HooVA

Automated Air Removal Device for Infusion Pump

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Capstone Design ECE 4440 / ECE 4991

Signatures

Leah Bianchi 12/10/2020

Manuel Alvarado 12/10/2020

Quinn Lewis 12/10/2020

Orian Churney 12/10/2020

Bradley Lund 12/10/2020

Statement of work:

Leah Bianchi

My primary role for this project was the interface with the infusion pump and testing and building the board. At the beginning of the semester, I reached out to various parties with access to infusion pumps and found one for our team to work with. I spent time at the hospital speaking with experts on the device and figuring out the best way to set up our project. I created a preliminary detailed test plan that Orian used to create our final one. I also worked with 3w electronics to have the board filled and carried out a large portion of the testing, along with Manuel and Quinn.

Manuel Alvarado

My primary role was the PCB design of the project. I created the footprints for the DC power jack DCJ200-05, motor driver DRV8601, and adapted the existing MSP430 package pins for the MSP432. I produced both Ultiboard PCB designs for our two boards. In addition, I worked with Quinn to create the motor driver schematic in Multisim based on our voltage and current requirements. I also helped Leah to debug the overheating linear regulator and lack of power delivery to the MSP432 on the first PCB board.

Bradley Lund

My primary role was writing the code for our device. Initially I researched the capabilities of the various microcontrollers to determine which one we should use and what the limitations of our algorithm would be. I selected the MSP432 to give us extra processing power/flexibility without too much extra cost. Later, I wrote the code for the MSP432 using the Driverlib library from the MSP432P4 SDK available in Code Composer Studio's Resource Explorer. I worked with Leah and Manuel to gain an understanding of how the code should work in relation to the motor drivers and thus be able to debug the code.

Orian Churney

My primary role was creating the Test Plan for the device. I wrote the overall timeline of which parts of the device need to be tested and which devices go first, or which ones go afterwards. I also worked with Leah to find which parts of the system can be used to test, as in which test points to use.

Quinn Lewis

My primary role was initially the mechanical aspect of our project. I spent time researching various ERM and coin vibration motors and decided on a primary and back-up motor. A major part of this task was working with Manuel to find motors that would work with our motor drivers and power constraints. In addition to this, I was in charge of the audio detection portion of our PCB board. This included researching microphones and designing a bandpass filter and peak detector that would be compatible with the ADC input of the MSP432. Lastly, I worked with Leah to test the final board and set up a working project.

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Abstract

A device to automate the currently accepted technique for removing air from an IV line would decrease the burden on healthcare workers and improve patient experience in a hospital. This device will be an appendage of industry standard infusion pumps, which presently set off an alarm when air is detected in the line. Rather than requiring a nurse to manually interfere with the line, our device will be given a window of time - the length of which can be set by the user – to carry out a mechanical action consisting of powering vibration motors at various strengths and lengths of time via a PWM signal to move the air upwards into the IV bag, while the alarm is delayed. The device will be controlled by an MSP432, which will be powered through a wall transformer. The vibrating components will be powered through the wall transformer, and controlled by the MSP432. This flexible and essential product could be easily incorporated into modern healthcare systems to aid staff and decrease the annoyance associated with the IV alarm

Background

Intravenous (IV) fluids that include nutrients and medications are often administered to patients in hospitals with the aid of an infusion pump, which controls the drip speed and detects anomalies in the system. Air can enter an IV line for a variety of reasons, including during the manufacturing and filling process for the plastic IV fluid containers, when fluids are first attached or drugs injected into the line, and for some medications that tend to be more foamy such as some chemotherapy agents [1]. When even small air bubbles enter an IV line, it puts the patient at risk for fatal venous air embolism, especially older patients and those with comorbidities [2]. Therefore, the infusion pump plays the key role of alerting the patient and healthcare workers when air is present in the IV line so that someone can take action to remove it. This is often done with a “flick and float” technique, where the IV line is clamped below the IV pump, the tubing is removed from the pump, the IV line is held taut and flicked in an upward motion to force the bubble back into the drip chamber , and the line is re-clamped [3].

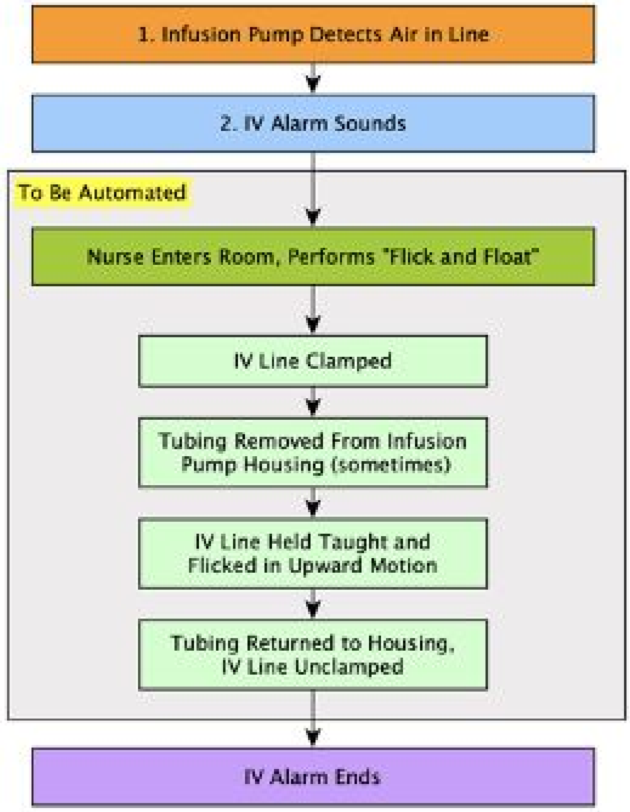

Figure 1: Current Methods Taken to Remove Air In IV Line

If this method does not work, other more time-consuming efforts may be taken. In addition, while the "flick and float" technique is safe and effective, it does allow an alarm to go off every time within a patient's room which can have adverse effects on sleep, mental health, and overall patient comfort. Furthermore, as most floors are understaffed, this tends to be a frustrating, tedious task for nurses and other healthcare workers. Our project is to create a device that automates this process by using previously existing technology to detect air in line and delaying the IV alarm while a mechanical action is carried out in an attempt to remove the bubble. By decreasing the number of times an IV alarm goes off, we hope to improve the patient experience and decrease this time-consuming burden for healthcare workers.

The prior art shows that the concept of controlling vibration via pulse-width modulated (PWM) signals is not new[16]. Using vibration to separate liquids and gases is likewise not a new concept [17] [18]. However, this project involves some additional challenges, most notably the need for our system to integrate with already-existing infusion pump IV systems present in hospitals. The aim of the project is to improve the experience of health-care workers. If our device has a high failure rate, then it simply becomes another burden for workers to periodically check. Our device will improve upon existing concepts by combining vibration motors with the pre-existing alarms that notify healthcare workers to remove air bubbles from the IV line.

The knowledge and tools for this project will draw primarily from previous coursework in software development, embedded systems and electrical engineering fundamentals. More specifically, we will use our experience gained from CS 3430 (Introduction to Embedded Systems) and the equivalent robotics pilot program with embedded C (ECR I and II) to implement analog-to-digital conversion (ADC), pulse-width modulation (PWM), and motor control. We will also implement a bandpass filter and peak detector, drawing from the Fundamentals series.

Constraints

Design Constraints

Our current setup with four motors attached to an MSP works well in a localized manner. However, our device was already struggling sometimes to provide enough current to each motor. If we were to expand our setup to have more motors (perhaps 8-10), as would likely be necessary to be able to vibrate along the entire length of the IV line, we would need a better power/current source.

Economic and Cost Constraints

The cost per-device is currently affordable, but risks becoming too expensive for hospitals and other medical care facilities if the parts of the device are upgraded. Since this device is intended to be used in a medical setting, it is very likely that medical-grade parts would be needed. It is especially likely that the motors would need to be upgraded; while our current motors were able to have some success in removing air, in order for our device to be a viable replacement for nurses and other humans in this role, it would need to be far more accurate and fine-tuned than our current motors allow.

Manufacturability

Each device currently needs an MSP LaunchPad. These are decently expensive and are not always readily available. If we were manufacturing this device in-bulk for hospitals, we would likely want to modify the design to be able to use just the MSP chip rather than the full LaunchPad. This could save about 75% (about $15) of the price of the LaunchPad and ensure that our device does not deplete the relatively-limited stock of LaunchPads.

Additionally, some parts of the PCB are somewhat limited in availability. It may be necessary to find equivalent substitute parts for these in case they experience periods of unavailability. This may not be possible when taking the rest of the constraints into account, since any change, however slight, would likely require additional testing to ensure the device still meets all health and safety standards. An alternative, perhaps more viable approach could be to source the parts directly from their manufacturer on-demand.

External Standards

Because our device is intended for healthcare workers, there are many standards related to the medical field to take into consideration. Firstly, the International Electrotechnical Commission (IEC) publishes guidelines for the general safety and performance of medical electrical equipment sold in the US known as the IEC 60601-1 [14]. In order for our device to be certified to be in compliance with the IEC 60601-1, it needs to be audited and verified by a qualification vendor such as Intertek[9], increasing the unit cost per device. Secondly, the International Standards Organizations (ISO) publishes the ISO 13485, which is a wide international standard for quality management.. For compliance, manufacturers of electrical medical devices need to provide documentation for risk management, management of user training, traceability, handling, and quality standards [23] so that the medical device is of a consistent quality. Furthermore, the FDA in the United States administers the Title 21 Part 807 of the Code of Federal Regulations, which establishes the process and requirements for bringing a medical device to market [4]. Unlike the standards which depend on international cooperation and compliance, the FDA enforcement is mandatory. Due to these standards and compliance costs, we have shifted our goal to provide a proof of concept of the device.

