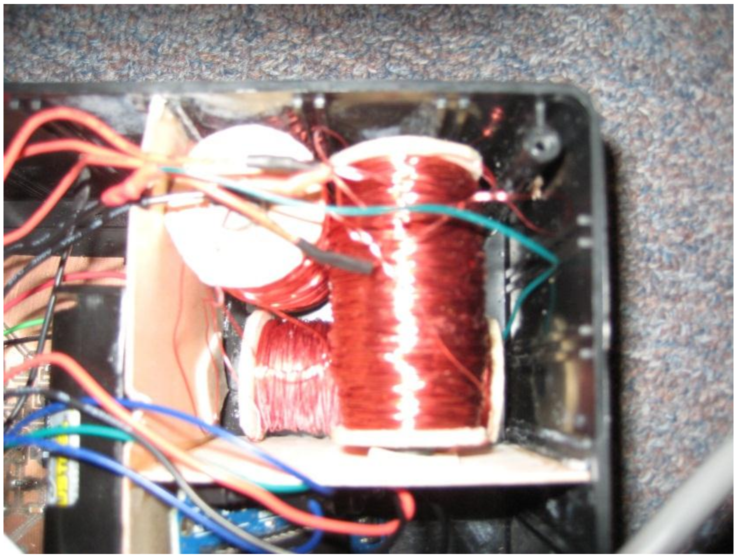

Figure 2: Detection Module

Based on this design choice, the appropriate number of turns for each coil could be determined. Two major coil parameters that depended on the number of turns were the inductance and the resistance. The inductance of the coil was calculated with the following formula, where r is the average coil radius, N is the number of turns, μ is the total permeability, and b is the coil build or thickness:

$$L = \frac{\mu \pi r^2 N^2}{l_c\left(1+0.9\frac{r}{l_c}+0.32\frac{b}{r}+0.84\frac{b}{l_c}\right)} \quad (5)\ [1]$$

The resistance of the coil was calculated by using the resistance per unit length of 26 gauge wire. Based on the ratio of these two quantities (R/L), it could be determined at what frequency the pickup of the coils would start attenuating. The goal was to keep this ratio below 60, and ideally below 45, in order to assure no significant attenuation in the pickup of 60-Hertz signals. However, it was also desirable to minimize the amount of wire that the design would incorporate, in order to contain the cost and the weight of the system. Thus, after several design iterations, it was decided that the design would incorporate 2500 turns of 26 gauge enameled wire per coil, which would both limit the weight and cost of the system, while assuring 60-Hertz radiation detection. The last design modification that was made to the antenna system design added in wooden stoppers to assure that each coil keeps its shape, as seen in Figure 2.

For the final design, the coil parameters were re-calculated to ensure that the design met specification. Given that the length of the core was 63.5mm, and the initial relative permeability was 2000, applying Equations 1 through 4 demonstrates that the effective permeability of the core was indeed 19.946, which is rounded to 20. The resistance of the coils was calculated using the unit-length resistance of 26 gauge wire, which is 1.339e-4 ohms/mm. The length of the wire in millimeters used in each coil was calculated given the following formula

$$125\pi \sum_{k=0}^{20} [9.7275 + k * 0.405] \quad (6)$$

which is just the sum over diameters of the circumference formula, where 9.7275mm is the diameter of the first layer ($d_c + 0.405/2$), and 0.405mm is the diameter of the wire. The length of the wire used for each coil in the design was 113,619 mm, and the resistance was thus 15.2135 ohms. The inductance was calculated using Equation 5, and was 0.42 H. The cutoff frequency (R/L) was thus around 38 Hertz, which was good enough to meet specifications.

Given the coil parameters, the induced voltage in each coil can be obtained as a function of the ambient 60-Hertz magnetic field, as shown below:

<u>Faraday's Law</u>

$$\epsilon(t) = -N\frac{d}{dt}\big(\varphi(t)\big) \text{ , where } \varphi(t) = BAcos(\theta) \tag{7}$$

$$\epsilon(t) = -NAcos(\theta)\frac{dB(t)}{dt} \tag{8}$$

Due to the standards of power generation and transmission, 60-Hz noise will have the following form:

$B(t) = B_0\cos(\omega t)$, where $\omega = 120\pi$

Thus,

$$\epsilon(t) = NAB_0\omega cos(\theta)\sin(\omega t) = 2\pi f NA\mu_0\mu_{eff}H_0\cos(\theta)\sin(\omega t) \tag{9}$$

Due to the three-axis detector setup, the only fields of interest to any one detector are those having components parallel to its axis; additionally, only those components are of interest. Thus, $\cos(\theta) = 1$.

Finally, plugging in:

$$\epsilon(t) = 120\pi NA\mu_0\mu_{eff}H_0\sin(120\pi t) = 1.688H_0\sin(120\pi t)\text{ mV} \tag{10}$$

For ambient field strengths of 0.01 µT, we obtain an EMF of around 0.01 mV. For ambient field strengths of 10 µT, we obtain an EMF of around 10 mV.

After construction of the coils, it was realized that the exact number of turns per coil was unknown. Thus, each coil was weighed against the cores and the wooden stoppers to obtain a good estimate as to the weight of the wire in each coil. Given the weight of each coil, it was determined that we had wrapped around 1.5 to 2 times the number of necessary turns per coil. Thus, the filter design had to be modified to decrease the gain, in order to keep the range of detection the same as the specification. The changes to the module requirements based on this change and the results of testing and characterizing the detection module are discussed in Section 4.

2.2 Isolation Module Design

The isolation module needed to band-pass the input signals around 60-Hertz, and amplify them to a level where the identification module can successfully detect the amplitudes. Given the results stated below Equation 10, a gain of around 500 would have been required to map the range of detection to the range of the identification module. More specifically, if a 60-Hertz field was present with an intensity of 10uT, then the induced voltage in the coils would vector sum to 10mV. Since this is the upper end of the detection spectrum, it needs to map to 5V, which is the upper end of detection for the Arduino in the identification module. Likewise, 0.01uT induces 0.01 mV, which must map to 5mV. Thus, this mapping corresponds to a gain of 500 in the isolation module.

