ECE 445
Spring 2016

Sound Controlled Smoke Detector

Design Review

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2016-March-2

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Introduction

Statement of Purpose

Almost all of us encounters false fire alarms at some point in our life. Although many modern fire alarms have the ability to mute temporarily with a push of button, the physical location of the smoke detector does not always make it easy to do so. At the same time, voice controlled products are entering markets and gaining popularity in recent days. These products, such as Android phones and Amazon Echo, can be activated by keyword such as “OK Google”, “Alexa” or “Amazon”.

Therefore, we propose a sound controlled fire alarm that allows users to easily turn the alarm off by shouting the keyword "cooking" when false alarm happens (in addition to a push button). In specific, we plan to use many different human version of “cooking” as the training data. Then the processor will find and store the Mel-Frequency Cepstral Coefficients (MFCCs) for the training word. Then once the alarm is triggered, the core will be turned on and actively listens for the keyword, finding the MFCCs for what it hears, and comparing with the stored MFCCs. If the mean square error is below a threshold, the core will stop the alarm. In additional, we may also look into Dynamic Time Warping (DTW) to improve our detection accuracy.

Objectives

Goals and benefits:

- Allow false fire alarms to be safely turned off by shouting the keyword "cooking"
- Prevent unnecessary interruption to everyday activities such as cooking
- Maintain sufficient warning against possible fire hazard.

Functions and features:

- Sense environment condition relating to fire, specifically, Carbon Monoxide concentration.
- Activate alarm and power on Digital Signal Processor (DSP) if fire hazard is detected.
- Capture human voice if alarm is triggered
- Implement an algorithm to recognize keyword by feature extraction using Mel-Frequency Cepstral Coefficients
- Process audio data in real time using our algorithm and check if there is a match to the keyword
- Interpret CO sensor data to calculate ppm
- Pause the alarm if keyword is matched and if it is safe to do so