In addition to the medical standards, the PCB board must also adhere to electrical and PCB manufacturing standards. The IPC 6011 establishes the different classifications for electronic devices [22]. Due to the required reliability of the device for healthcare workers, it could be classified as a Class 2 electronic device. Because of this, we have added in large safety margins for the current and voltage requirements by at least twenty percent, and increased the trace width for power traces beyond what online calculators estimate. Another important standard for our use case is the IPC/WHMA-A-620C which governs the requirements for cables and wire assemblies for reliability and quality control [14]. Since we have four motors and a microphone, we had to take into account how to produce clean and stable terminal connections so that the wires would not rip easily.

Tools Employed

For the PCB design, we used Multisim[20] and Ultiboard[20]. Multisim was also used for simulation and verification of the bandpass filter, peak detector, and linear regulator. We used the software Code Composer Studio[3] for the microprocessor MSP432. Additionally, we used MATLAB[11] to produce a short table that lists the corresponding input voltage for incremental increases in duty cycle for the PWM signals.

Ethical, Social, and Economic Concerns

Environmental Impacts

The environmental cost of prototyping several PCB boards has a detrimental effect on the environment to the electronic waste. In the future, it would be best to further research and make more careful design decisions so that fewer prototypes can be produced to reduce the amount of electronic waste.

Sustainability

The component with the shortest lifespan is likely the vibration motor. According to the Marathon Electric Manufacturing Corp [19], the motor environment, supply voltage variations, number of starts, and supply sources are all factors that contribute to the lifespan. They create large motors, but the principles should be the same. Since our motor will almost certainly have less than 1 HP rating and hospitals are climate controlled, we believe it is reasonable to expect at least 3 years lifespan minimum in the case the motors are not properly taken care of.

Health and Safety

This device could possibly be dangerous if the bubbles in the IV tube don't get removed in a certain amount of time (although with the device it should still cause the alarm to go off). To further mitigate this risk, the alarm delay time can be configured to a low amount, such as 20 seconds instead of a minute.

Manufacturability

With the exception of the infusion pump and IV tubes, the mechanical and electrical parts needed are readily available and low cost. These parts include the motors, MSP432 board, connectors, and printed circuit boards.

Ethical Issues

One ethical issue is the case of failure. False confidence in air bubbles removal is plausible, and could lead to delayed or missed nurse action for manual air bubbles removal. In addition, the device might have a problem itself and cause an error that would lead to bubbles still being in the device, which would lead to an injury. It will be of high importance for the design team to ensure that while in the delay state, it is not preventing the alarm from sounding for reasons other than air in line. However, the device will be built with the clear expectations and guidelines that it is only intended to reduce the frequency of manual air bubbles removal, and does not automate patient attention.

Intellectual Property Issues

In the patent US5653860A , the inventors claim a system that removes air bubbles from the surface of an electroplated article by vibration through an ultrasonic transducer [17]. They also claim the method of removing air bubbles from “an article immersed in an electroplating solution.” These claims improve on the dependent claims of a vibratory apparatus and a corresponding vibratory plating apparatus (for electroplating) by introducing the idea of converting AC current energy to mechanical energy. Although we are producing a proof-of-concept, our device is still much different as our project does not depend on electroplating solutions, and they have no claim of removing bubbles in an enclosed tube such as an IV tube. Presumably it is more difficult to remove air bubbles in an enclosed space than an open solution.

Similarly, in patent US4205966A, the inventor claims a method for removing bubbles from a liquid by applying ultrasonic wave vibration to the liquid [18]. It is different from the previous patent in that he uses a tank of liquid while the previous patent removes bubbles on an article that is immersed in a solution. Dependent claims include the generic acoustic bubble removal method, except he claims a system improvement over pre-existing ultrasonic vibrating apparatus. The goal is similar to our device where bubbles in liquids are removed. A key distinction is that the inventor’s system relies on a tank of solution as well as a heat exchanger and a coating section. This is not practical for a hospital setting. A more practical solution would be a series of vibration movements that could move air bubbles along a clamped IV tube until they are removed from the open end.

In patent US9041321B1, the inventor claims a method for controlling a vibration motor using PWM in a consistent manner regardless of battery voltage [16]. Some dependent claims are based on battery voltage monitors, rechargeable tools, and a compensating voltage controller system. These claims are considerably much more detailed than our device. The idea of controlling vibration motors with PWM is not new, yet this is the key design choice for our electrical device. We aim to activate PWM control when the frequency of the alarm is detected. In light of this patent combined with the two previous patents, it appears our device may not be easily patentable as combining subsystems does not seem novel enough for a patent application.

Detailed Technical Description of Project

The purpose of our device is to decrease the amount of times a nurse is required to remove air from an IV line. While a nurse may carry out many techniques to remove air from a line, our device will only automate the first, simplest method carried out – the “flick and float” technique. To do this, the device will need to carry out two main functions: 1) know when the infusion pump has detected air in line, 2) carry out a mechanical action equivalent to what a nurse would do when first attempting to remove air bubbles. The device will be given a short window of time to carry out this action after air is first detected in the line. After 30 seconds or 3 seconds after the alarm stops going off, the mechanical action will cease. This flexibility allows the device to better fit the wide variety of needs set forth by patients and hospitals as well as individual's comfort levels in regards to new technology.

The Subsystems of the Device

The air removal device can be divided into three subsystems. The first is purely responsible for controlling the interface between the infusion pump and controller. Its role is to alert our device when the infusion pump has detected air in line and to electronically delay the IV alarm. Therefore, it has one input. The input is a synchronous boolean that depends on whether air is detected in the line, and it is denoted by "AIR IN LINE" in Figures 2 and 3. The output is a state-dependent Boolean variable that controls when the IV alarm is being delayed. On the microcontroller, this is determined with a voltage of 1.85 V exists a the end of the peak detector

The second subsystem is the controller. It will have an input for AIR IN LINE from the interface subsystem. It will have an output to begin or cease the mechanical action of each vibrating cuff, denoted by "MECH" in Figures 2 and 3. There will be 4 MECH outputs, each with a PWM scheme configured to set the voltage within the limits of the vibrating motors.

The third subsystem is the mechanical aspect that will carry out its actions on the IV line. It has 1 input, MECH, from the controller to control when each cuff of the subsystem enters off and on conditions. It uses motor drivers to set the voltage of the cuffs.