The original design called for a gain of 500 and a 3dB bandwidth of around 5 Hertz. However, as the build progressed, the requirements changed as unexpected results were encountered. There were a few elements of the original design that lasted through the entire design process, however. Because the center frequency on the band-pass filter is at 60 Hertz, a very low frequency, necessity required an active filter in order to mitigate the requirement for very large inductors in the corresponding passive filter design. At the beginning of the design process, the circuit was split into three parts: a 2-pole filter, an amplifier, and a half-wave rectifier. However, the 2-pole design did not give the bandwidth that was desired, so the order of the filter was increased to 4-pole. The filter and amplifier were combined as well, so each stage filtered and amplified partially [4].

There were three major hurdles in the design and construction of the isolation module. The first came after the coils were built; each coil was much more sensitive than originally designed, due to the extra turns wrapped. Thus, the gain of the isolation system had to be decreased to around 170, which was successfully done. The second major hurdle occurred when breadboard testing of the modified design began. It appeared that the center frequency of the pass-band had shifted to 67 Hertz, so we expanded the bandwidth of the filter for the final PCB implementation from 5 Hertz to 10 Hertz, which was acceptable because there is no commonly occurring radiation within at least 30 Hertz of 60 Hertz. However, when the PCB was constructed, the shift in the center frequency disappeared, and it was concluded that the error occurred due to the parasitic capacitances in the axial resistors that were used for the breadboard and perfboard designs. When surface-mount resistors were used, these parasitic capacitances disappeared.

Concurrently with the last hurdle, it was realized that the gain of the design was nonlinear with the input intensity. This was due to the half-wave rectifier, which incorporated diodes that contributed to the nonlinearity of the gain. Thus, the design was changed to a single-supply design, which would result in an offset signal which would clip before becoming negative, which would eliminate the need for a rectifier. The rectifier was used to ensure that the input pins on the Arduino in the identification module were never exposed to negative voltages, but the single supply design did the same. The supply voltage

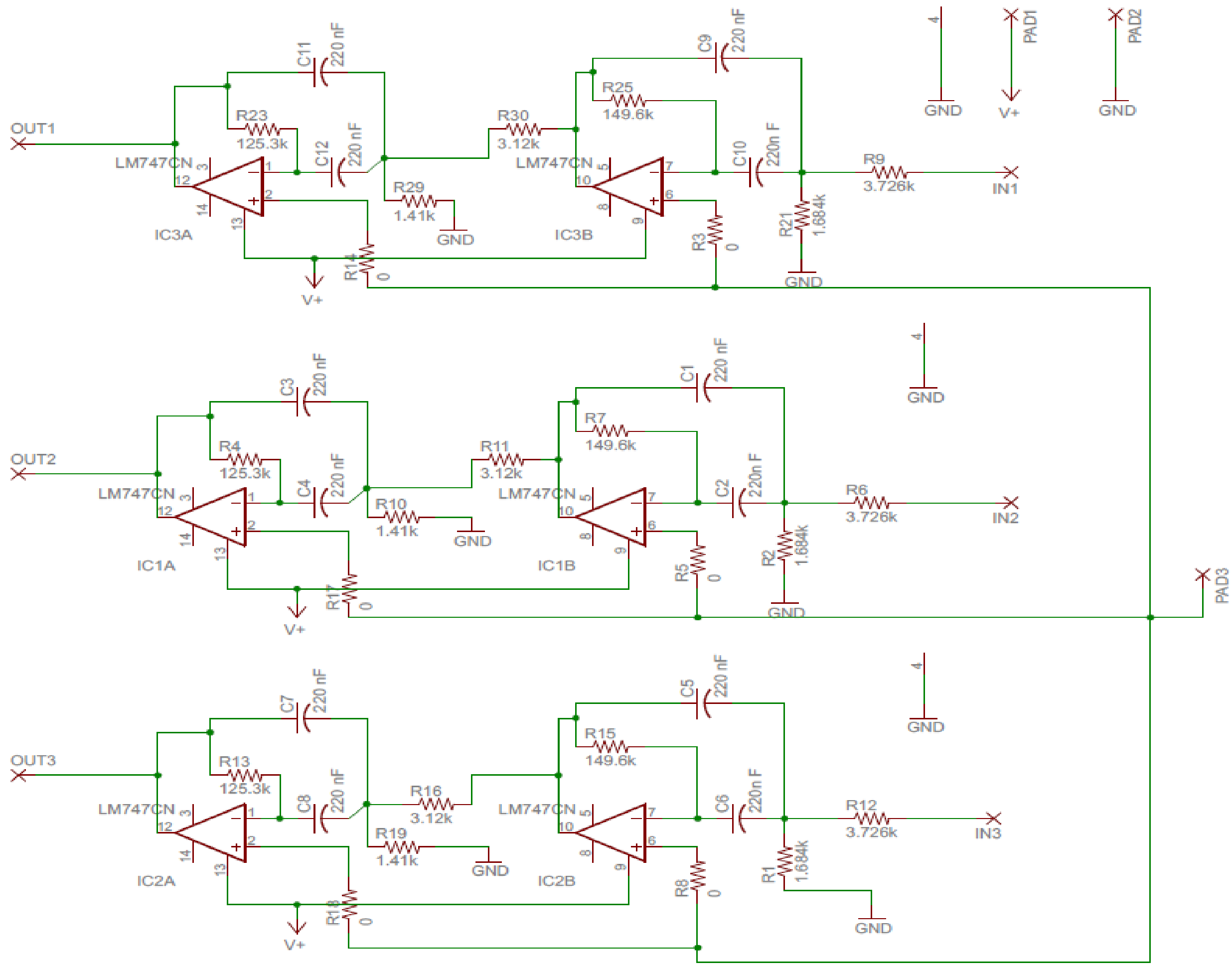

Figure 3: Final Design of Isolation Module

for the operational amplifiers was 6V, which meant that the offset would be around 3V. This meant that the Arduino would be required to find the amplitude of a sinusoidal signal with an offset of 3V, which is not a daunting task at all.

The final design incorporated 3 identical channels, one for each polarization, on a PCB. The PCB layout is shown in Figure 7 in Appendix B. The operational amplifiers used were general purpose LM747CN dual op-amps. The resistors and capacitors used were surface-mount packages, and their values are shown in Figure 3, and in the requirements and verifications table in Appendix A. The op-amps are in the single supply configuration, powered by a single 6V power supply.