Design

Block Diagrams

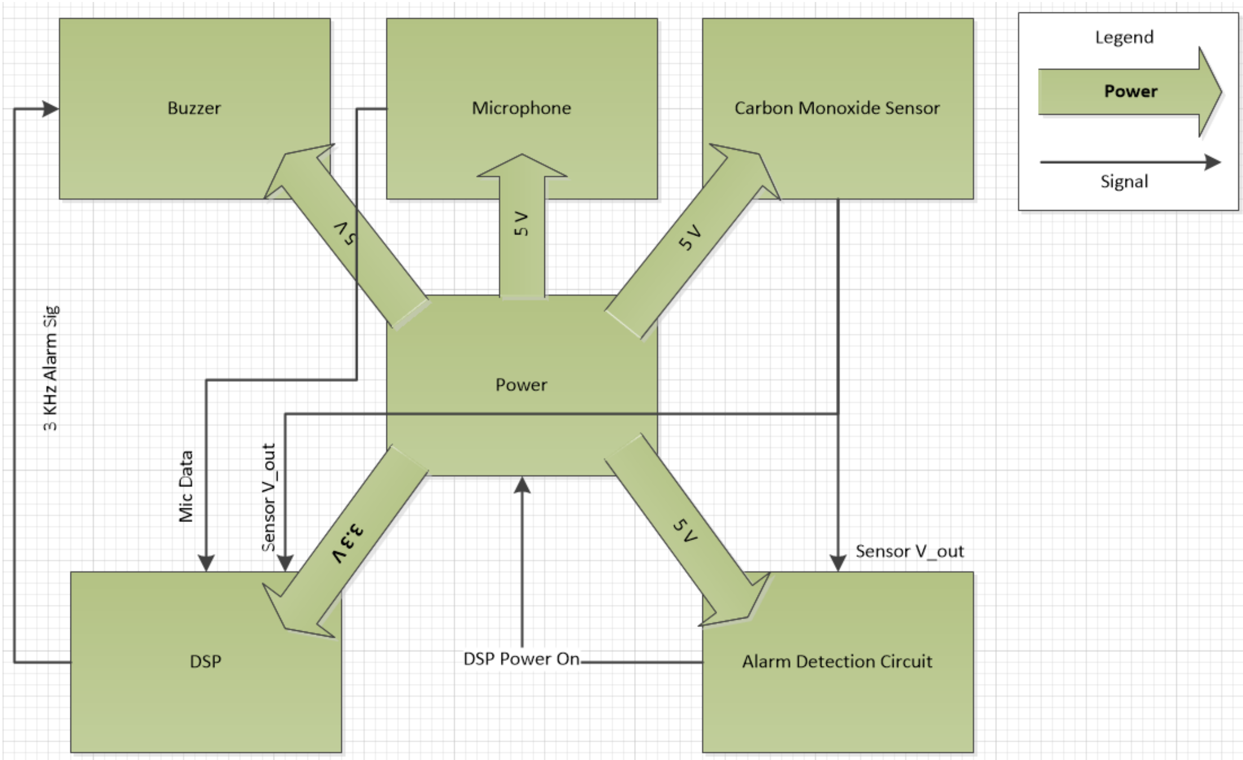

Figure 1: Block Diagram

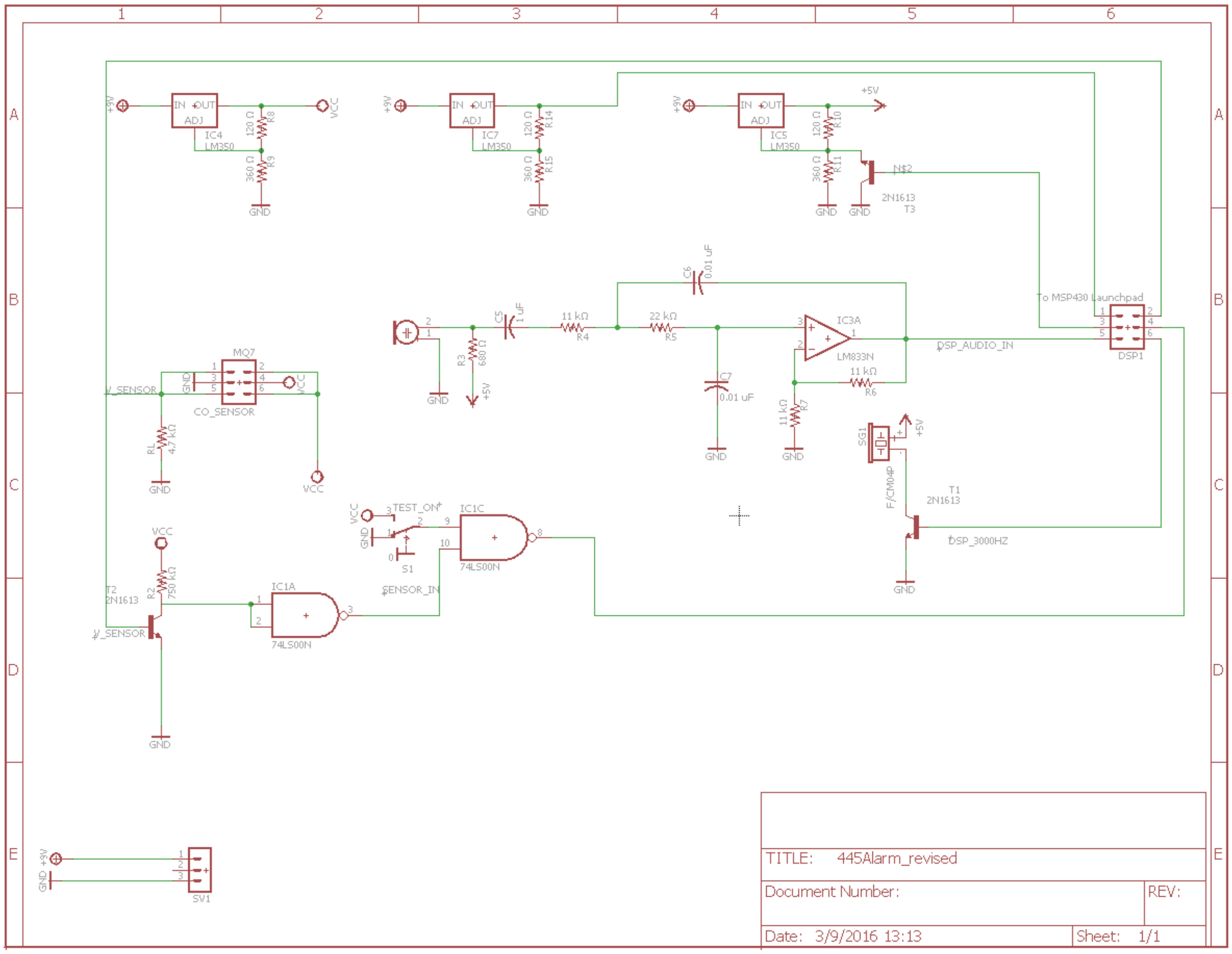

Figure 2: Complete Circuit with MQ-7 Carbon Monoxide sensor

Sensor

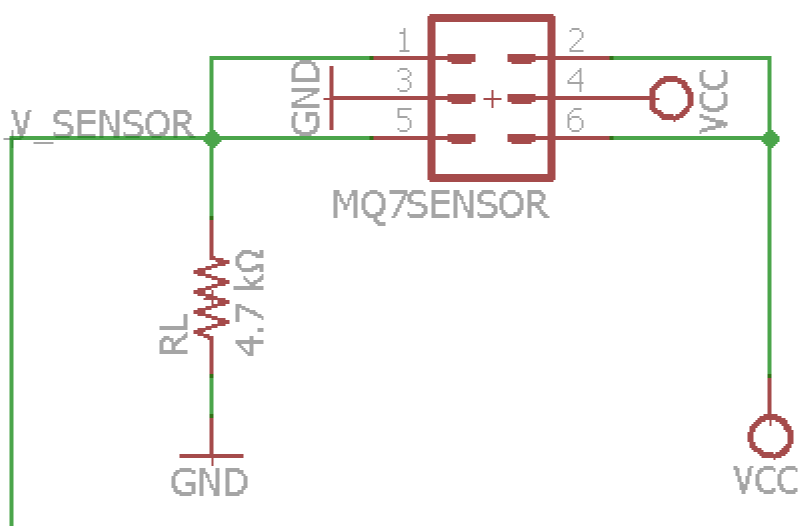

Figure 3: CO Sensor Schematic

Output:

V_Sensor: Analog voltage that is proportional with CO concentration.

Description:

We will use an off the shelf CO sensor. Under high CO concentration, the sensor resistance will decrease, and the voltage across the load resistor will increase. The output of the circuit is an analog voltage that is proportional to the CO concentration in air, where +2.5V indicates above threshold concentration.