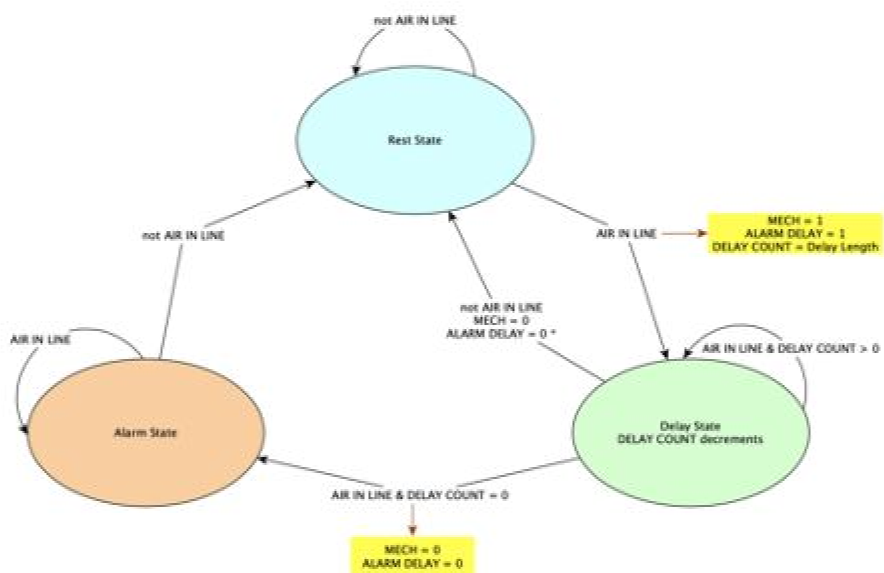

Figure 2: Finite State Diagram of Device Functionality

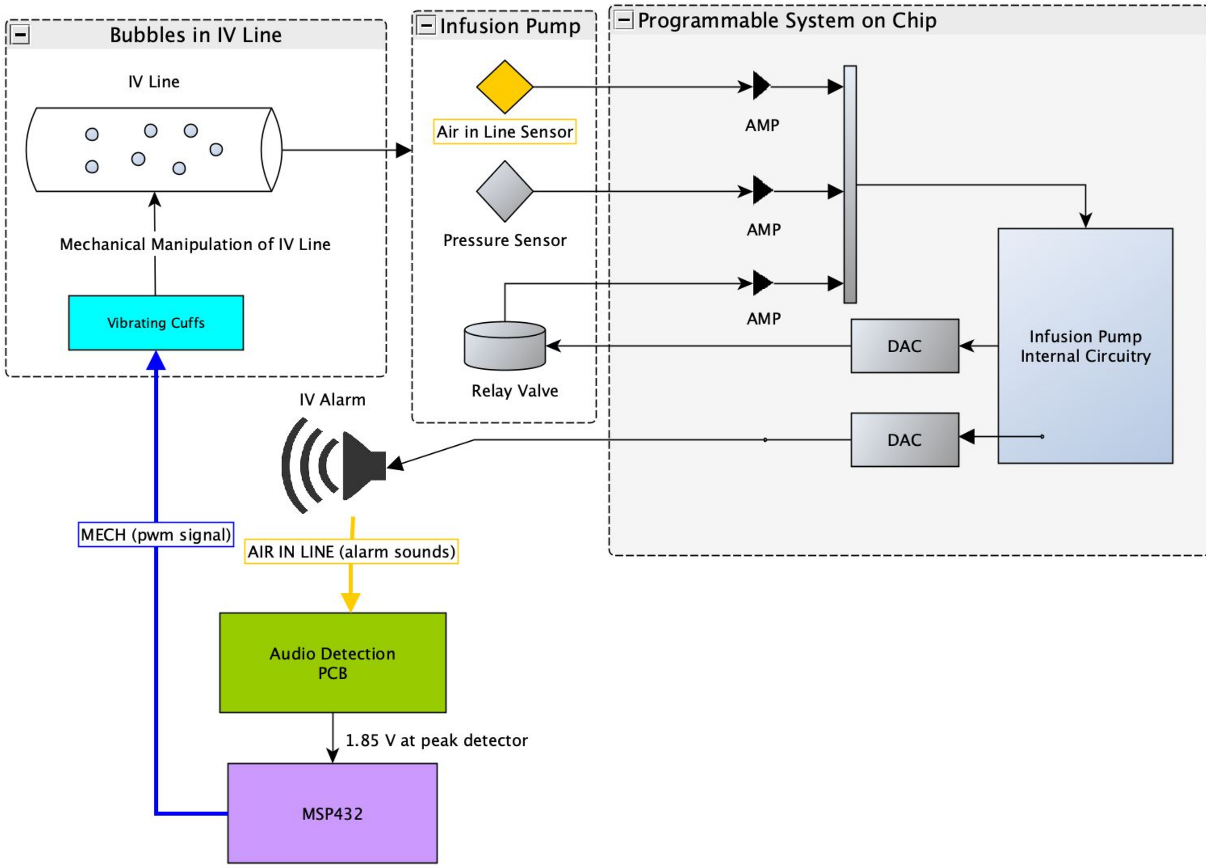

Figure 3: Block Diagram of Interactions Between Subsystems and Infusion Pump Components

Audio Detection

Because we could not directly interface with the infusion pump, we decided to make an audio detection subsystem of our project. This system consists of a microphone, bandpass filter, and a peak detector. First, we had to decide on a frequency that we wanted to detect. We took a recording of the air in line alarm from the IV pump and ran a frequency spectrum analyzer. Figure 4 shows the results.

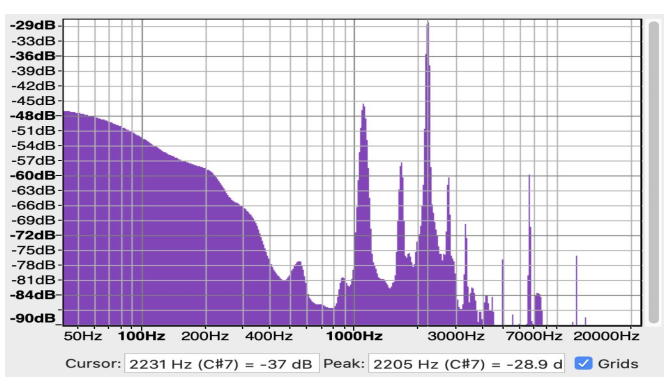

Figure 4 Frequency Spectrum of Alarm

This analysis gave us a peak frequency of 2205 Hz. In order to power the MSP432 only when the alarm was present, a bandpass filter was designed. Because of large amounts of ambient noise in a hospital, the filter needs to have a high Q value. This creates a steeper drop off on either side of the center frequency. For this reason we decided to use a Multiple Feedback Bandpass filter as it gave us the most flexibility with the Q value. Figure 5 shows the design of this filter.

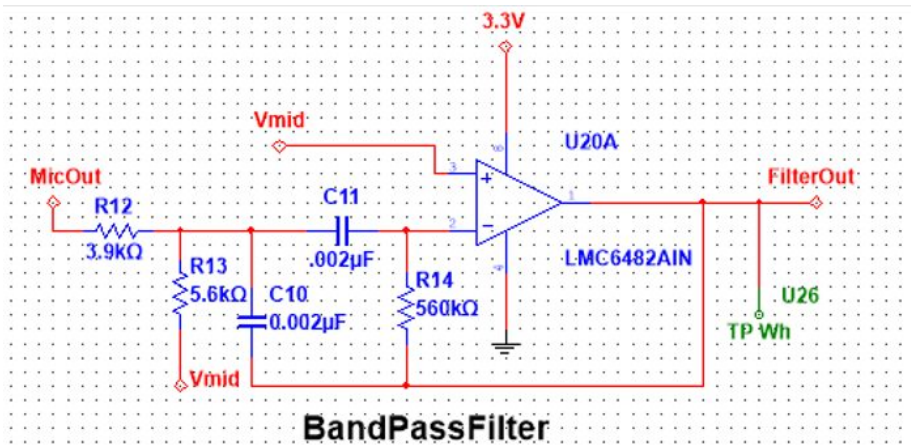

Figure 5: BandPass Filter

Values for this filter were obtained using the following three formulas for center frequency, bandwidth, and Q value. In addition, we took into consideration what resistors and capacitors we had on hand. Using Python code, the values from Figure 5 were decided upon.

$$f_0 = \frac{1}{2*pi*\sqrt{C_1*C_2*R_4*R_3}} \ where\ R_4 = R_1 \| R_2$$

$$Q = \frac{1}{2} * \sqrt{\frac{R_3}{R_4}}$$

$$BW = \frac{2}{R_3*\sqrt{C_1*C_2}}$$

These values yielded a center frequency of 2217 Hz, gain of 37.12dB, and a quality factor of 7.8 [12]. Having a significant gain was necessary as well as it allowed us to leave out an amplification stage. The output of the microphone was only about 10mV and this needed to be amplified so debugging the ADC was easier. Lastly, the output of the filter was passed through a peak detector as shown in Figure 6. The RC time constant of R18 and C16 were configured so the peak would not drop between the beeps of the IV alarm.

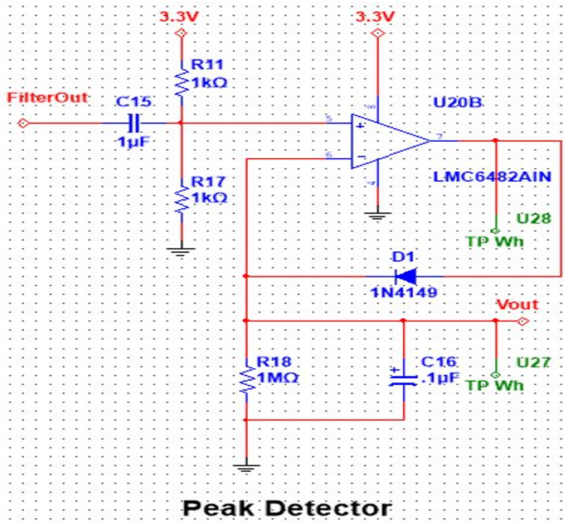

Figure 6 Peak Detector

Lastly, the microphone schematic is shown in Figure 7. It consists of a voltage to power the microphone. This is followed by a pull-up resistor. Additionally, a capacitor is added to block DC signals from entering the filter.

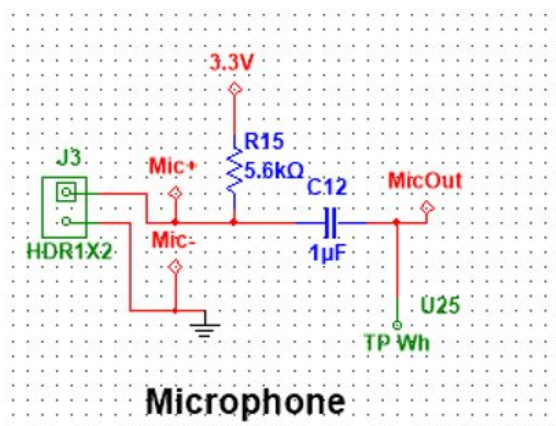

Figure 7 Microphone circuit

Motor Driver

The selected coin motors were rated at 3 V and 90 mA. Based on our voltage and current requirements, we selected the Texas Instruments DRV8601 motor driver to allow for simple MSP432 control of the vibration motors [24]. The power supply for the driver can range from 2.5 V to 5.5 V and has a maximum of 400 mA current output to accommodate larger motors if necessary. The schematic is shown below in Figure 8.

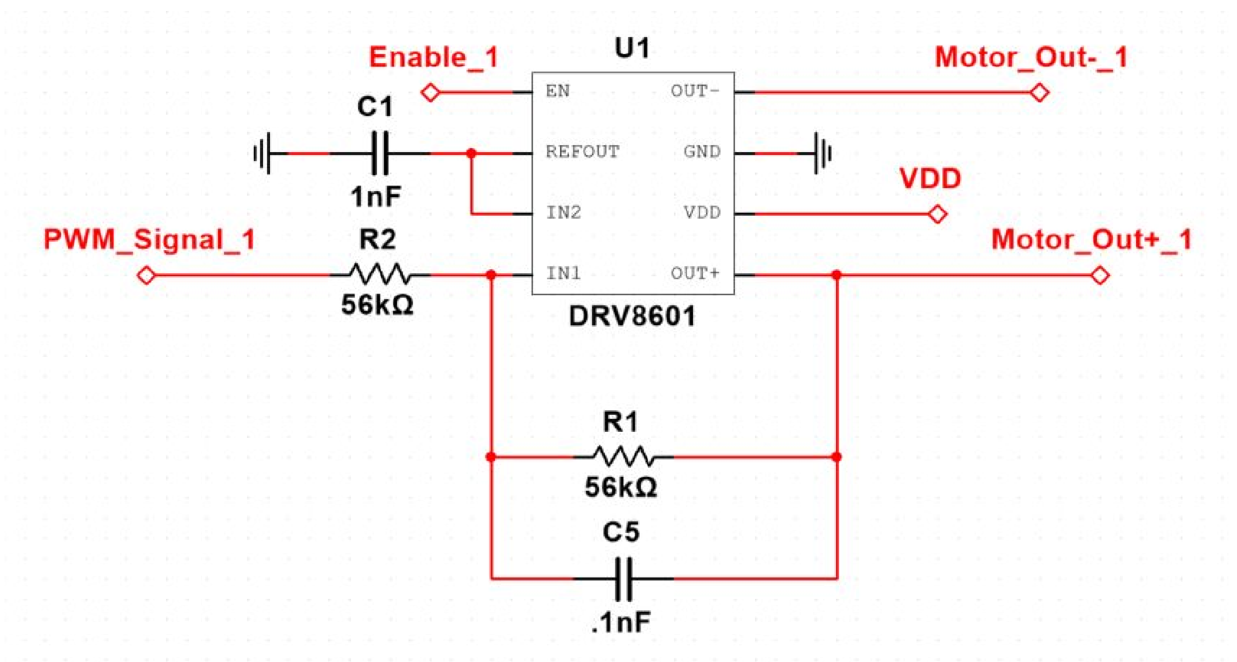

Figure 8 Motor Driver Schematic

For the feedback and input resistors, the datasheet recommends resistor values in the range between 20 kΩ and 100 kΩ. We selected 56 kΩ close to the middle of the range. For fast turn on, a value of 0.1 nF for the feedback capacitor is selected, which is recommended as well in the datasheet. For debugging the correct voltage output of the drivers, we used the formula given where RF/RI represents gain:

$$V_{O,DIFF} = \left(V_{in} - \frac{V_{PWM}}{2}\right) \cdot gain$$

Power Supply

The coin motors are rated at 90 mA, but have a maximum of 175 mA. For four motors, it is a maximum of 700 mA in the extreme scenario. The MSP432 inrush current is 100 mA. Each output pin for the MSP432 can source 2 mA. For our purposes, we estimated approximately 150 mA for a safe margin of operation. The total is then 850 mA for our current specification. We first searched for a wall transformer with the specifications of 5 V and 1 A and settled on Tensility International Corp 16-00014. This has a positive center pin diameter of 2.1 mm. We therefore had to create a footprint and multisim model for an appropriate DC power jack to mate with the wall transformer. Shown in Figure 9 is our Multisim model of our selected DC power jack with a 2.00 mm pin.

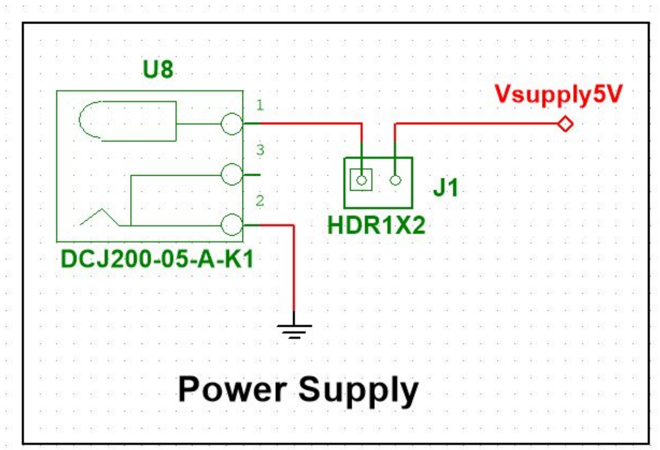

Figure 9: DCJ200-05 Power Jack

Linear Regulator

The 3.3 V output LT1121 linear regulator [10] requires 0.4 V dropout voltage, which means our 5 V power supply is sufficient to operate it. In addition, its current output is 150 mA. While there are other cost-equivalent regulators with greater adjustability for output voltage or current, we accepted the trade-off for a smaller footprint to minimize the PCB size for cost reasons. We also do not anticipate using it for other components other than the MSP432.

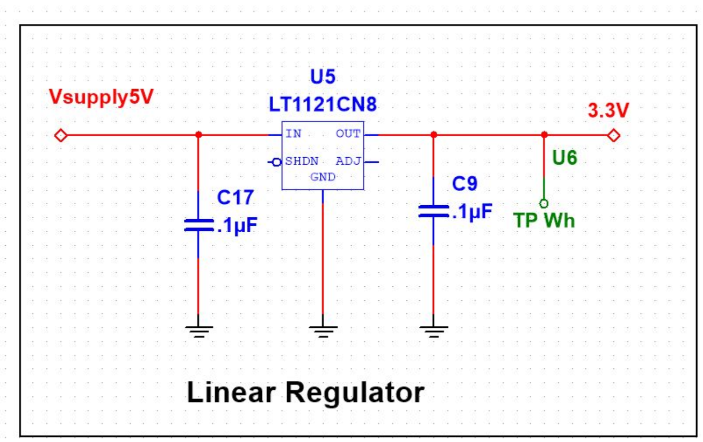

Figure 10: LT1121CN8 Linear Regulator

Board Layout

For each block schematic in Multisim, we chose to group the parts together on the Ultiboard design file to make the debugging process easier. For example, all the feedback and input resistors/capacitors for the four motors are grouped at the top left while the microphone schematic components are grouped at the bottom right. The power supply (DC jack) and linear regular are grouped together next to the microphone components. They are highlighted in colored boxes in Figure 11. The peak detector and mid supply components were mixed together in the middle of the board due to space constraints.

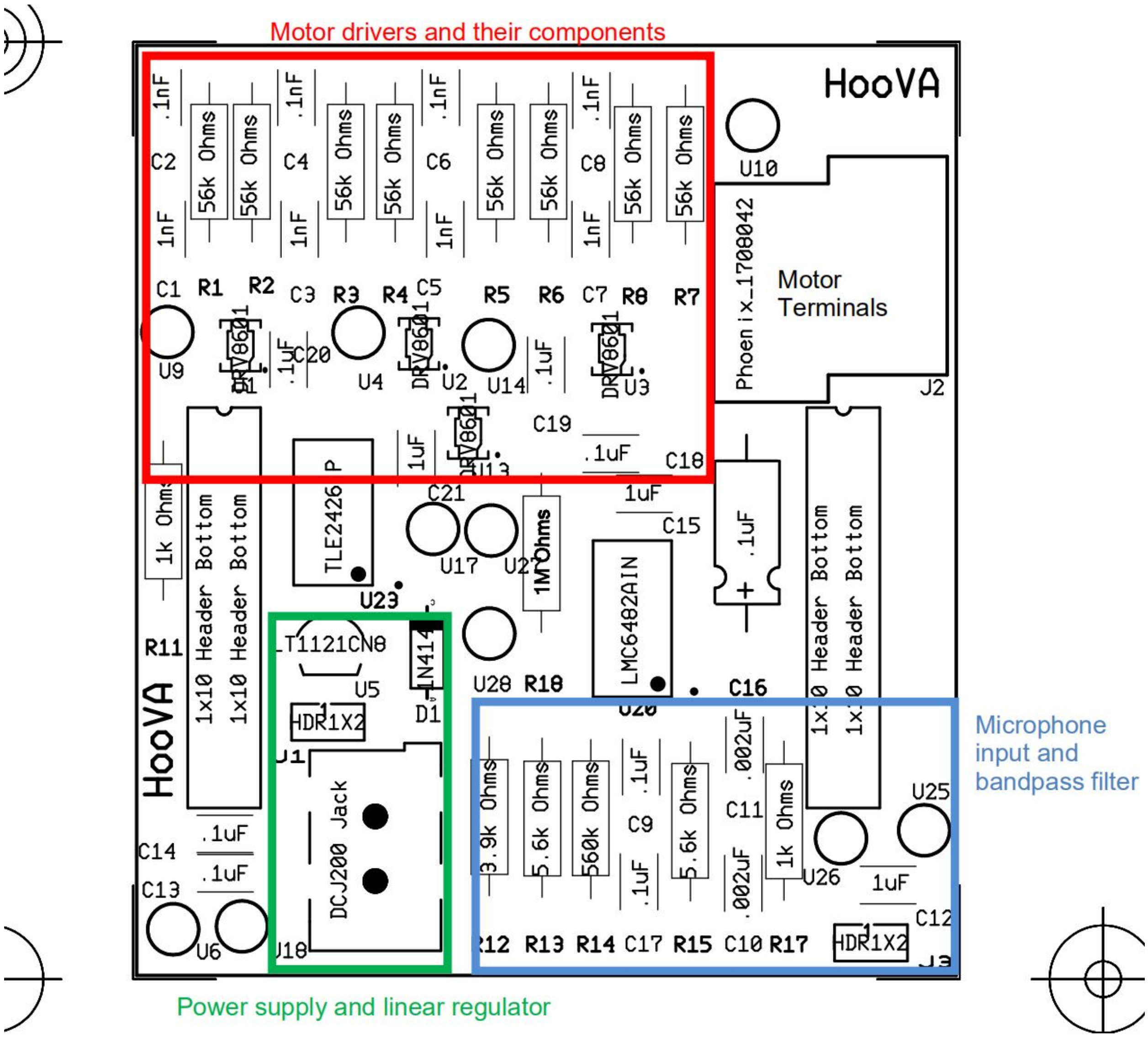

Figure 11: How Parts are Placed

In exchange for the ease of debugging, we needed to use more vias and longer traces as this is not the most efficient way to place tracks. As seen in Figure 12, the top copper traces were primarily used for vertical tracks and the bottom copper traces for horizontal tracks to ensure completion was possible. We also made sure to add bypass capacitors next to each active component, and the main 5 V power supply trace does not have vias except to create thinner traces that were required for the small DRV8601 drivers.