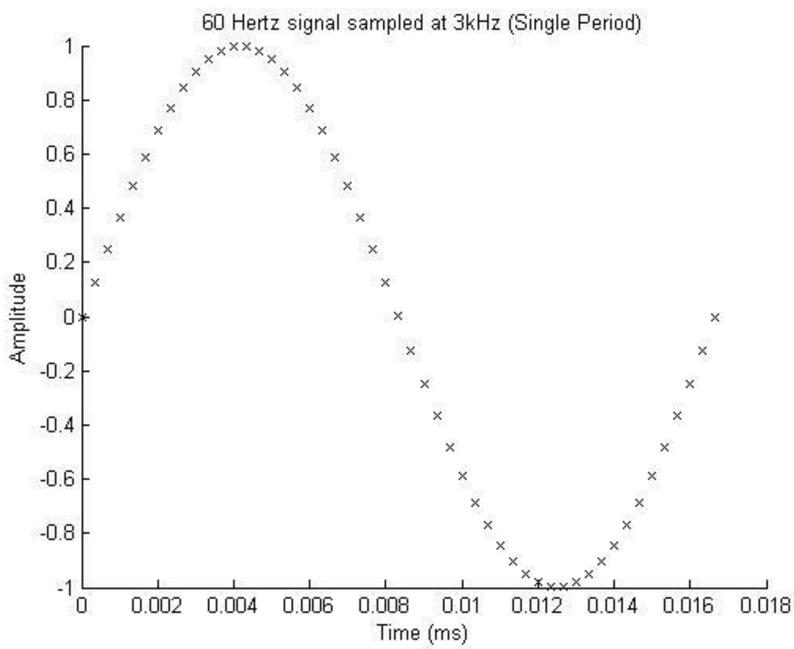

Figure 4: 60 Hertz Signal sampled at 3 kHz (Single Period)

2.3 Identification Module Design

The identification module needed to successfully detect the amplitudes of the input sinusoids on all three polarization channels. This was accomplished by using the analog inputs on an Arduino microcontroller, which are able to sample input voltages between 0 and 5 Volts at a resolution of 5mV. The first two modules of the system have specifically mapped the detectable range of 60-Hertz magnetic field intensities (0.01uT to 10uT) to this range (5mV to 5V), so all that is left to be done is to sample the input signal and identify the amplitude.

This was accomplished by first subtracting off the offsets generated by the single supply design, and then sampling values for two periods for each of the input signals, and retaining the maximum values sampled as the amplitudes. The sampling speed of the Arduino microcontroller is around 10 kHz; because three channels are being sequentially sampled, the sampling speed for each channel is around 3 kHz. This provides around 50 samples per period for each signal, which is sufficient to accurately determine the amplitude of the signal, as shown in Figure 4.

After the amplitudes of each input channel have been determined, the vector sum of the amplitudes is taken to produce a total intensity. Because each channel is orthogonally oriented with respect to the others, the vector sum simplifies to the square root of the sum of the squared amplitudes. After the total intensity of the 60-Hertz radiation has been determined, the Arduino drives a certain number of digital outputs high proportional to the calculated intensity, subject to two modifications. If the intensity is below a certain threshold level, determined by the internal noise in the filter and the base radiation level in the environment, then no outputs are driven high and the haptic interface stays off. This is to ensure that the Arduino does not respond to the noise in the filter, and to allow for thresholding in areas where the base level of ambient 60-Hz radiation is high where the user may be annoyed by a constant vibration on the skin.

The system also needed to handle channel saturation, where the gain would have pushed the output signal above the limit determined by the rail voltage on the op-amps (around 5.3 Volts). In this case, the output of the filter begins to saturate and clip at the top and the amplitude stops increasing. If any one of the detection coils is in saturation, any calculation of the intensity is invalid because the output becomes nonlinear with respect to the input. The saturation levels were actually determined by the maximum voltage capable of being read by the Arduino, which is 5V, not 5.3 V. Thus, whenever a coil reads 5V or very close to that value, it is assumed to be in saturation, and the feedback array begins to pulse to indicate that the system has saturated. This will be further discussed in the next section.

If the Arduino reads an intensity between the threshold and saturation, that is, between around 20mV and 4.95V, the intensity is classified into one of 8 equally spaced bins within that range, much like analog to digital conversion. Depending on which bin the intensity falls into, the Arduino activates that number of digital outputs, which activate the same number of micro-transducers on the feedback array. The detection range is split up into 8 bins because there are 8 micro-transducers on the array, which limits the resolution of the feedback. The Arduino code worked flawlessly, and was able to accurately determine the amplitude of the input signals, vector sum them, and activate a corresponding number of digital outputs. The code is included in Appendix C. This will be discussed further in Section 4.

2.4 Haptic Interface Module Design

The haptic interface module needed to be able to successfully deliver vibrational intensity information to the user. The module consisted of 8 micro-transducers mounted on a wristband, 4 above the wrist and 4 below. Each micro-transducer is driven by a 2N2904 NPN bipolar junction transistor that

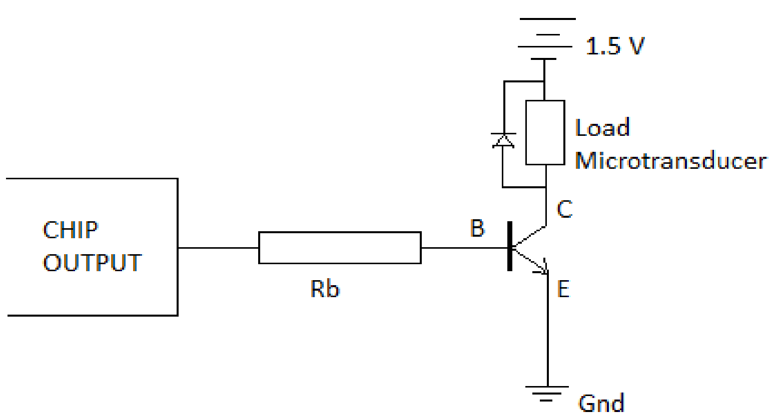

Figure 5: Single BJT/micro-transducer circuit

switches on and off depending on the corresponding digital output from the microcontroller, because the pins on the Arduino cannot source the required current to drive the micro-transducers. When the BJT is switched on by a high digital output from the Arduino, its micro-transducer draws current from a 1.5V AA battery. One BJT/micro-transducer circuit is shown in Figure 5 (R_b = 2200 Ohms); the complete circuit consists of 8 identical copies of this circuit in parallel. The initial design for this circuit worked perfectly in practice, and no design modifications were necessary.