Power

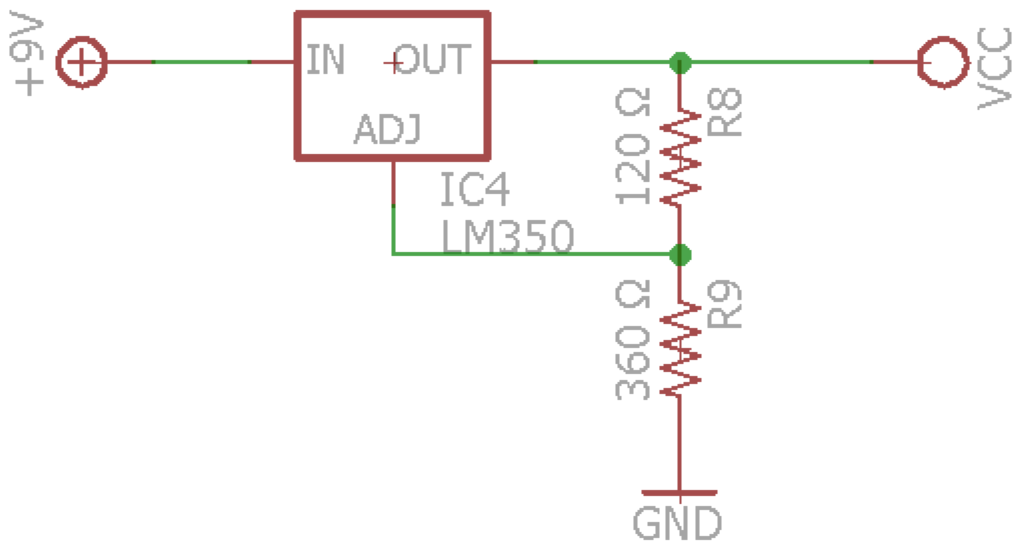

Figure 4: Power +5V Schematic

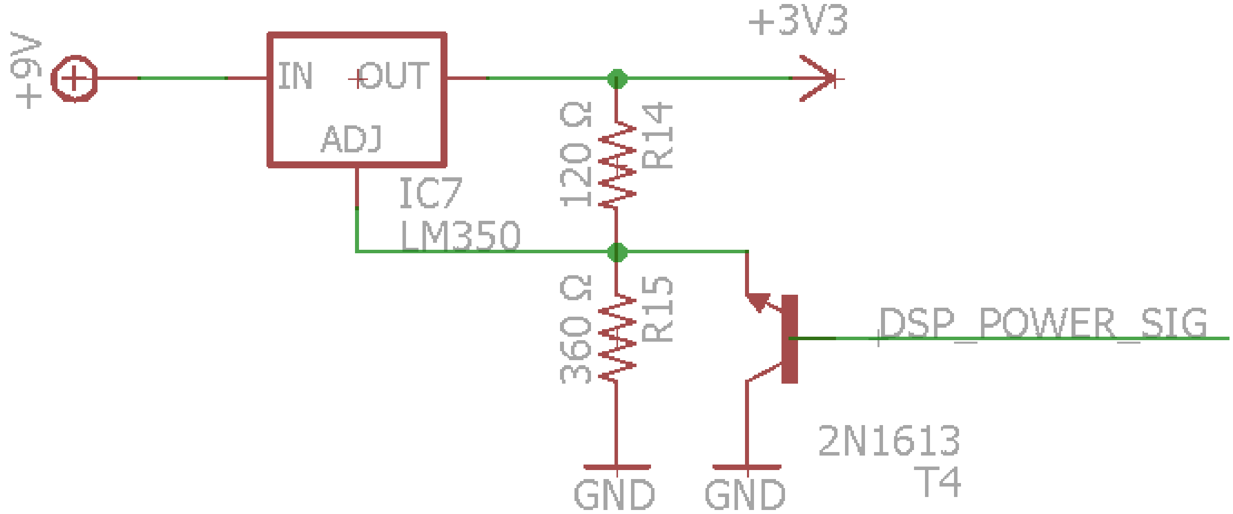

Figure 5: Power switchable +3.3V Schematic

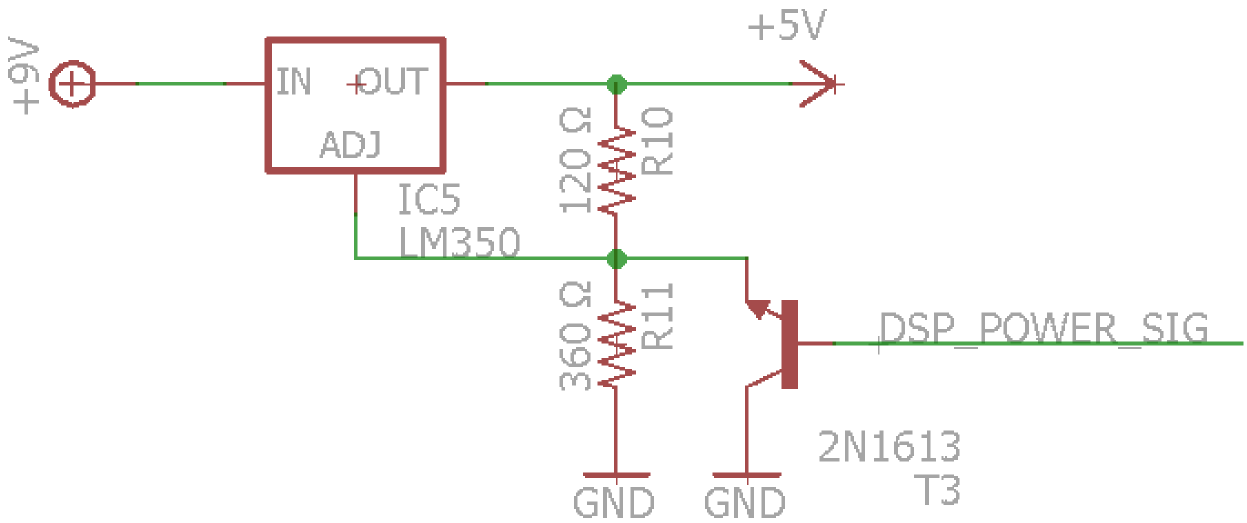

Figure 6: Power switchable +5V Schematic

Input:

DSP_POWER_ON: +5V to turn on DSP, or 0 V to turn off DSP.

Output:

DETECTION_POW: always on +5V to the alarm detection circuit

DSP_POW: +3.3V power to the DSP

AUD_POW: +5V power to the mic and buzzer

Description:

The power unit uses a 9V battery, and it provides an always on +5V to the Alarm Detection Circuit. When CO concentration is above threshold, Alarm Detection Circuit raises DSP_POWER_ON, and the power unit will power on the DSP and its power peripherals.

Microphone

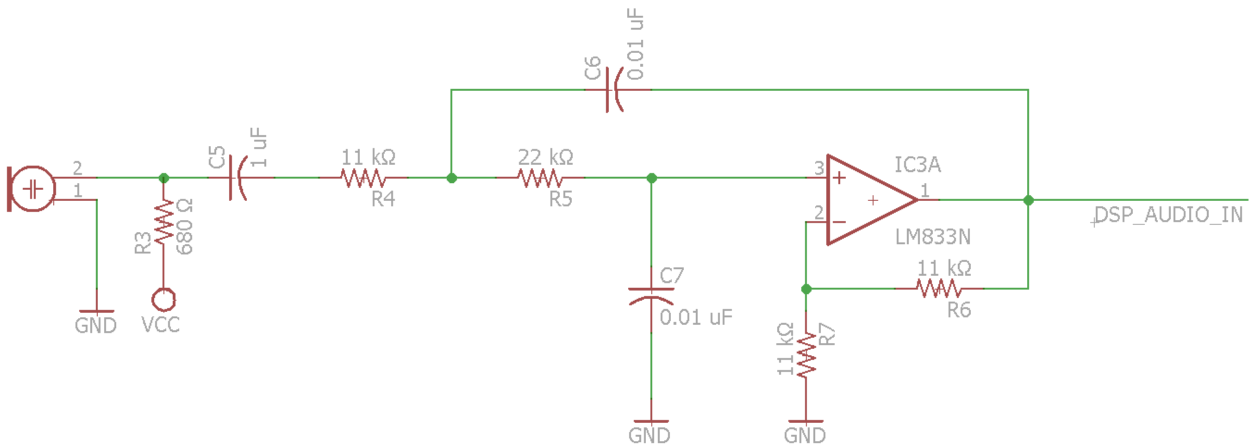

Figure 7: Microphone and Low Pass Filter Schematic

Output:

DSP_AUDIO_IN: Filtered analog audio output

Description:

The circuit uses an off the shelf Omni-Directional Microphone, filters and amplifies the output, and passes the analog signal to the DSP. We will assume that the human voice is below 1 kHz, where the noise is around 3 kHz. Therefore, our cut off frequency is 1 kHz. This ensures that our input is band limited, and satisfies Nyquist, which allows the DSP will handle additional filtering at 8 kHz sample rate if needed.

Buzzer

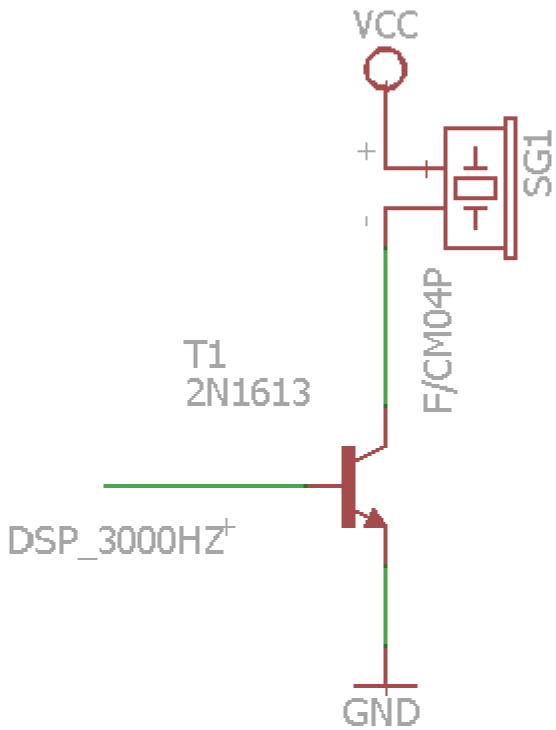

Figure 8: Buzzer Schematic

Input:

DSP_3000HZ: 3000Hz tone generated from the DSP

Description:

This block is an off-the-shelf buzzer to produce the alarm sound.