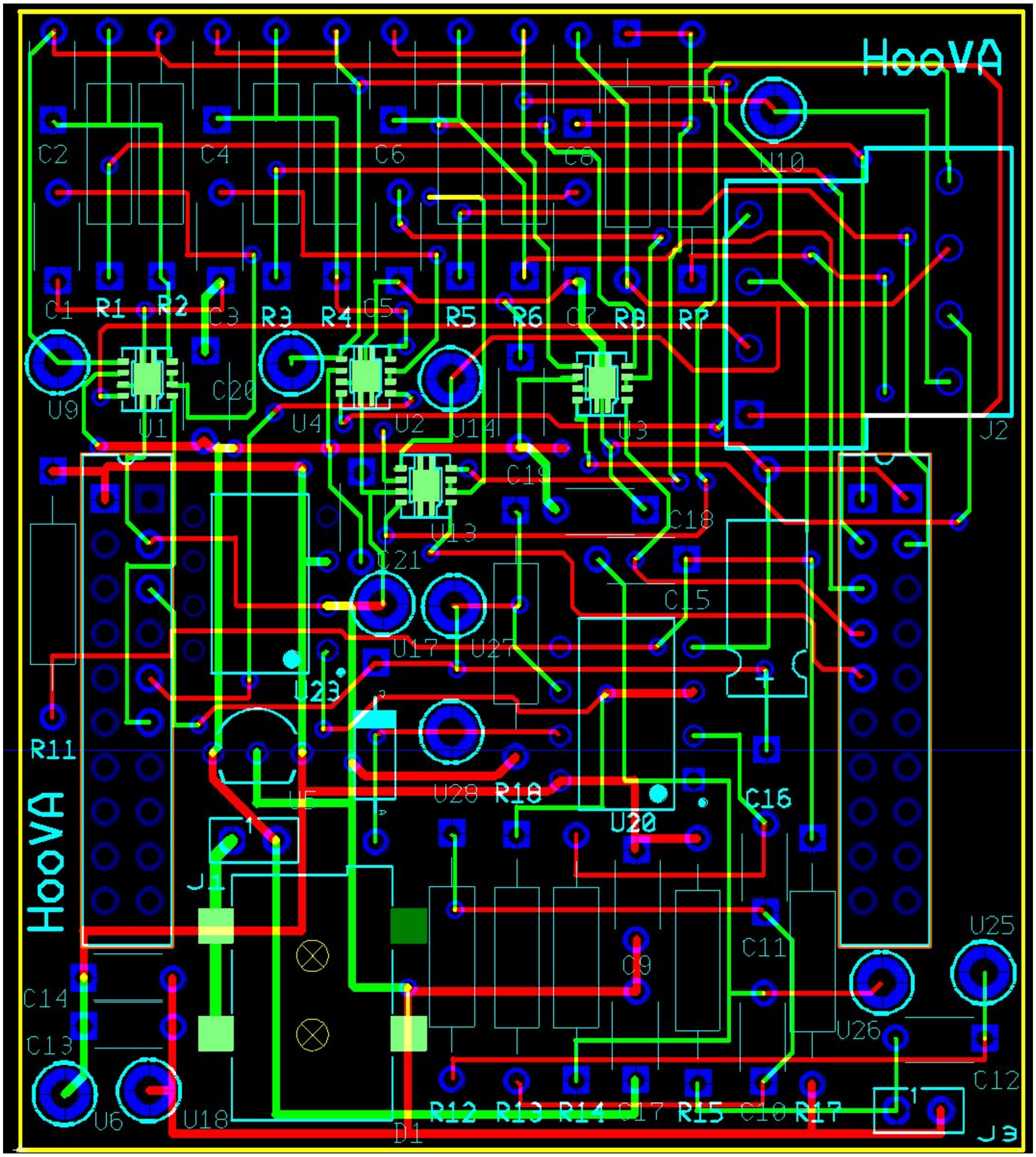

Figure 12: Ultiboard Layout

Microcontroller Code

To make writing the code easier, we planned ahead while creating the schematic and PCB design such that the microphone input and PWM outputs would be directly connected to one of the default ADC input pin (P6.1) and the default Timer A.0 pins (P2.4-P2.7) respectively. The enable outputs were able to be selected from any of the remaining pins; pins 4.2, 4.4, 5.6, and 6.6 were chosen. As a result, no pin remapping was required.

After the pins were decided upon, we wrote the code. It was initially written at a lower level, but this made debugging and collaboration much more difficult than necessary. In the second half of the semester, the code was rewritten to use Driverlib, a higher-level library that abstracts away many of the lower level details and is used by most MSP example code. The code was formatted with C define statements to allow for settings to be easily reconfigured while debugging and to provide additional abstraction to the code.

Vibration Motors

After research into various kinds of vibration motors we decided to use a coin motor. This was due to the size of the motors. They allowed us to add various motors in a ring on the IV line. We believe this design gave us the best chance to dislodge air bubbles. We decided to use the W0825AB001G [21] coin motor from Jinlong Machinery and Electronics Inc [21]. This motor fit our design because it had an operating voltage of 2.6-3.5V and a rated load current of 90mA.

Housing

A housing piece was designed to contain the device if it were to be used in a hospital setting. It was 3D printed at the MAE Rapid Prototyping Lab at UVA. It has 3 openings, one for the microphone and power cord, one for the vibration motor wires, and a small one to see the green light so the user can make sure it is on. It can be opened from the top to access the board and microcontroller. More detailed, dimensioned drawings can be found in the appendix.

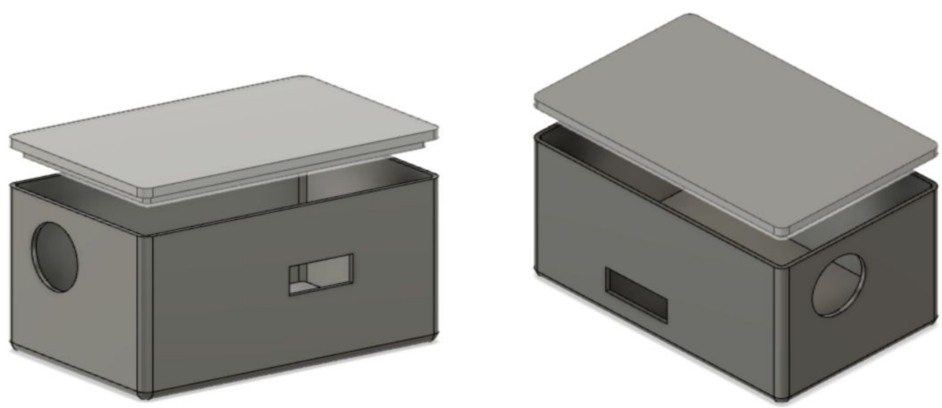

Figure 13: Autocad Drawings of the Housing Piece

Project Timeline

The completion of our device can be separated into four categories: software/interfacing, PCB, Mechanical, and testing. Manuel was in charge of the PCB design. Bradley took the lead on the Software aspect of our project. Quinn is in charge of the mechanical aspect of the device. Orian developed the testing plan and worked with Leah to make sure we could test all the systems before we put them all together. Leah had an active role in coordinating getting access to IV pumps as well as in person testing and assembly. Figure 14 shows our initial Gantt chart. We planned to do these four main categories in parallel. The tasks of each category were done in serial.

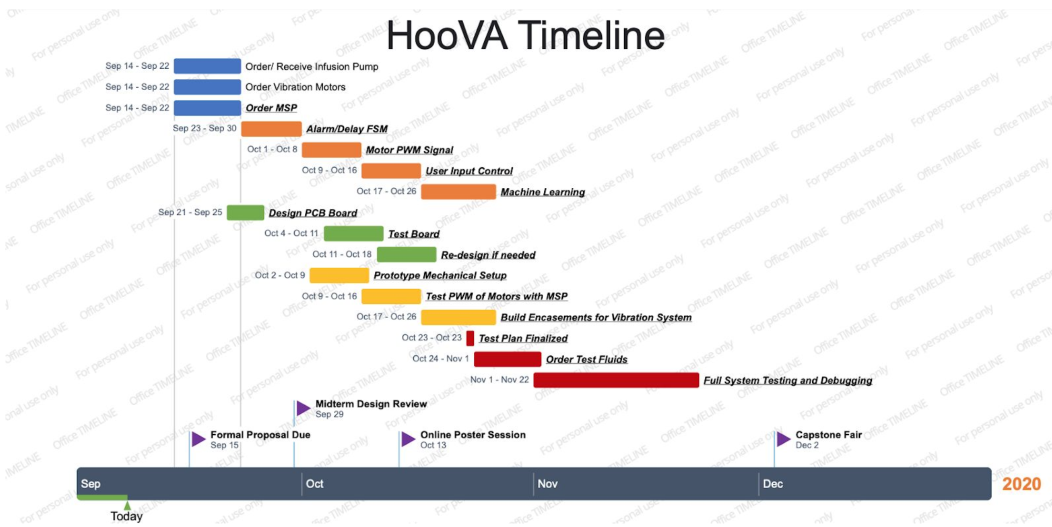

Figure 14: Original Gantt Chart

Figure 15 shows our modified Gantt chart. We had to add and modify our tasks to accommodate the changing nature of our project. One big challenge was that we could not interface directly with the pump, so we had to add an audio detection subsystem to our PCB layout. Additionally, we experienced a longer gap between sending out our first and second boards. We underestimated both the time for shipping and how much testing needed to be done to ensure our second board would work. Lastly, all categories got delayed as we needed the PCB working to properly modify the software.