2.5 Power Supply Module

The power supply module needed to successfully deliver power to the op-amps, the Arduino microcontroller, and the micro-transducers. At the beginning of the design process, it was decided that the system would employ only one power supply that would power all of the modules that needed power. However, as the build progressed, the modularity of the design made it advantageous to use three distinct power supplies in this module: a 4 AA (6V) source for the op-amps, a 9V source for the Arduino, which has an in-built voltage regulator, and a 1.5V source for the micro-transducers. The module also incorporated a switch that could turn off power to the Arduino and op-amps, which would effectively disable the micro-transducers from drawing power as shown in Figure 5.

One of the concerns associated with this module is that the offset voltage in the output of the isolation module is determined by the actual value of the 6V source. As the voltage slowly drops, the offset will drop as well, which the Arduino code will need to account for. Other than this concern, the power supply module meets the needs of the circuit beautifully.

3. Design Verification

The original requirements and verification procedures are shown in Appendix A. However, a new requirements and verification table had to be made to incorporate the hurdles in the design, which is also shown in Appendix A. All of the changes were made to the module requirements; the verification procedures remained the same. The changes made did not affect the overall requirement of the system much, but were necessary based upon the initial coil build. The first change that was made was to double the expected induced voltages from the coils, because they incorporated almost double the wire. Thus, in order to keep the overall system requirements the same, the gain of the isolation module had to be reduced to around 200 from 500, which is a drop of just over 50%. The last change made was to increase the acceptable 3dB bandwidth of the isolation module to 10 Hertz, due to the fact we had not accounted for parasitic capacitances. This was an acceptable change to make to the system level requirements, because there is no other common radiation at frequencies in a band of at least 30 Hertz surrounding 60 Hertz. The last two changes affected the resistor values in the final design, which are also changed in the modified requirements and verification table. These changes all followed from the initial coil build, but did not affect the performance of the entire system in any way.

3.1 Testing

The test procedures and results for all of the modules in the system are shown below. For a complete explanation of the requirements and verification procedures for each module, refer to Appendix A.

3.1.1 Detection Module

The detection coils were placed in a Helmholtz coil one at a time. A known, 60-Hertz magnetic field was generated within the Helmholtz coil using a function generator. The peak-to-peak induced voltage in detection coil was measured using the cursors on an oscilloscope. The data was analyzed to determine the transfer function of each coil, shown in Table 1. During these tests, background noise was fairly constant. Thus, the slope of the data, which corresponds to the transfer function of the coils, is accurate.

The values in bold in Table 1 correspond to the relationship between magnetic field and induced voltage in the coils. These values (2.221, 1.7854, 2.2503) are more than double the requirement on the original table (Table 5) in Appendix, but when it is taken into account that the coils were twice as responsive as designed, all the values fall within around 10% of the expected response, which is acceptable (see Table 6).

Table 1: Detection Module Testing Data

Coil 1	Transfer Function: V = 2.3109I + 12.0705	Transfer Function: V = **2.221**B + 7.0056		
	Input Current (mA RMS)	Induced Voltage (mv P2P)	Input Current (mA P2P)	B-Field (uT P2P)
	2.02	24.38	5.713422792	6.76069319
	4.09	38.75	11.56826694	13.68873027
	5.97	52.5	16.88570993	19.98086057
	8.02	64.06	22.68398554	26.84196009
	10.15	78.75	28.70853532	33.97080984
	14.92	109.38	42.2001327	49.93541703
	19.98	142.5	56.51197395	66.87061878
Coil 2	Transfer Function: V = 2.1127I + 10.2038	Transfer Function: V = **1.7854**B + 10.2038		
	Input Current (mA RMS)	Induced Voltage (mv P2P)	Input Current (mA P2P)	B-Field (uT P2P)
	2.06	23.75	5.826559877	6.894568302
	4.12	35	11.65311975	13.7891366
	5.99	45	16.94227848	20.04779812
	7.98	57	22.57084846	26.70808498
	10	70	28.28427125	33.46877817
	14.95	99.39	42.28498551	50.03582336
	19.95	130	56.42712114	66.77021244
Coil 3	Transfer Function: V = 2.6628I + 8.6229	Transfer Function: V = **2.2503**B + 8.6229		
	Input Current (mA RMS)	Induced Voltage (mv P2P)	Input Current (mA P2P)	B-Field (uT P2P)
	2.12	25.16	5.996265504	7.095380971
	3.94	38.12	11.14400287	13.1866986
	6.01	54.37	16.99884702	20.11473568
	8.03	69.38	22.71226981	26.87542887
	10.01	82.5	28.31255552	33.50224695
	14.85	120	42.0021428	49.70113558
	19.91	159.4	56.31398405	66.63633733

3.1.2 Isolation Module

Each channel in the filter array was swept with 60 Hertz waveforms of varying intensities to characterize the gain. Because the filters were designed to be single-supply, the output waveform clips