DSP

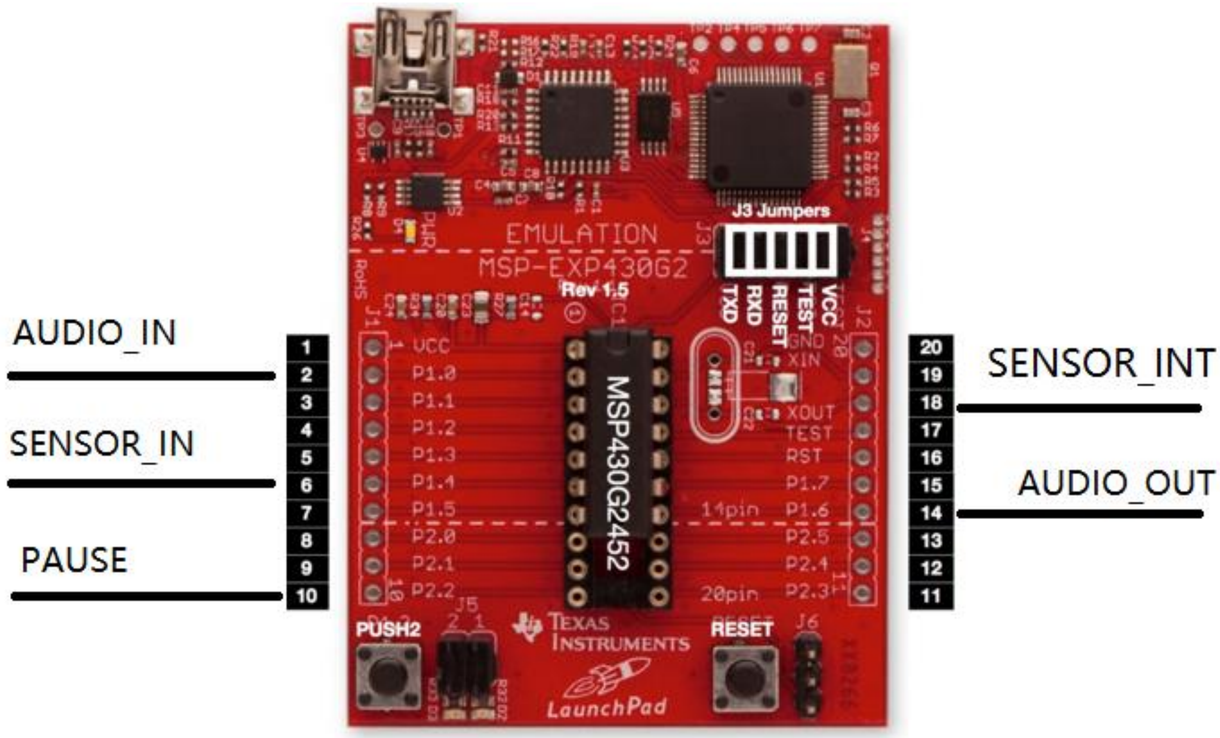

Figure 9: DSP Connection Schematic

Input:

AUDIO_IN: Analog audio data from the mic.

SENSOR_IN: Analog output from CO sensor

PAUSE: Digital input, Manual pause signal from a switch.

SENSOR_INT: Digital input, active high interrupt signal to wake up DSP from low power mode

Output:

AUDIO_OUT: 3 kHz Alarm tone.

Description:

We use MSP430 as our DSP, it is responsible for sounding the alarm and pausing the alarm. The DSP will be put in low power mode whenever possible. If the sensor detects high CO concentration, SENSOR_INT interrupt will wake up the DSP, and the DSP will then turn on the alarm and continuously listen for the keyword "cooking". When keyword is recognized, the DSP will pause the alarm. A manual pause switch is also provided in case the recognition fails to recognize keyword (false negative). Sensor reading is also taken in so that we can re-trigger the alarm if CO concentration is too high or if the DSP is on for too long (false positive, or alarm falsely turned off by user).

Software

Mel-Frequency Cepstrum

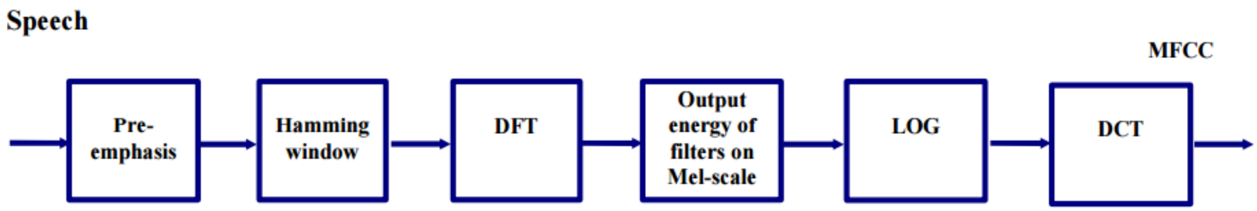

Figure 10: MFCC Flow Chart

Input: audio

Output: 12 Mel-frequency cepstrum coefficients

The MFCC is the model we will use to extract the features of the sound. The calculation steps are shown in the graph above.

Converting from frequency to Mel: $M(f) = 1125\ln(1 + \frac{f}{700})$

Converting from Mels back to frequency: $M^{-1}(m) = 700(e^{\frac{m}{1125}} - 1)$

DFT(Distributed Fourier Transform): $S_i(k) = \sum_{n=1}^{N} s_i(n)h(n)e^{-j2\pi k\frac{n}{N}}$

Hidden Markov model

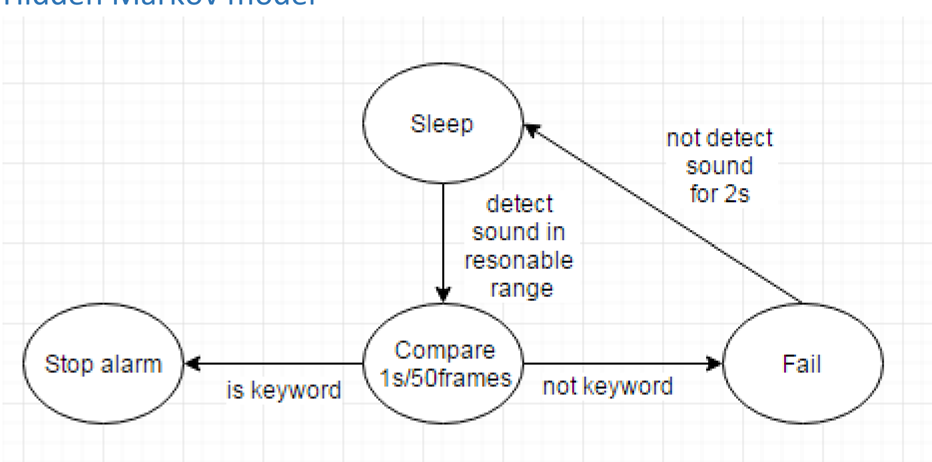

Figure 11Hidden Markov FSM

The Bayesian inference is used to calculate the probability of that the input is the keyword. First, we need a huge number of training data of both keyword and non-keyword, which will be collected from our teammates. Then, we use the MFCC model described above to get a set of 12 MFCCs for each training data and store them. Whenever a new input come in, it will be compared with the stored MFCCs to calculate the difference between it and the keyword.

In our design, we will use MAP strategy to make the decision, which is we will classify the input to the set which has higher probability.