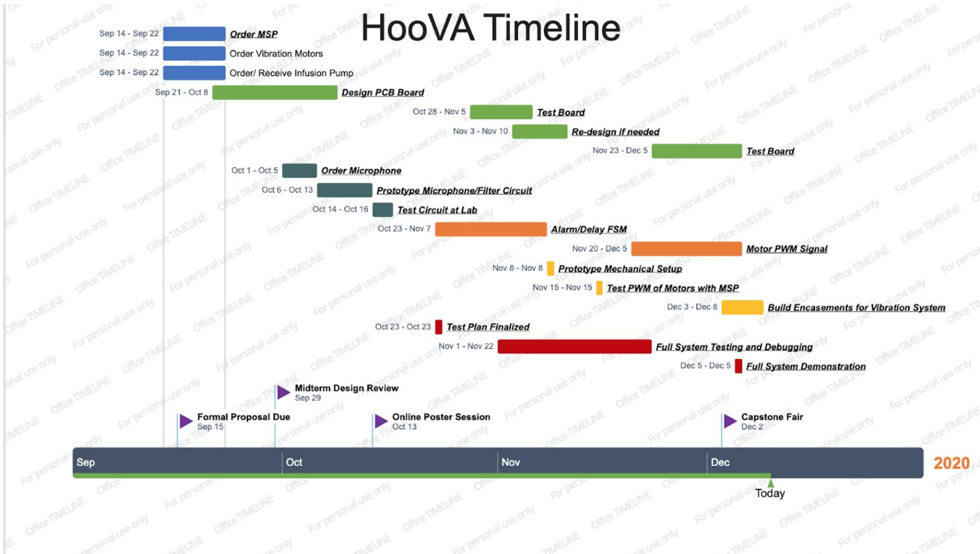

Figure 15: Final Gantt Chart

Test Plan

The overall test plan was tested sequentially starting with the circuit board, with the sequence being first: the power sources, then the microphone, then the amplifier, the filter, then the peak detector, and finally the motor drives. After that, we tested the code by testing the MSP432, and then hooking it up to the circuit board. After testing the board, we ended up testing the entire system with the Infusion Pump.

To test the power sources, we took out the shunts and checked if the power is working correctly for the 5V and 3.3V supplies by removing the shunts for J1 and U6 and checking the voltages.

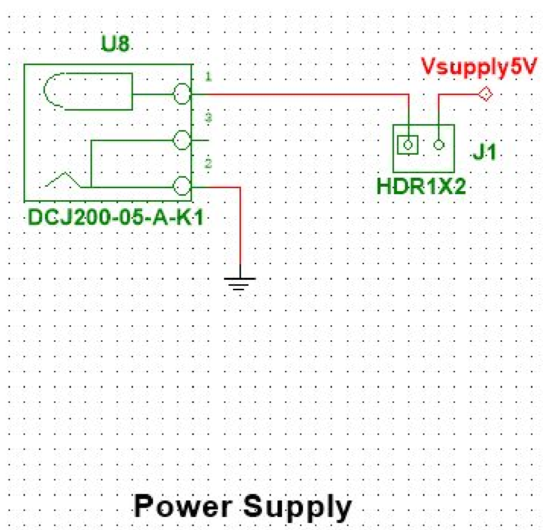

Figure 9: DCJ200-05 Power Jack

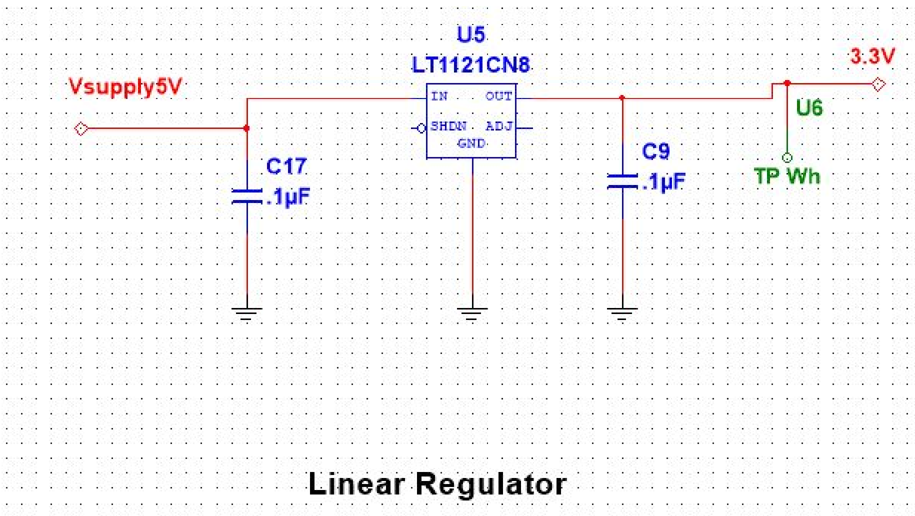

Figure 10: LT1121CN8 Linear Regulator

The microphone was tested by using a recording of the alarm noise that the pump makes when there are bubbles in the line. U26 was then checked while the alarm was going off to see if there was a signal going to that part of the circuit.

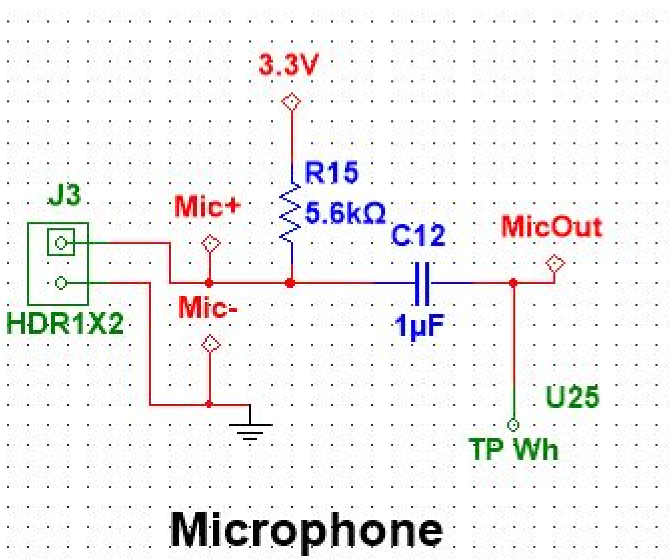

Figure 7: Microphone Circuit

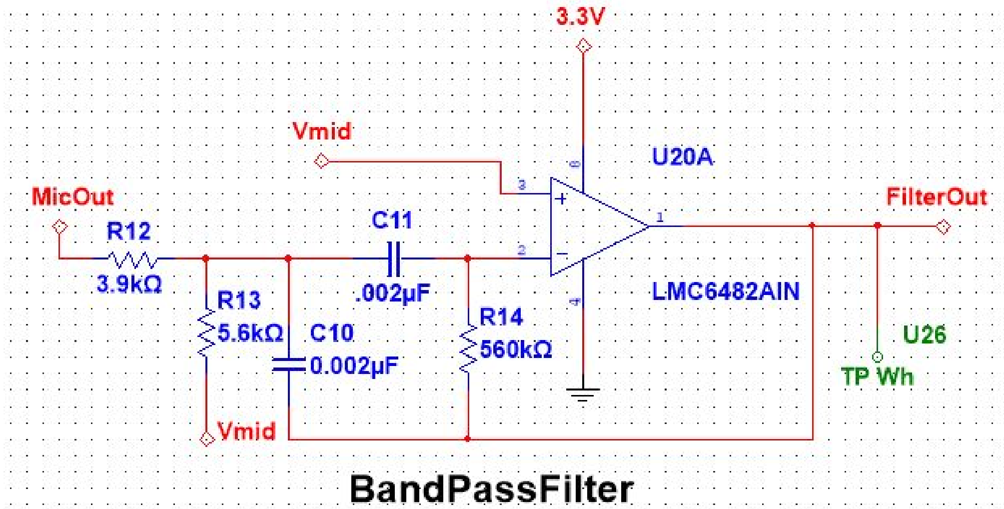

Figure 5: Bandpass Filter

The amplifier and filter was tested by adding a signal to U26, and checking if U28 has the amplified version of the signal. Then, the bode function in Labview was used to ensure that the frequency analysis was correct.

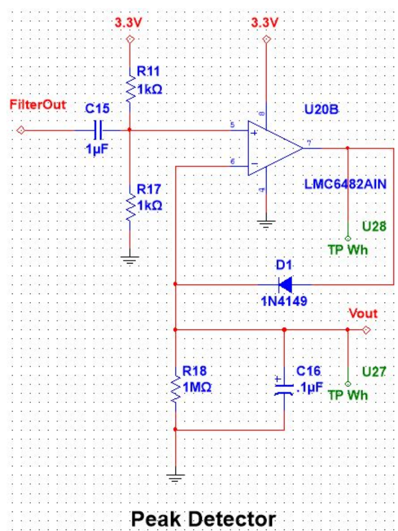

Figure 6: Peak Detector

The Peak Detection signal was used by adding a signal to U26, and checking if the peak detection works on U27. For the motor driver, we input an input signal to each of the motor subsystems, and checked if the correct output voltage was being output.

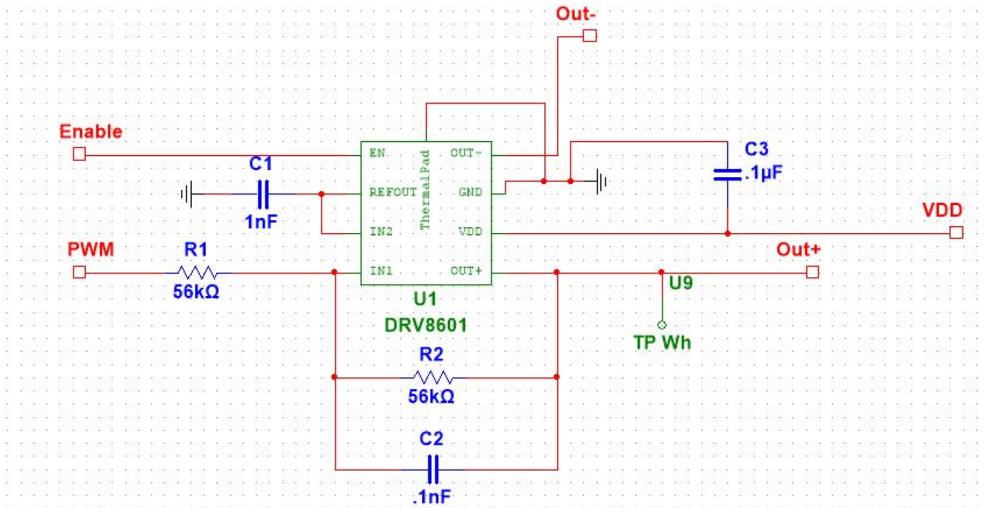

Figure 8: Motor Driver Schematic

After testing the circuit board, we tested the MSP 432 with different test codes, and then hooked the board up to the MSP 432 to do more testing to see if both parts work together. After testing a variety of test codes, we then tested the system with the overall infusion pump that the system is supposed to work with.