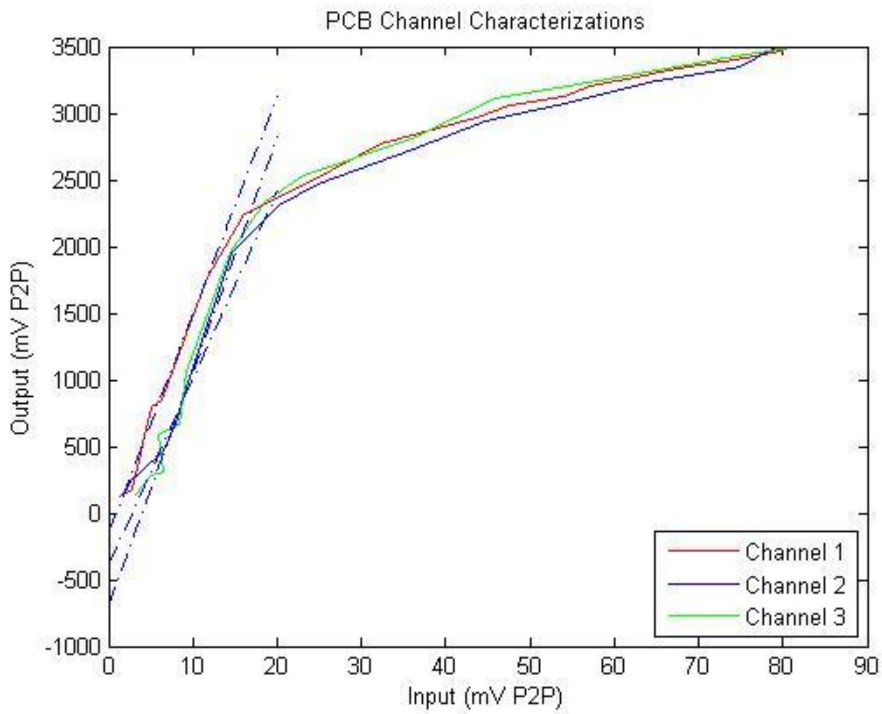

Figure 6: PCB Channel Characterizations

after hitting a certain value (between 10 and 20 mV in Figure 6). The output then saturates when it reaches a certain peak-to-peak value (while being clipped). The bandwidth of each filter was qualitatively judged by sweeping the frequency of the input waveform around 60 Hertz. The waveform had a 3dB bandwidth of around 10 to 15 Hertz, which is in accordance with the modified requirements and verification table. The results of the testing are shown in Figure 6; a detailed table of values can be found in Table 7 in Appendix B. The gains, calculated from the output values before clipping, are 163.7, 175.6, and 140.2 for channels 1, 2, and 3 respectively, as shown in Figure 6. This is an acceptable result, given the performance of the overall system and the modified requirements and verification table.

3.1.3 Identification Module

The robustness of the code on the Arduino was tested by outputting serial data regarding the detected amplitudes to a computer, and comparing with the input waveform from a function generator. The serial data was impossible to format or organize into a table, but was qualitatively determined to be an almost perfect measurement of the amplitudes. The results showed that the code worked perfectly and decoded the amplitude of the input signal, by looking for the maximum value over two periods. The Arduino is also successfully able to output the correct number of high digital outputs, and tell whether the sensor has been saturated.

3.1.4 Haptic Interface Module

The haptic interface module was easy to test. Each BJT in the feedback array was individually driven with a high digital Arduino output, and the corresponding micro-transducer turned on. The array worked exactly to specification.

3.1.5 Power Supply Module

Each battery unit in the power supply module had its voltage checked, and all of the voltages fell within the tolerances laid out in the requirements and verification table in Appendix A. The switch was also tested; when it was turned off, the Arduino turned off, the op-amps lost power, and the feedback array ceased all vibration. This module worked exactly to specification.

3.1.6 Overall System

Table 2 details the test of the entire system. For this test, the threshold was set to 20mV, the lowest possible value (determined from analysis of filter). As the figure shows, the system can detect magnetic field strengths from around 0.01uT to around 10uT, which was the overarching goal of the design. The response is also linear with respect to the input, as shown by the slopes in Table 2. The first value in the table is a B-Field value that can reliably be detected. 0.01uT can also be detected, but due to the noise fluctuation in EL 445, that low of a value could not be reliably detected at the given threshold value.

Table 2: Full System Test

I_{rms} (mA)	B_{P2P} (uT)	Digital Outputs On	Slope at Point
0.01280	0.02140	1	0.598131
0.51900	0.86800	2	0.597926
0.93520	1.56500	3	0.597572
1.36800	2.28000	4	0.600000
1.74000	2.91300	5	0.597322
2.23400	3.73800	6	0.597646
2.97300	4.97500	7	0.597588
4.02200	6.73000	8	0.597623
5.49300	9.19200	Saturation	0.597585

4. Costs

4.1 Parts

Table 3 outlines the cost of parts.

Table 3: Parts Cost

Part	Manufacturer	Number	Retail Cost ($) per Unit	Actual Cost ($) Total
Vibration Motor	PagerMotors.com	8	2.00	19.20
Project Box	RadioShack	1	3.19	3.47
Project Box	RadioShack	1	6.29	6.84
AA Battery Cover	ECE Store	1	0.87	0.95
Vinyl Sheet	Joann Fabrics	1	6.66	7.24
Velcro	Joann Fabrics	1	14.99	16.30
5-Pack 2.2kOhm Resistors	RadioShack	1	2.38	2.59
Arduino Uno	RadioShack	1	34.99	38.05
4 AA Battery Cover	ECE Store	1	1.17	1.27
PC Board	ECE Store	2	2.19	4.76
Heat Shrink	RadioShack	1	4.19	4.55
Female Crimp Pins	ECE Store	1 PACK	1.45	1.58
Male Crimp Pins	ECE Store	1 PACK	4.71	5.12
8 Conductor 22 Gauge Cable	ECE Store	6 FEET	3.84	4.17
Right Angle Headers	ECE Store	1 PACK	1.23	1.34
77 Material Ferrite Rods	Alltronics.com	4	8.50	42.47
Magnet Wire	Amazon.com	1	17.75	17.75
EN 91-AA Battery	ECE Store	5	0.34	1.84
2N3904 NPN BJT	ECE Parts Shop	8	0.10	0.00
22 Gauge Wire	RadioShack	1 PACK	7.69	8.36
Handle	Home Depot	1	1.92	2.08
PCB	ECE Parts Shop	1	10.00	0.00
DPDT Switch	RadioShack	1 PACK	3.19	3.47
3.72kOhm Resistors	ECE Parts Shop	6	0.10	0.00
1.68kOhm Resistors	ECE Parts Shop	6	0.10	0.00
149kOhm Resistors	ECE Parts Shop	6	0s.10	0.00
3.12kOhm Resistors	ECE Parts Shop	6	0.10	0.00
1.41kOhm Resistors	ECE Parts Shop	6	0.10	0.00
125kOhm Resistors	ECE Parts Shop	6	0.10	0.00
220 nF Capacitors	ECE Parts Shop	12	0.10	0.00
9V Battery Clips	RadioShack	1 PACK	2.99	3.25
Birch Plywood	Hobby Lobby	1 SHEET	2.99	3.25
LM747 Op-Amp	ECE Parts Shop	3	0.50	0.00
Total				**199.90**

4.2 Labor

Table 4 outlines the labor costs involved in this project.