Bayesian inference MAP decision: $x^* = argmax_x \, P(x|e) = P(x) \prod_{i=1}^{n} P(e_i|x)$

Calculation

Power Consumption in Low Power Mode

When there is no indication of fire (high CO concentration). Most of the circuit will be powered off, only the DSP and the sensor will be operating:

The DSP in Low Power Mode draws 0.5uA from 3.3V source.

The sensor heater has resistance 29 Ω and is connected to 1.5 V source.

Thus the total power consumption is

$$P = I \times V = \frac{V^2}{R}$$

$$P = 0.5uA \times 3.3V + 1.5^2 \div 29 = 77.6 \, mW$$

Power Consumption in Active Mode

When CO concentration is high enough (above 70 ppm), the DSP will wake up and subsequently power on everything else:

The DSP in Active Mode draws 1mA at 3.3V.

The sensor heater has resistance 29 Ω and is connected to 1.5 V source.

The microphone draws 0.5mA at 5V.

The buzzer draws 3mA at 5V.

The LPF circuit draws 5mA at 9V.

Thus the total minimum power consumption is

$$P = I \times V = \frac{V^2}{R}$$

$$P = (1 \, mA \times 3.3V) + (1.5^2 \div 29) + (5 \, mA \times 9V) + (3 \, mA \times 5V) + (0.5mA \times 5V)$$

$$P = 145 \, mW$$

Low Pass Filter for Microphone

Choosing the Sallen-Key Achitecture for building a Butterworth filter, and define

$$K = \frac{R6 + R7}{R6}$$

$$FSF \times fc = \frac{1}{2\pi\sqrt{R4R5C5C6}}$$

$$Q = \frac{\sqrt{R4R5C5C6}}{R4C5 + R5C6 + R4C6(1 - K)}$$

Where R4, R5, R6, R7, C5, C6 are shown in figure 7. The transfer function for the filter can be written as:

$$H(f) = \frac{-K}{(\frac{f}{FSF \times fc})^2 + \frac{1}{Q}\frac{jf}{FSF \times fc} + 1}$$

Where f is the frequency, fc is the cutoff frequency, FSF is the frequency scale factor, Q is the quality factor, and K is the gain of the LPF.

Plugging in the RC values chosen from figure 7, the transfer function is:

$$H(s) \approx \frac{82644628}{s^2 + 9091s + 41322314}$$

Where $s = j2\pi f$. The frequency response of the LPF is plotted in figure11.

Power Module

The output power from LM350 is:

$$Vout = 1.25 \times (1 + \frac{R2}{R1})$$

R1 is chosen to be 120 Ω as suggested in the datasheet, and R2 are chosen to output +5V and 3.3V.