Final Results

We were able to build a device that was able to detect the air in line alarm and then provide power to the motors. In addition, when the alarm was no longer present, the motors would turn off within 3 seconds. The audio detection aspect of the project was selective in which signals passed for the alarm. This demonstrates that our quality factor of our bandpass was properly tuned. In addition, the four motors were given enough power to power to vibrate continuously. Unfortunately, the ability of the vibration motors to remove air in line was limited. We demonstrated that the motors could push air back up the tubing, but we were not able to remove a bubble from the tubing where the air in line sensor was. Stronger vibration motors could make this possible.

Points	Infusion Pump Interface	Mechanical Circuit	Software
3	User has the ability to set alarm delay length	Clean PCB with sufficient vibration capability	MSP432 can assign a sequential order of vibrations (Vibrate Motor 1, 2, 3) or in reverse
2	Can detect air in line and	Demonstrated working	MSP432 simple control

	delay air in line alarm	prototype on breadboard	vibration motors
1	Working alarm detection	No working circuit, direct connection to MSP432 for single vibration motor PWM control	MSP432 can receive basic alarm signal and send voltage
0	No alarm detection or signal sent to the MSP432	No vibration / No current	Failure to interface with mechanical circuit or alarm detection

Figure 16: Expectations from Proposal

Many of our goals were made no longer realistic by the changing nature of our project. First, we no longer attempted letting the user delay the alarm once we realized we were not going to be able to interface directly with the alarm. We were able to detect the air in line very effectively. Next, the final PCB board had no errors and was able to push a good amount of power to the vibration motors. The problem may be more with our physical set-up rather than our power limitations. We did not build our software to vibrate in sequential order. This would be a quick addition, but we did not follow this plan because we had to limit our motors to four rather than the 8 or 12 we initially wanted. This made the idea of sequentially setting off rings of motors impractical.

Points	Grade
8-9	A
5-7	B
3-4	C
0-2	D

Figure 17: Grading Scale

In the end, we obtained 7 of the points we set out to achieve in. It was disappointing to not be able to get the alarm to turn off due to our motors, but the other requirements we missed were due to design decisions made during the semester. Further discussion of these mistakes can be found in our future works section.

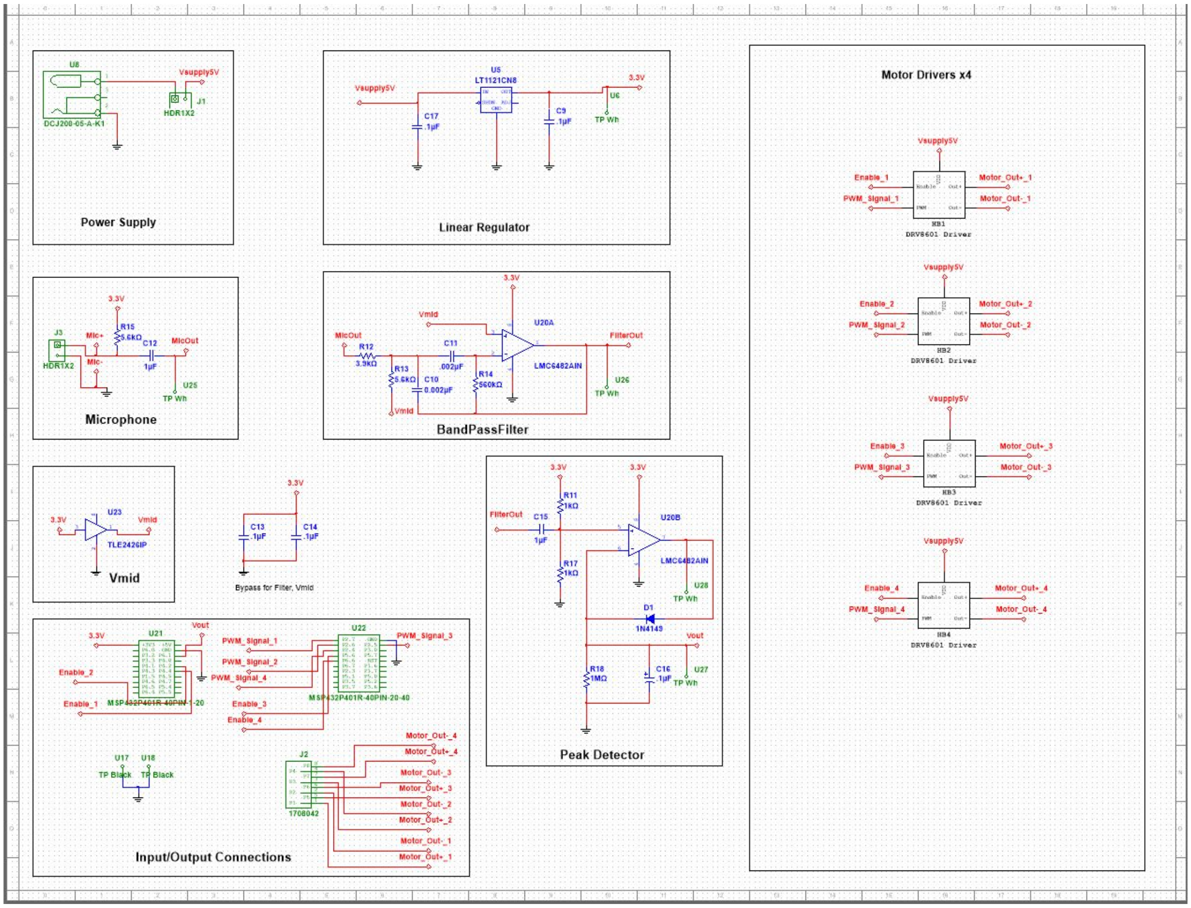

Figure 18 Final Schematic

Costs

A detailed spreadsheet of our costs can be seen in Appendix B.

The costs of our project can be divided into three areas: the MSP, the PCB (parts and production), and the housing. Our design makes use of an MSP-EXP432P401R LaunchPad. With some design changes, it may instead be possible to use only the MSP432P401R. However, because the feasibility and impact of this change has not been thoroughly analyzed, it will be assumed for purposes of this analysis that bulk production will continue to use the LaunchPad.

Thus, based on the prices analyzed in the spreadsheet, it costs about $187.03 to produce a single device and about $161.80 for each device in bulk production as an upper bound. This assumes constant prices for the MSP, PCB production/shipping, and housing. These can likely be produced/purchased in bulk also, giving much greater savings than are currently accounted for.

Additionally, this analysis does not yet take into account the cost of PCB assembly. Our device used 3W Electronics in Charlottesville for board assembly. This cost about $0.40 per part. If we were to produce in-bulk, we could likely pay a one-time fee of about $12000 to acquire an automatic soldering robot, which would lower the price-per-board assembly down to a near-negligible amount (electricity, solder, and robot maintenance).

Thus, an upper-bound for the total cost of producing 10000 can be calculated as follows:

$12000 (one-time fee) + 10000*$161.80 = $1,630,000

With a total per-device cost of $163 when taking into account the cost of automation. As mentioned before, this can likely be lowered further by using an MSP chip instead of a LaunchPad and through bulk-shipping and bulk-production pricings on PCB production.

Future Work

This device is a version 1, experimental prototype; many modifications could be made in order to increase performance and actually remove a bubble within an IV line. First, the vibration motors could be changed. The problem we encountered during testing was that the spot on the infusion pump where the photo sensor used to detect air in line was located was locked in place, preventing vibrations within the line. A new method of air remove could be used that is not inhibited by this problem. Such ideas may be reversing flow in the line or placing the vibration motors on a loose spot on the line. It should be noted that we attempted to do this while the infusion was going and the downward force of the liquid was too much to allow the vibration motors to push the air up, at both a high infusion rate (300 mL/hour) and the low infusion rate (100mL/hour). So a future system would need to stop the flow before carrying out this action.

Another component that could be changed is the infusion pump interface. This device uses the air detection system that the infusion pump includes, but a new device could use its own photosensor to determine when air is in line and stop the flow. This could prevent the issue we encountered with the vibrations not reaching the bubbles because the photo sensor could be unlatched from the line, allowing it to vibrate and move the bubbles upward. This would also allow the device to be used on any infusion pump, because it does not depend on the frequency of the alarm.