Table 4: Labor Cost

Name	Hourly Rate	Hours	Total = Hourly Rate * Hours * 2.5
Bhaskar Vaidya	$35	130	$11,375.00
Gaurav Jaina	$35	130	$11,375.00
Kuei-Cheng Hsiang	$35	130	$11,375.00
		Total:	$34,125.00

5. Conclusion

5.1 Accomplishments

We are extremely happy with how the project turned out. The project was split up into hardware and software components, and the hardware parts raised several challenges. However, we were able to overcome those challenges. The first challenge was dealing with 60 Hertz radiation, because that specific frequency of radiation is normally considered just noise. Usually, a circuit designer tries to get rid of it, but we needed to intentionally pick up 60 Hertz radiation. There were very few references about picking up such low frequency radiation, and even less documentation regarding common household levels of electromagnetic fields. However, the few sources we managed to find proved reliable. The other big challenge was to build the antenna. We had to design and build three identical coils with very large numbers of turns, which led to complications when we did not build them exactly to specification, but we managed to accomplish this project despite the complications. We were happy that we managed to complete the project to the specifications that we laid out at the beginning; however, our crowning achievement was building a system that impressed the client thoroughly.

5.2 Uncertainties

We have just one concern about this project, which is the problem with an unregulated battery source. As the battery voltage drops, the software will constantly have to be updated to reflect the current voltage in order to ensure proper operation of the system. A solution to this problem would be to either indicate to the user when the battery voltage starts dropping, or to have a regulated source that either outputs a constant voltage or outputs nothing at all.

5.3 Ethical considerations

We commit ourselves to abide by the ethical code laid down by the IEEE. A few considerations specific to our product are outlined below.

1. Safety may be of concern, if this product will be used in areas of high radiation density. To this effect, we will implement a safety mechanism to ensure that currents do not exceed normal levels.
2. Many Electromagnetic Field Detectors are marketed as Ghost Hunting Devices. As no evidence is currently available to us regarding the viability of this application, we clearly state that our product is not intended for detecting paranormal activity.
3. Developing this product for a doctoral student in the neuroscience program requires that the team not promise to deliver a product that may not meet specifications or may be excessively costly.

5.4 Future work

The system functions as per the requirements; however, there are many improvements that could be made. The system could utilize a tunable filter that could pick up a range of low frequencies, or even high frequencies, instead of specifically 60-Hertz. It could also be made more compact by using a smaller project enclosure. The current feedback array consists of only 8 micro-transducers; making use of more would increase the resolution of the feedback device. The system could also be made more aesthetically pleasing by fitting the feedback within a glove instead of a wristband. Probably the most important change to make to the system, however, would be to implement wireless communication between the sensor and the feedback device, which would eliminate the need for long cable and make the system much more versatile.

References

[1] Kazimierczuk, Marian K. High-Frequency Magnetic Components. pp 27-29 2011.

[2] Milligan, Thomas A. Modern Antenna Design. pp 259-262. 2005.

[3] Seran, H.C. and Fergeau, P. An optimized low-frequency three-axis search coil magnetometer for space research. AIP: Review of Scientific Instruments. 76, 044502 (2005).

[4] Filter Design in Thirty Seconds. Texas Instruments.

[5] Federal Office for Radiation Safety, Germany, 1999.

Appendix A Requirement and Verification Table

Table 5: Original System Requirements and Verifications

Module	Requirement	Verification
Sensory Apparatus	1. Each detector must possess the ability to detect electromagnetic radiation within an intensity range of 0.01 uT to 10 uT and a frequency range of 58 to 62 Hertz.	1. The apparatus will be placed between the loops of a specially constructed Helmholtz coil, and the coil will be driven at the upper and lower limits of the specified intensity and frequency. The sensory apparatus will be rotated within the constant field to verify that the variation in changing orientation is no more that 10%. At the lower level of the intensity range, the average induced voltage should be 0.01 mV, and at the higher level of the intensity range, the average induced voltage should be 10 mV.
Amplifying Filter	1. Filter must possess gain of around 500, and 3 dB width of less than 10 Hz around 60 Hertz. a. Operational amplifier must behave correctly in amplifying configuration. b. Resistor values must match theoretical values (see diagram): i. R1: 3.726 kOhms ii. R2: 1.684 kOhms iii. R3: 149.6 kOhms iv. R4: 3.12 kOhms v. R5: 1.41 kOhms vi. R6: 125.3 kOhms	1. Filter will be swept with various AC signals, from 1 Hz to 1 kHz, and the outputs will be displayed on the oscilloscope to confirm attenuation outside of band. a. Operational amplifier will be tested in inverting amplifier configuration with signals described above to assure proper operation. Input and output will be shown on oscilloscope. b. Resistors values will be checked using a DMM.
Arduino Amplitude Detector	1. Must be able to correctly identify amplitude of 60-Hz AC signal, and set a certain number of digital outputs high based on that amplitude.	1. Arduino analog inputs will be driven by 60-Hz signals of varying amplitudes, up to 1V peak-to-peak, and the outputs from the Arduino will be probed using a DMM.
Haptic Feedback	1. Output digital signals from microcontroller must be able to switch micro-transducers on and off using BJT array.	1. Each BJT will be tested individually to assure that a digital high base voltage turns on attached micro-transducer, and digital low base voltage turns off attached micro-transducer.
Power Supply	1. Constant voltage of +/- 6 Volts DC must be delivered to the operational amplifiers. +6V DC must be delivered to BJT array and Arduino.	1. The power supplies will be probed with a voltmeter. The current across a 1kOhm resistor will be measured in order to confirm the battery is capable of delivering the required current.