$$Vout = 1.25 \times \left(1 + \frac{360}{120}\right) = 5V$$

$$Vout \approx 1.25 \times \left(1 + \frac{200}{120}\right) = 3.3V$$

When the 5V and 3.3V source is off, the output voltage is

$$Vout = 1.25 \times \left(1 + \frac{0}{120}\right) = 1.25V$$

Sensor Sensitivity

Plots

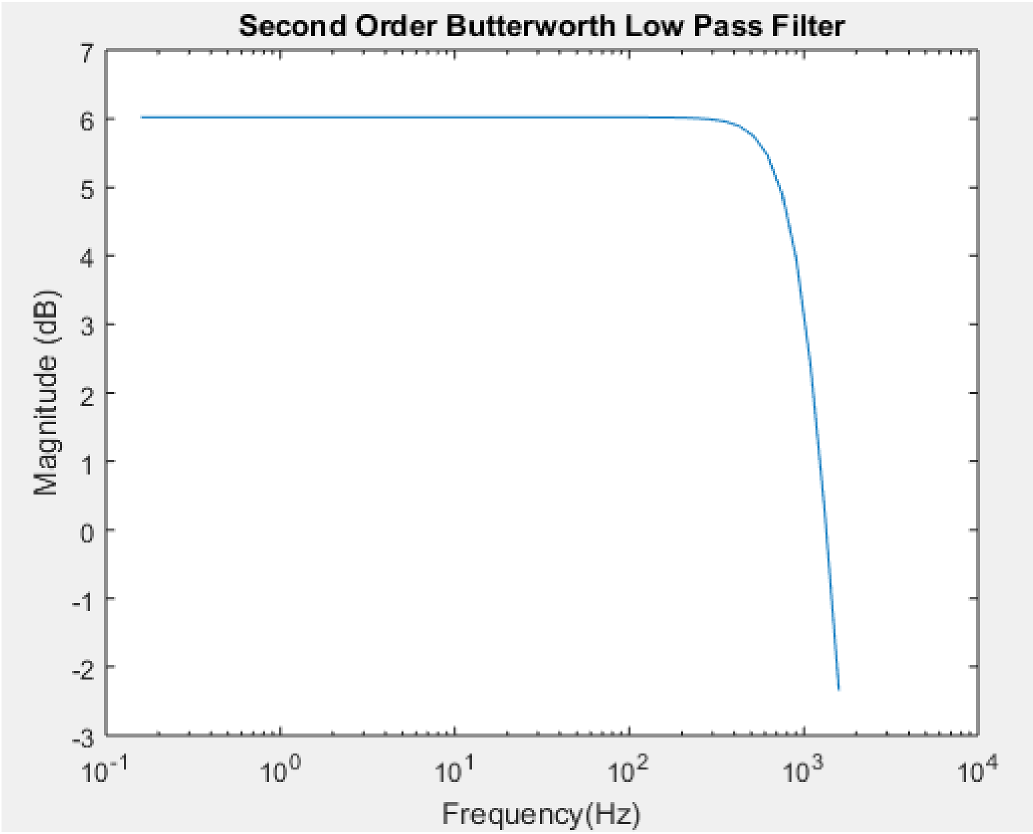

Figure 12: Simulated Frequency Response from the Low Pass Filter

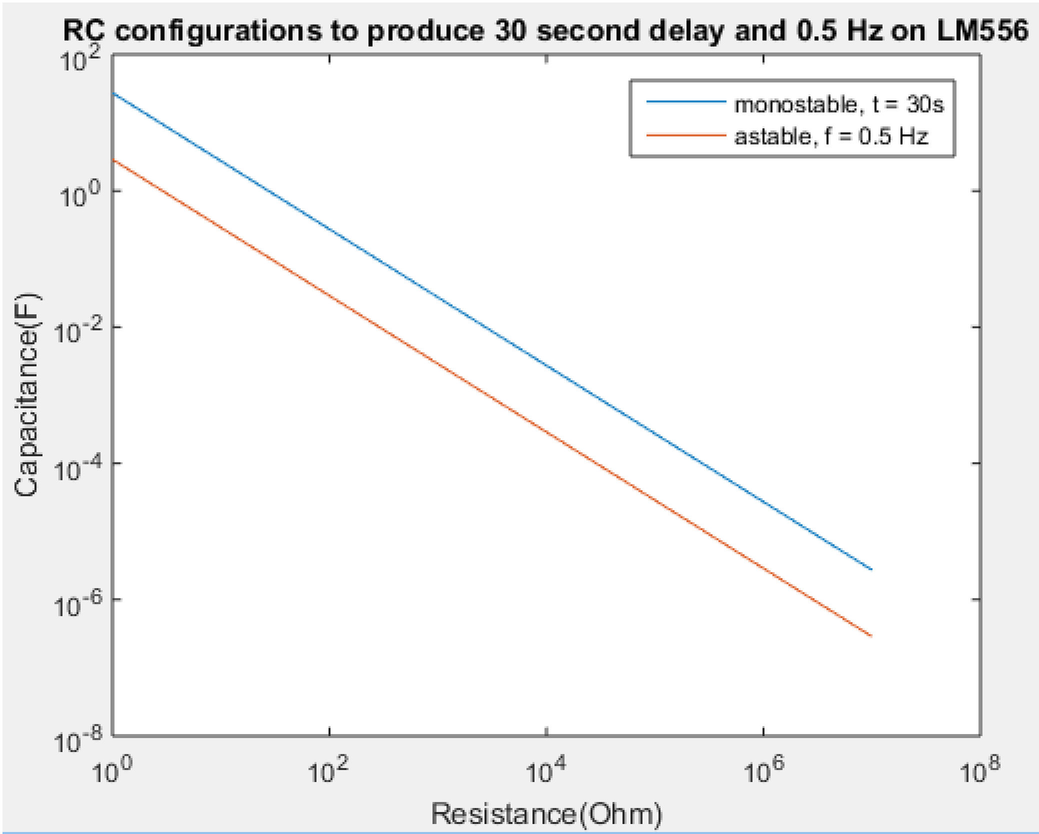

Figure 13: Resistor and Capacitor choices for Alarm Detection circuit

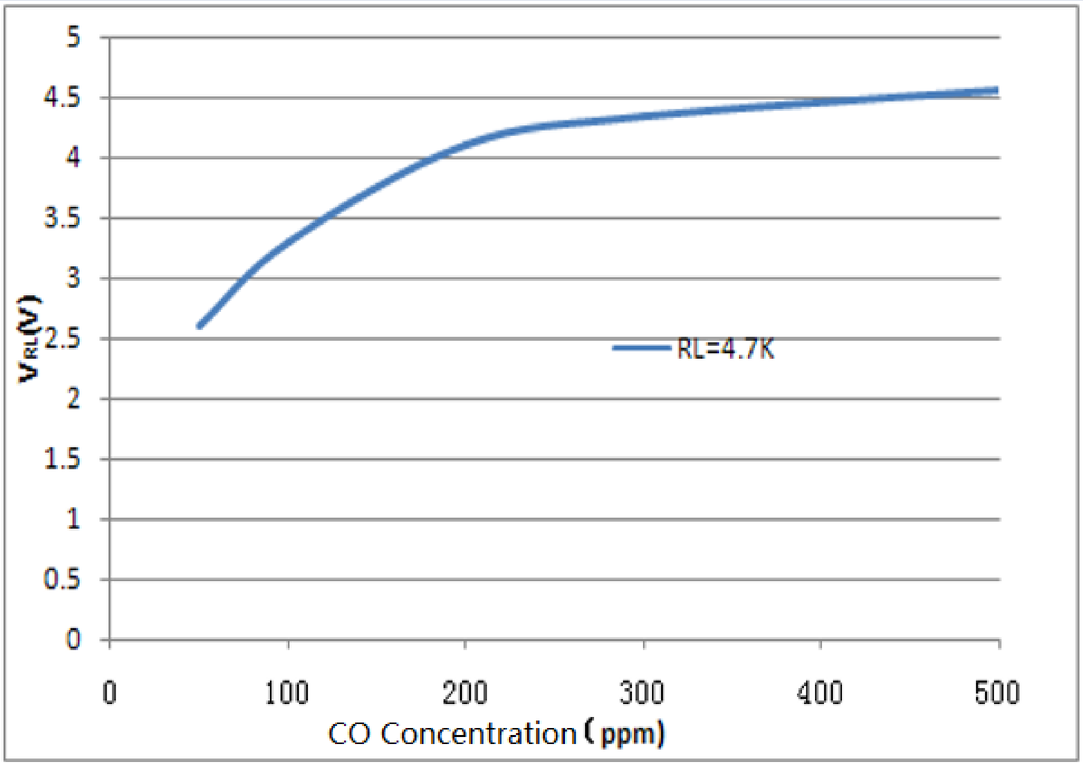

Figure 14: MQ7 Load Voltage vs. CO Concentration using 4.7K Ohm resistor [8].

Requirements and Verification

High Level Requirements and Alternative Plans

Component	High Level Requirement	Alternative Plan
MQ-7 CO Sensor (0 pt)	Off the shelf product. Assume that the output complies with documentation with similar configuration.	Using Photo Electric Sensor Or Using actual smoke alart (Preferred)
Microphone Module (12 pt)	This module should obtain captured audio and amplifies it to a 0 to 5V	
Power (5 pt)	Provides 3.3 V, 5V, and 9V power. 5V and 9V power can be switched off when not needed.	
DSP (3 pt)	Can control the alarm, can be put in low power mode and be woken up by external interrupt.	
Matlab Model for key word recognition (15 pt)	Able to recognize the key word “cooking” on PC in Matlab and print out result.	Recognize Clap Patterns on PC in Matlab (8 pt)
Key word recognition on DSP (15 pt)	Able to recognize the key word “Cooking” on the DSP, and give visual feedback.	Recognize Clap Patterns on DSP (15 pt)

Table of Requirements and Verification*

Name	Requirements	Verification
Power (5 pt)	Source 1 outputs +5±0.5 V at 1.67±0.2uA Source 2 outputs +5±0.5 V at 200±20mA when is on Source 3 outputs +3.3±0.3 V at 33±3mA when source 3 is on Source2 and source 3 output 1.25±0.1V or less when they are off	A) 1. Attach 3 MΩ resistor across source 1 as load 2. Attach multi-meter across load 3. Supply regulator with 9 V DC 4. Ensure output voltage remains 5±0.5V B), D) 1. Attach 22 Ω resistor across source 2 as load 2. Attach multi-meter across load 3. Supply regulator with 9 V DC 4. Ensure output voltage remains at or below 1.35V 5. Supply power unit input 5 V DC 6. Ensure output voltage remains 5±0.5V C), D) 1. Attach 100 Ω resistor across source 3 as load 2. Attach multi-meter across load 3. Supply regulator with 9 V DC 4. Ensure output voltage remains at or below 1.35V 5. Supply power unit input 5 V DC 6. Ensure output voltage remains 3.3±0.3V
Microphone Low Pass Filter (12 pt)	Mid band gain is 500±50 at 400 Hz Cutoff Frequency at 1024±24Hz 200 to 800 Hz should have gain 500±50 3 kHz signal should have gain at most 100±10	A) 1. Attach oscilloscope probes at pin 1 of the op amp and ground 2. Attach function generator probes at input of the low pass filter 3. Output 300 Hz sine wave with amplitude 10 mV from function generator. 4. Ensure Oscilloscope reads amplitude within 5±0.5 V B) 1. Attach oscilloscope probes at pin 1 of the op amp and ground 2. Attach function generator probes at input of the low pass filter 3. Swipe the function generator across 300 to 4000 Hz using sine wave with amplitude 10 mV. 4. Ensure the oscilloscope shows 5±0.5 V amplitude below 1000 Hz, and rapidly decreasing between after 1024±24 Hz