One last change that could be made is to implement the silencing function we had originally planned for. In order to do this, several trials would need to be carried out to ensure the device actually works as intended and only silences when absolutely necessary. It may be more difficult to get approval as a medical device, but would have a great impact on alarm fatigue within hospitals

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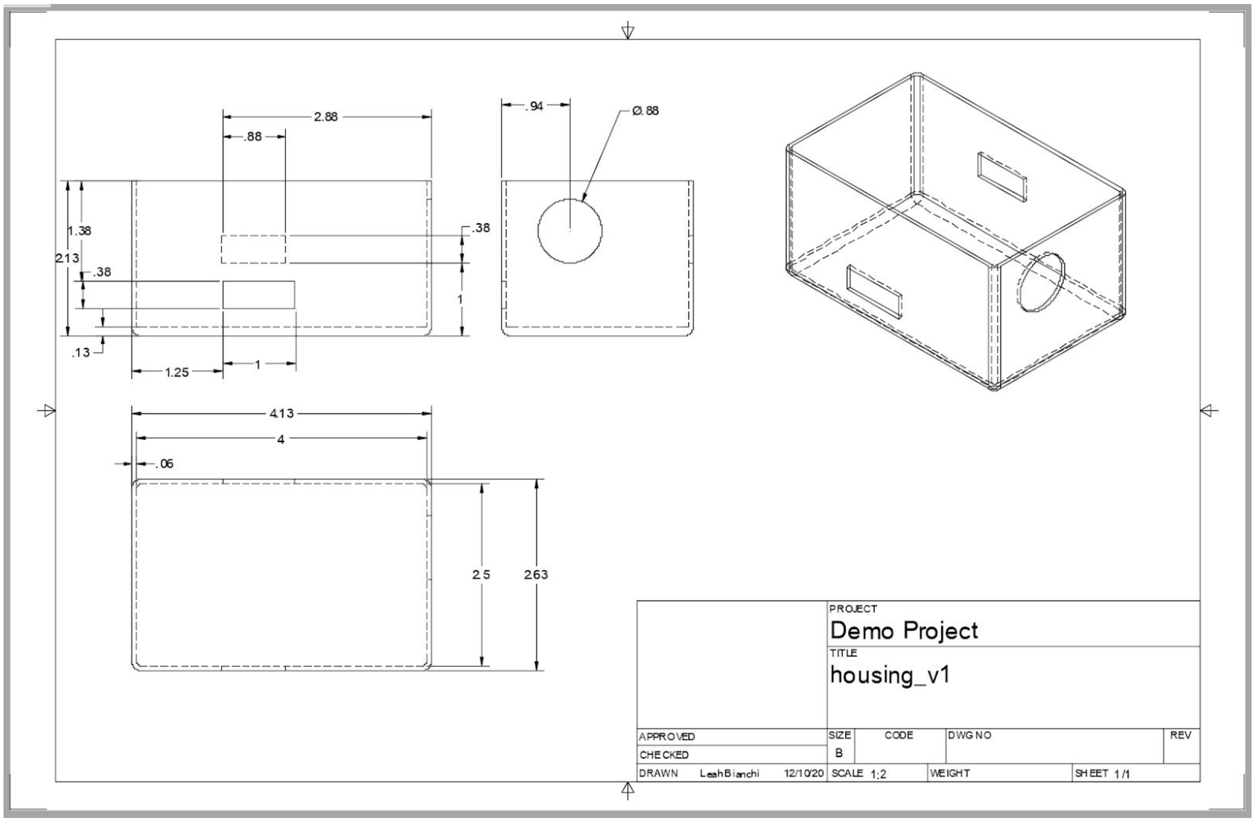
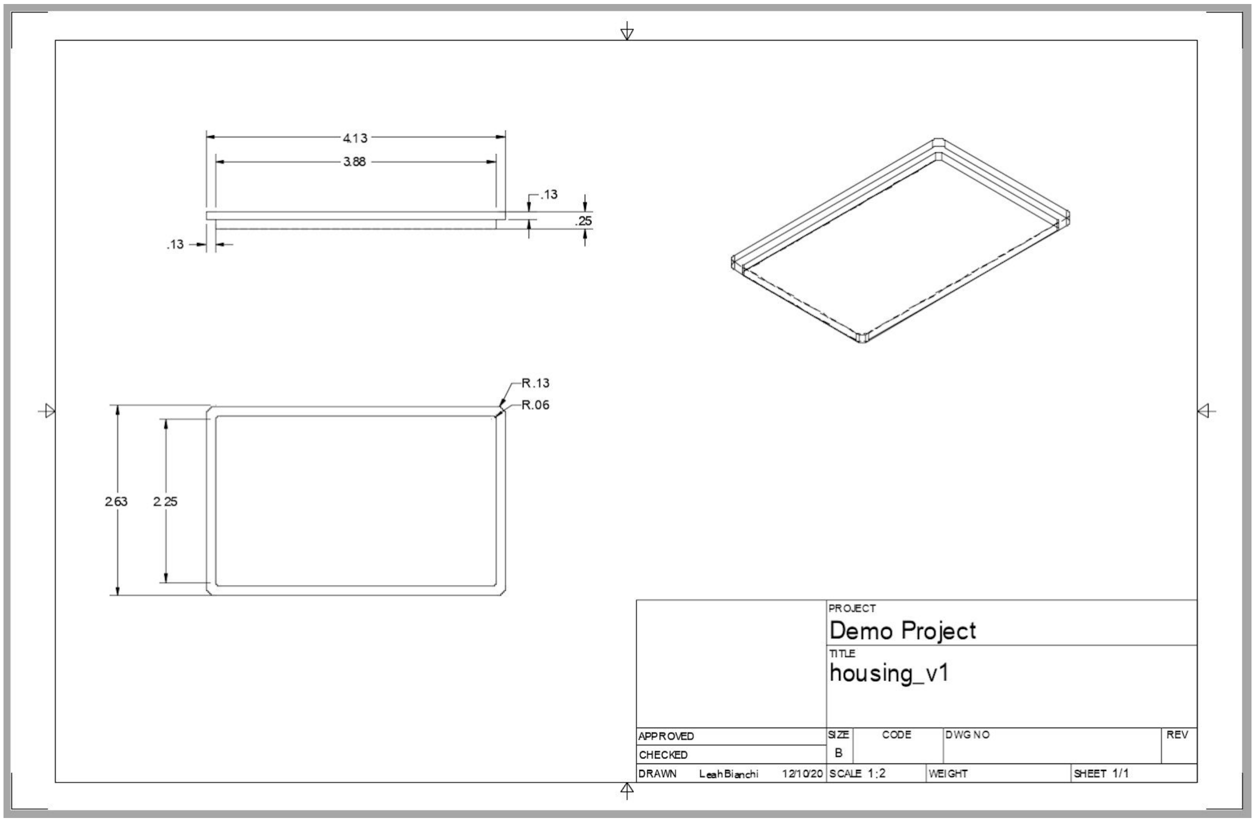
Appendix

Appendix A : CAD Drawings





Appendix B: Costs

	Quantity	Description	Indiv. Price per device	Total price per device	Indiv. price per bulk	Total price per bulk	Manufacturer	Manu. Part No.	Vendor Part No.
MSP	1	MSP-EXP432P401R LaunchPad	$23.99	$23.99	$23.99	$23.99	Texas Instrume	MSP-EXP432P401R	296-39653-ND
PCB and mech.	4	Vibration ERM MTR 15000 RPM 3V	$4.04	$16.16	$2.66	$10.64	Jinlong Machir	W0825AB001G	1670-1071-ND
	1	AC/DC WALL MOUNT ADAPTER 5V 5W	$8.62	$8.62	$8.62	$8.62	Tensility Interr	16-00014	839-1659-ND
	1	MICROPHONE COND ANALOG OMNI	$0.85	$0.85	$0.44	$0.44	CUI Devices	CMEJ-4618-42-L177	102-6534-ND
	1	DCJ200-05-A-K1	$0.96	$0.96	$0.43	$0.43	GCT	DCJ200-05-A-K1-A	2073-DCJ200-05-A-K1-ACT-ND
	14	HCPGeneratedParts, TP Wh	$0.40	$5.60	$0.25	$3.53	Keystone Elect	5014	36-5014-ND
	4	HCPGenerateParts, TP Black	$0.40	$1.60	$0.25	$1.01	Keystone Elect	5011	36-5011-ND
	5	Motor, DRV8601	$0.86	$4.30	$0.29	$1.44	Texas Instrume	DRV8601DRBR	296-28765-2-ND
	12	RESISTOR, 56kΩ	$0.14	$1.68	$0.01	$0.17	Vishay Beyschl	SFPR2500005602FR5	PPC56.0KYTR-ND
	1	TERMINAL BLOCKS, 1708042	$7.56	$7.56	$5.22	$5.22	Phoenix Conta	1708042	277-1358-ND
	5	CAPACITOR, .1µF	$0.33	$1.65	$0.07	$0.35	KEMET	C320C104M1U5TA	399-4265-ND
	1	SPECIAL FUNCTION, TLE2426IP	$2.30	$2.30	$0.98	$0.98	Texas Instrume	TLE2426IP	296-6550-5-ND
	2	HEADERS TEST, HDR1X2	$0.15	$0.30	$0.05	$0.11	Harwin Inc.	M20-9990245	952-2261-ND
	1	OPAMP, LMC6482AIN	$5.05	$5.05	$2.36	$2.36	Texas Instrume	LMC6482AIN/NOPB	LMC6482AIN/NOPB-ND
	4	CAPACITOR, 1µF	$0.67	$2.68	$0.19	$0.77	KEMET	C340C105K1R5TA73(	399-13969-2-ND
	1	DIODE, 1N4149	$0.10	$0.10	$0.01	$0.01	ON Semicondu	1N4149	1N4149-ND
	1	CAP ELECTROLITIC, .1µF	$0.38	$0.38	$0.09	$0.09	Nichicon	UKL2A0R1KDD	493-16876-ND
	1	VOLTAGE REGULATOR, LT1121CN8	$3.25	$3.25	$1.66	$1.66	Analog Devices	Lt1121CZ-3.3#PBF	LT1121CZ-3.3#PBF-ND
Housing	1		$25	$25.00	$25	$25.00			
PCB productior	1		$75	$75.00	$75	$75.00			
Total Cost			Price to produce one:	$187.03	Price to produce in bulk:	$161.80			