Table 6: Final System Requirements and Verifications

Module	Requirement	Verification	Verification Status (Y/N)
Sensory Apparatus <u>Common Field Strengths</u> - - - - -	Each detector must possess the ability to detect electromagnetic radiation within an intensity range of 0.01 uT to 10 uT and a frequency range of 55 to 65 Hertz.	The apparatus will be placed between the loops of a specially constructed Helmholtz coil, and the coil will be driven at the upper and lower limits of the specified intensity and frequency. The sensory apparatus will be rotated within the constant field to verify that the variation in changing orientation is no more that 10%. At the lower level of the intensity range, the average induced voltage should be 0.02 mV, and at the higher level of the intensity range, the average induced voltage should be 20 mV.	Yes
Amplifying Filter	Filter must possess gain of around 200, and 3 dB width of less than 10 Hz around 60 Hertz. Operational amplifier must behave correctly in amplifying configuration. Resistor values must match theoretical values (see diagram): R1: 3.726 kOhms R2: 1.684 kOhms R3: 149.6 kOhms R4: 3.12 kOhms R5: 1.41 kOhms R6: 125.3 kOhms	Filter will be swept with various AC signals, from 1 Hz to 1 kHz, and the outputs will be displayed on the oscilloscope to confirm attenuation outside of band. Operational amplifier will be tested in inverting amplifier configuration with signals described above to assure proper operation. Input and output will be shown on oscilloscope. Resistors values will be checked using a DMM.	Yes
Arduino Amplitude Detector	Must be able to correctly identify amplitude of 60-Hz AC signal, and set a certain number of digital outputs high based on that amplitude.	Arduino analog inputs will be driven by 60-Hz signals of varying amplitudes, up to 1V peak-to-peak, and the outputs from the Arduino will be probed using a DMM.	Yes
Haptic Feedback	Output digital signals from microcontroller must be able to switch micro-transducers on and off using BJT array.	Each BJT will be tested individually to assure that a digital high base voltage turns on attached micro-transducer, and digital low base voltage turns off attached micro-transducer.	Yes
Power Supply	Constant voltage of +6 Volts DC must be delivered to the operational amplifiers. +9V DC must be delivered to Arduino. +1.5V must be delivered to feedback array	The power supplies will be probed with a voltmeter. The current across a 1kOhm resistor will be measured in order to confirm the battery is capable of delivering the required current.	Yes

Appendix B Extra Data Tables and Layouts

Table 7: PCB Test Data

	Channel #1					Channel# 2					Channel# 3				
freq. (Hz)	Vin (mV)	Vin_actual (Vm)	Vout (Vm)	Clipped	Saturation	Vin (mV)	Vin_actual (Vm)	Vout (Vm)	Clipped	Saturation	Vin (mV)	Vin_actual (Vm)	Vout (Vm)	Clipped	Saturation
60	0	1.313	120	NO	NO	0	1.72	135.9	NO	NO	0	3.28	135	NO	NO
60	1	2.813	171.9	NO	NO	1	2.81	253	NO	NO	1	5.16	287	NO	NO
60	2	3.75	453	NO	NO	2	3.91	315.6	NO	NO	2	6.56	306	NO	NO
60	3	4.188	581	NO	NO	3	6.56	472	NO	NO	3	5.94	481	NO	NO
60	4	5	793.8	NO	NO	4	7.97	675	NO	NO	4	8.31	668	NO	NO
60	5	6.375	850	NO	NO	5	9.69	1019	NO	NO	5	9.22	1063	NO	NO
60	10	11.72	1766	NO	NO	10	14.69	1950	NO	NO	10	14.38	1953	NO	NO
60	15	16.09	2250	Yes	NO	15	20.31	2310	Yes	NO	15	18.63	2340	Yes	NO
60	20	23.75	2480	Yes	NO	20	24.7	2470	Yes	NO	20	23.13	2530	Yes	NO
60	30	32.19	2770	Yes	NO	30	36.25	2730	Yes	NO	30	35.94	2810	Yes	NO
60	40	43.75	2970	Yes	NO	40	44.69	2940	Yes	NO	40	45.94	3110	Yes	NO
60	50	54	3130	Yes	NO	50	55	3080	Yes	NO	50	55.63	3220	Yes	NO
60	60	62.5	3270	Yes	NO	60	64	3230	Yes	NO	60	66.25	3340	Yes	NO
60	70	75.62	3420	Yes	NO	70	75	3350	Yes	NO	70	75.62	3440	Yes	NO
60	75	78.75	3450	Yes	Yes	75	79.37	3500	Yes	Yes	75	81.88	3500	Yes	Yes
60	80	80	3470	Yes	Yes	80	85.63	3500	Yes	Yes	80	85.63	3500	Yes	Yes