		5. Ensure that the oscilloscope shows below 1 V for frequencies greater than 2800 Hz
DSP (3 pt)	Receives analog input Outputs 3000±30 Hz Receives digital input and pauses alarm	A) 1. Attach function generator to pin 2 2. Output 1 Hz sine wave from function generator 3. Visually inspect that on board LED flashes at 1 Hz B) 1. Attach oscilloscope to DSP pin 14 as labeled in figure 9. 2. Power on DSP 3. Ensure oscilloscope oscillates 3000±30 Hz C) 1. Attach oscilloscope to DSP pin 14 as labeled in figure 9. 2. Power on DSP 3. Ensure oscilloscope sees 3000±30 Hz 4. Send +5V to DSP pin 10 5. Ensure that output stops oscillation
Matlab Model (15 pt)	Correct output when saying the keyword “cooking”, false negative rate below 40% Correct output when saying the non-keyword, false positive rate below 5%	A) 1. Connect microphone to the computer 2. Run the program 3. Say keyword and check whether the output is True 4. Repeat step 2 and 3, ensure the success ratio reach above 60% B) 1. Connect microphone to the computer 2. Run the program 3. Say non-keyword and check whether the output is True 4. Repeat step 2 and 3, ensure the success ratio reach above 95%
Keyword Recognition On DSP (15 pt)	Correctly stop alarm when saying the keyword “cooking”(accuracy reach 60%) Correctly keep alarm when saying the non-keyword (accuracy reach 95%) Correctly retriggers alarm when the DSP is on for more than 10 min or higher than 400±100 ppm (accuracy reach 100%)	A) 1. Turn on the program on DSP manually 2. Send a signal to DSP to indicate the CO concentration is between 70 – 150. 3. Say keyword and check whether the alarm has been shut down. 4. Repeat step 2 and 3, ensure the success ratio reach above 70% B) 1. Turn on the program on DSP manually 2. Send a signal to DSP to indicate the CO concentration is between 70 – 150.

		3. Say non-keyword and check whether the alarm hasn't been shut down. 4. Repeat step 2 and 3, ensure the success ratio reach above 90% c) 1. Turn on the program on DSP manually 2. Send 4.5V signal to DSP pin 6 to indicate the CO higher than 400ppm. 3. Ensures that the alarm retriggeres.

* The CO sensor is an off-the-shelf component, thus the RV does not test its performance and accuracy, but simply assumes that it will behave as specified on the sensor documentation.

Tolerance

The most important block in our design is the implementation of voice recognition algorithm. This is because this algorithm ultimately decides if our fire alarm will disregard a potentially life threatening condition and stop warning the user about it. Therefore, we have zero tolerance for false positives, and we never want to falsely turn off a fire alarm. On the other hand, while we strive to catch every keyword, we are certainly able to tolerance a lot more false negative, where the user may just need to shout the keyword one or two more times when fire alarm triggers. In fact, even with 60% recognition, there can be as much as 0.6+0.4*0.6+0.4*0.4*0.6=93.6% chance that the keyword will be detected in less than three tries.

Being aware of the difference in tolerance for false negative and false positive, we can make trade-off by lowering our matching threshold, thus lower overall accuracy but eliminates false positives as much as possible. Moreover, we send the CO sensor output to the DSP as well. This allows the DSP to check and calculate the precise concentration of CO in air before it turns off the alarm. This not ensures fail-safe operation in case of false positive; it also protects the user from falsely turning off the alarm or anyone from intentionally tampering with the alarm.

Secondly, the load resistor value attached to our CO sensor is crucial to the triggering of our alarm. Although we are using the 4.7 kΩ resistor as specified in the documentation, the resistor may still be off by $\pm$1%. Figure 15 shows the relationship between Rs, the sensor resistance as a function of the CO concentration in ppm, and we can estimate that:

$$\log_{10} ppm \approx 19.114\frac{Rs}{R0} + 3.25$$

Since the sensor and the load resistor are in series, and Vcc = 5 V, we can express Rs as a function of the load resistance and the measured load voltage:

$$Isensor = Iload$$

$$\frac{Vl}{Rl} = \frac{Vs}{Rs}$$

$$Rs = (Vcc - Vl)\frac{RL}{Vl}$$

Assume that R0 = RL/0.08, the sensor resistance will be roughly RL at 70 ppm, will produce an output of 2.5V, and the estimated ppm will be 51.4.

If the load resistance is 1% smaller, the output will be 2.487 V, and the corresponding Rs will be 1% larger. The estimated ppm is 49.53.

If the load resistance is 1% larger, the output will be 2.512 V, and the corresponding Rs will be 1% smaller. The estimated ppm is 53.15.

Therefore, at low ppm, the estimated ppm are close together enough that they are roughly the same. They are only off by 7% in this case, and we are able to tolerate this amount of error. Although this error will explode at higher ppm, we are not concerned about it, since the DSP will not behave any different whether it sees 400 ppm, 1000 ppm, or even more.

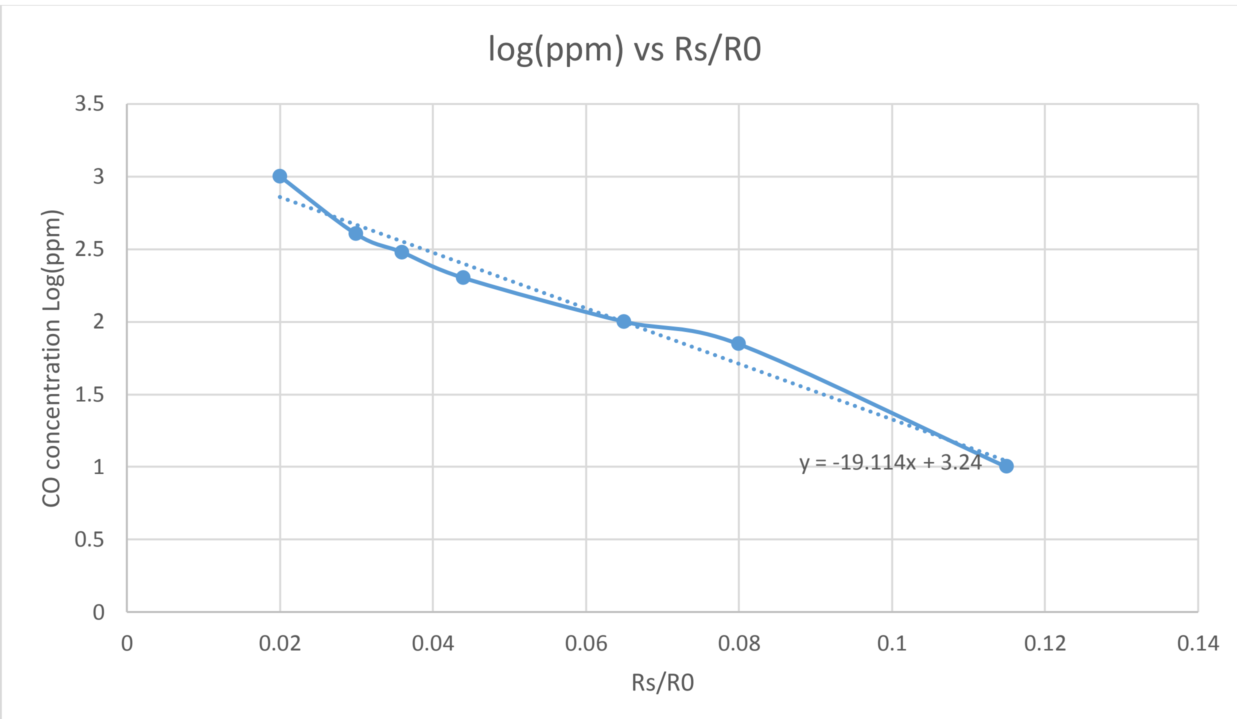

Figure 15 CO Concentration vs. Rs/R0 Ratio. Rs is the sensor resistance, and R0 is the sensor resistance in clean air