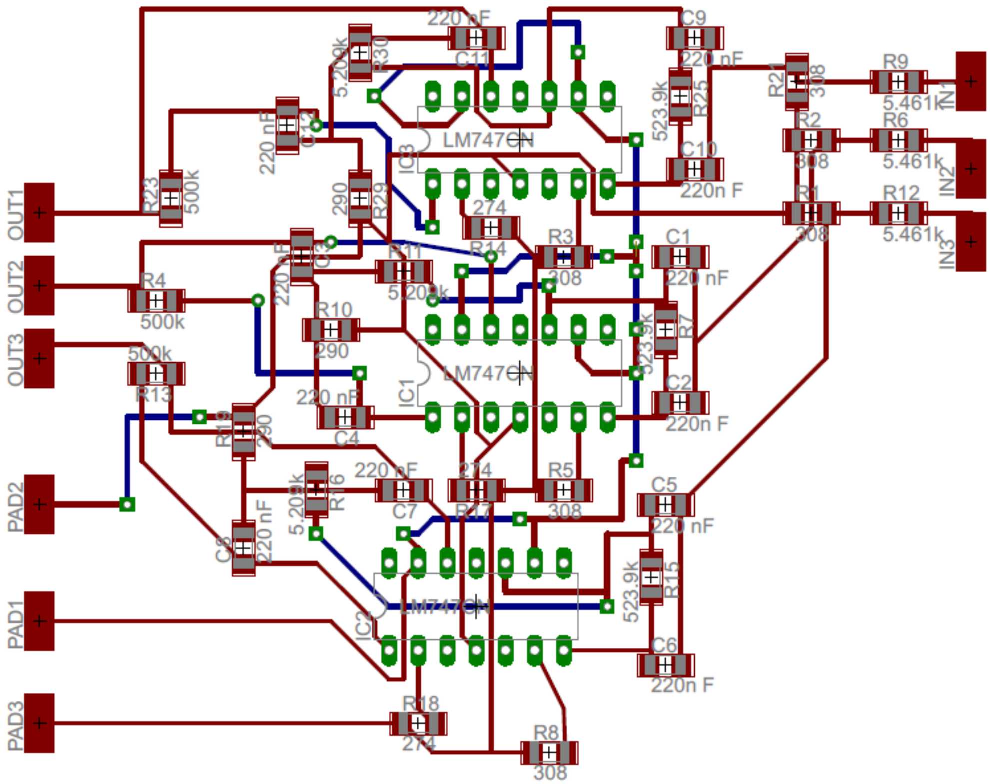

Figure 7: PCB Layout

Appendix C Arduino Code

```
const double NOISE_THRESHOLD = 150;//should be 20
unsigned long time = 0;
double intensity = 0.0;
const double width = (1854)/8;
int numOn = 0;

void pulse(){
  digitalWrite(0,HIGH);
  digitalWrite(1,HIGH);
  digitalWrite(2,HIGH);
  digitalWrite(3,HIGH);
  digitalWrite(4,LOW);
  digitalWrite(5,LOW);
  digitalWrite(6,LOW);
  digitalWrite(7,LOW);

  delay(500);

  digitalWrite(0,LOW);
  digitalWrite(1,LOW);
  digitalWrite(2,LOW);
  digitalWrite(3,LOW);
  digitalWrite(4,HIGH);
  digitalWrite(5,HIGH);
  digitalWrite(6,HIGH);
  digitalWrite(7,HIGH);

  delay(500);
}
void setup(){
  //Serial.begin(9600);
  pinMode(0,OUTPUT);
  pinMode(1,OUTPUT);
  pinMode(2,OUTPUT);
  pinMode(3,OUTPUT);
  pinMode(4,OUTPUT);
  pinMode(5,OUTPUT);
  pinMode(6,OUTPUT);
  pinMode(7,OUTPUT);

  digitalWrite(0,LOW);
  digitalWrite(1,LOW);
  digitalWrite(2,LOW);
  digitalWrite(3,LOW);
  digitalWrite(4,LOW);
  digitalWrite(5,LOW);
  digitalWrite(6,LOW);
```

```
  digitalWrite(7,LOW);
}

void loop(){
  int xmax = 0;
  int ymax = 0;
  int zmax = 0;
  int x;
  int y;
  int z;

  time = millis();
  while(millis() - time < 34)
  {
    x=analogRead(0);
    y=analogRead(1);
    z=analogRead(2);

    if(x > xmax){xmax = x;}
    if(y > ymax){ymax = y;}
    if(z > zmax){zmax = z;}
  }

  //3136 is average of no input output of pcb channel

  double xamp = xmax*4.9-3136;
  double yamp = ymax*4.9-3136;
  double zamp = zmax*4.9-3136;

  intensity = sqrt((xamp)*(xamp) + ((yamp)*(yamp)) + ((zamp)*(zamp)));

  if(xamp >= 1854 || yamp >= 1854 || zamp >= 1854)
  {
    pulse();
    numOn = -1;
  }
  else{
  if(intensity <= NOISE_THRESHOLD)
    {
      digitalWrite(0, LOW);
      digitalWrite(1, LOW);
      digitalWrite(2, LOW);
      digitalWrite(3, LOW);
      digitalWrite(4, LOW);
      digitalWrite(5, LOW);
      digitalWrite(6, LOW);
      digitalWrite(7, LOW);
      numOn = 0;
    }
   if(intensity > NOISE_THRESHOLD + width*0 && intensity <= NOISE_THRESHOLD + width*8)
  {
```

```
    digitalWrite(0, HIGH);
    digitalWrite(1, LOW);
    digitalWrite(2, LOW);
    digitalWrite(3, LOW);
    digitalWrite(4, LOW);
    digitalWrite(5, LOW);
    digitalWrite(6, LOW);
    digitalWrite(7, LOW);
    numOn = 1;
  }
  if(intensity > NOISE_THRESHOLD + width*1 && intensity <= NOISE_THRESHOLD + width*8)
  {
    digitalWrite(0, HIGH);
    digitalWrite(1, HIGH);
    digitalWrite(2, LOW);
    digitalWrite(3, LOW);
    digitalWrite(4, LOW);
    digitalWrite(5, LOW);
    digitalWrite(6, LOW);
    digitalWrite(7, LOW);
    numOn = 2;
  }
  if(intensity > NOISE_THRESHOLD + width*2 && intensity <= NOISE_THRESHOLD + width*8)
  {
    digitalWrite(0, HIGH);
    digitalWrite(1, HIGH);
    digitalWrite(2, HIGH);
    digitalWrite(3, LOW);
    digitalWrite(4, LOW);
    digitalWrite(5, LOW);
    digitalWrite(6, LOW);
    digitalWrite(7, LOW);
    numOn = 3;
  }
  if(intensity > NOISE_THRESHOLD + width*3 && intensity <= NOISE_THRESHOLD + width*8)
  {
    digitalWrite(0, HIGH);
    digitalWrite(1, HIGH);
    digitalWrite(2, HIGH);
    digitalWrite(3, HIGH);
    digitalWrite(4, LOW);
    digitalWrite(5, LOW);
    digitalWrite(6, LOW);
    digitalWrite(7, LOW);
    numOn = 4;
  }
  if(intensity > NOISE_THRESHOLD + width*4 && intensity <= NOISE_THRESHOLD + width*8)
  {
    digitalWrite(0, HIGH);
    digitalWrite(1, HIGH);
    digitalWrite(2, HIGH);
```

```
    digitalWrite(3, HIGH);
    digitalWrite(4, HIGH);
    digitalWrite(5, LOW);
    digitalWrite(6, LOW);
    digitalWrite(7, LOW);
    numOn = 5;
  }
  if(intensity > NOISE_THRESHOLD + width*5 && intensity <= NOISE_THRESHOLD + width*8)
  {
    digitalWrite(0, HIGH);
    digitalWrite(1, HIGH);
    digitalWrite(2, HIGH);
    digitalWrite(3, HIGH);
    digitalWrite(4, HIGH);
    digitalWrite(5, HIGH);
    digitalWrite(6, LOW);
    digitalWrite(7, LOW);
    numOn = 6;
  }
  if(intensity > NOISE_THRESHOLD + width*6 && intensity <= NOISE_THRESHOLD + width*8)
  {
    digitalWrite(0, HIGH);
    digitalWrite(1, HIGH);
    digitalWrite(2, HIGH);
    digitalWrite(3, HIGH);
    digitalWrite(4, HIGH);
    digitalWrite(5, HIGH);
    digitalWrite(6, HIGH);
    digitalWrite(7, LOW);
    numOn = 7;
  }
  if(intensity > NOISE_THRESHOLD + width*7 && intensity <= NOISE_THRESHOLD + width*8)
  {
    digitalWrite(0, HIGH);
    digitalWrite(1, HIGH);
    digitalWrite(2, HIGH);
    digitalWrite(3, HIGH);
    digitalWrite(4, HIGH);
    digitalWrite(5, HIGH);
    digitalWrite(6, HIGH);
    digitalWrite(7, HIGH);
    numOn = 8;
  }
 }
}
```