Cost and Schedule

Labor

Name	Hourly Rate	Hours	Total = Hourly X Hours X 2.5
Meng Gao	35	165	14437.5
Yihao Zhang	35	165	14437.5
Xinrui Zhu	35	165	14437.5
		495	43312.5

Parts

Parts / Parts #	Quantity	Total	Order Status
Carbon Monoxide Sensor **MQ-7**	1	5	Not Ordered
Buzzer **MCP320B2**	1	4	Obtained
Microphone **54C6**	1	10	Obtained
Digital Signal Processor **TI MSP430**	1	10	Obtained
NAND Gate **74LS00**	2	2	Obtained
Operational Amplifier **LM833N**	1	1	Obtained
Variable Voltage Regulator **LM350T**	4	4	Obtained
Resistors **360 Ω** **120 Ω** **4.7k Ω** **750k Ω** **680 Ω** **11k Ω** **22k Ω**	 3 3 1 1 1 3 1	7	Obtained
Capacitors **0.01uF** **1uF**	 5 1	3	Obtained
Total		47	

Grand Total

Section	Total
Labor	43312.5
Parts	40
Total	43352.5

Schedule

Week of, (important dates)	Tasks	Assignee
2/14 **(Eagle assignment due 2/19)**	Prepare for Mock Design Review	Everyone
2/21 **(Design Review Signup 2/22)** **(Lab safety training due 2/24)**	Prepare for Design Review Start alarm circuit design Obtain hardware	Meng Gao Meng Gao Meng Gao

	Research MFCC, DTW, and Learn Matlab	Yihao, Xinrui
2/28 **(Design Review)**	Matlab Model - MFCC and voice recognition Matlab Model - DTW Build and test alarm circuit	Xinrui Zhu Yihao Zhang Meng Gao
3/6 **(Soldering assignment due 2/26)**	Matlab Model - test, debug, and analysis Microphone circuit - communication with DSP Microphone circuit – Low Pass Filter	Xinrui Zhu Yihao Zhang Meng Gao
3/13	Implement MFCC on DSP 1)Pre–emphasis 2) Framing - Yihao Zhang 3) Hamming windowing - Yihao Zhang 4)Fourier transform Power System Update Schematic and PCB layout	 Yihao Zhang Yihao Zhang Yihao Zhang Xinrui Zhou Meng Gao Meng Gao
3/20 **(Spring Break)** **(PCB first revision 3/23)**	Spring Break: No additional work allocated Wrap up any unfinished work Get head start on later work	
3/27 **(R&V 2nd Attempt due 3/28)** **(Individual progress reports due)**	Implement MFCC on DSP 5) Mel Filter Bank Processing - Xinrui Zhou 6) Discrete Cosine Transform - Yihao Zhang Hardware integration, test, and debug - Meng Gao	 Xinrui Zhou Yihao Zhang Meng Gao
4/3 **(R&V Final Attempt due 4/8)**	Integrate, test, debug voice recognition on DSP Circuit connection functionality checking Update Schematic and PCB layout	Xinrui Zhou Yihao Zhang Meng Gao
4/10 **(Mock Demo during TA meeting)** **(Revised PCB 4/11)**	Test, Debug, fix any issues arise from Mock Demo	Everyone
4/17	Retest & prepare for demo Start on final paper(software & algorithm) Start on final paper(hardware & circuit)	Yihao Zhang Xinrui Zhu Meng Gao
4/24 **(Demo)**	Finish Final Paper(software & algorithm) Finish Final Paper(hardware & circuit) Finish Final Paper(everything else) Prepare for presentation(PPT)	Xinrui Zhu Meng Gao Yihao Zhang Yihao Zhang

Safety Statement

Lab Safety

Testing of a fire alarm will involve fire at some point, and this poses a safety issue in the lab. As such, all the testing that involves fire must be done outside in an open space with no explosives around.

For laboratory testing, we are implementing a test switch that allows us to trigger the alarm without actually starting a fire. We can also use a function generator or DC power supply to simulate the sensor signal in accordance to the voltage vs. ppm characteristics on the documentation of our off-the-shelf CO sensor. All the testing in lab should use one of these methods to test our design.

In addition, members should complete the lab safety training to protect themselves with other common lab safety factors such as electricity.

Product Safety

Users should be aware of the danger of fire. Sound controlled smoke detector provides a means for users to exercise their own judgment and easily discard false alarms. However, whenever the alarm sounds, it indicates a potential safety concern. Whether the alarm is due to actual fire, cooking, or any other reason, appropriate actions should be taken to remove the safety concern.

To make a safer product, the DSP will continue to monitor CO level after alarm is turned off. If CO level is above 400 ppm, or above 150 ppm for more than 10 minutes, the situation will be considered sign of immediate life threat [3], thus alarm will retrigger regardless of user action. If alarm sounds again, immediately move outside to fresh air and call 911 [9].

Ethics:

1 - 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;

> When making design decisions, we will always consider the failure cases. Thus, our DSP is aware of the CO sensor output and its uptime, and takes these into account when making decisions.
>
> We will not only disclose the danger of turning off fire alarms, but also take into consideration that the alarm can be turned off by user who did not realizing the danger.

3 - to be honest and realistic in stating claims or estimates based on available data;

> We will be honest about our testing method and accuracy in fire detection and key word recognition.

5 - to improve the understanding of technology; its appropriate application, and potential consequences;

> We will continue to evaluate the application and potential consequences of our smoke alarm.

7 - to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others;

> We will continue meeting with our assigned TA every week to seek help and suggestions. When using off-the-shelf hardware components or software libraries, we will cite and credit the respective IP or copyright owners. The algorithm that we will implement will also be credited to the relevant owner.

9 - to avoid injuring others, their property, reputation, or employment by false or malicious action;

When testing our design with fire, we will take caution to not injure others, their property, reputation, or employment.

10 - to assist colleagues and co-workers in their professional development and to support them in following this code of ethics.

Our team members will work together and assist each other in our professional development and to support each other in following the ethics.

Citation:

[1] "Active Low-Pass Filter Design", Texas Instruments, Dallas, Texas. 2015. Available: www.ti.com/lit/an/sloa049b/sloa049b.pdf. [Accessed 2 March 2016]

[2] Adhar Labs, "RETRIGGERABLE 555 TIMING CIRCUIT: AN INTERESTING FIND", 2013. Available: m8051.blogspot.com/2013/02/retriggerable-555-timing-circuit.html. [Accessed 16 February 2016]

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