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INDOOR AIR QUALITY MONITOR

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ABSTRACT
This project focuses on the development of an air quality monitor that is able to gather and record several environmental parameters that may be produced as a result of cooking or heating. The air quality monitor in use before this project only collected data on the amount of particulate matter in the air and the temperature. The Indoor Air Quality Monitor developed as a result of this project measures particulate matter and temperature as well as humidity and detects Carbon Monoxide (CO) presence. This gives the user more insight into the testing environment for later study. After extensive testing of the Indoor Air Quality Monitor, it was found that it met or surpassed engineering requirements for the device. The work conducted to develop this monitor can be improved upon in future RIT projects, utilizing the groundwork laid out by this project.

INTRODUCTION
Public health researchers have been using air quality monitors to monitor the exposure of citizens of developing countries to airborne contaminants produced from cooking and heating homes. Haiti and Kosovo are two primary areas of focus for our customer because of the general lack of proper heating fuels in these areas. When burned openly, materials such as charcoal, wood, coal, and construction debris have the potential to produce gases that are hazardous to humans. Using the UCB-PATS and other existing air quality monitors, researchers are able to track PM (particulate matter) and temperature over a 5 day period. This data is used to help understand exposure and educate families on the benefits of using appropriate cooking and heating materials, as well as other practices such as ventilation during food preparation.

However, the researchers were not completely satisfied by the existing monitor technology. Our senior design project was established to support this research effort through the development of a new air quality monitor intended to better suit the researchers' needs, including an increase in the number of parameters. This included humidity and CO (Carbon Monoxide) levels, and increase the length of time that data could be collected.

PROCESS
The process that was followed in the design and execution phases of this project involved the documentation of customer needs, specifications, brainstorming, risk assessment, and Pugh concept selection to arrive at a complete system design. From there, the design was continued to the detailed level where specifics were determined including selection of sensors, detailed part drawings, a PCB (printed circuit board) layout, and a bill of materials. Later, a prototype was built and tested with documented assembly instructions and a user manual.

In a meeting with the team's customer, our team learned what data was being collected (particulate matter, temperature) using an existing monitor known as UCB-PATS (University of California Berkley – Particulate and Temperature Sensor) and how this monitor could be improved upon to meet the needs of public health researchers. These points formed the basis of our customer needs, including improving battery life, collecting humidity data (used to determine the effects of particulate matter on the lungs), and improving the user interface (UI) to make the software program easier to use. The researchers wanted to continue monitoring temperature and particulate matter, but were interested in other parameters such as CO, NOx (Nitrogen Oxide Gases), and SOx (Sulfur Oxide Gases).

Although there was an investigation to include nitrogen oxide and sulfur oxide sensors for a new monitor, both of these were found to be outside of scope because of limited funding, a desire to offer a low cost monitor, and low prevalence in the environment with low expected health impact. Because of the availability of CO monitors and detection, a CO sensor was included in the final product design. The customer needs that are shown in Table 1 were then confirmed with our customer to assure that all parties agreed on what was critical and desired in the final design.

Air Quality Monitor - Senior Design Project P13625		
Customer Need #	Importance	Description
CN1	9	Tracks and Records CO
CN2	9	Tracks and Records PM
CN3	1	Tracks and Records NOX
CN4	1	Tracks and Records SOX
CN5	9	Tracks and Records Temperature
CN6	9	Tracks and Records Humidity
CN7	9	Accurately records time with a high degree of precision
CN8	3	Records geographic location
CN9	9	Is sensitive to small changes in pollutant levels or environmental factors
CN10	9	Sensors have a high sampling rate (0.5-1 sec)
CN11	3	Variable sample rate
CN12	9	Stores and compiles data on user exposure over time to allow researchers to compile data
CN13	3	Monitor is stylish/unobtrusive
CN14	3	Footprint of monitor similar to UCB monitor
CN15	9	Housing and components resist damage from shipping/installation
CN16	9	Is reasonably priced for public health researcher use
CN17	9	Operates without user action for at least a week
CN18	9	Electronics need to resist local environmental factors in operating area
CN19	3	Battery is rechargable
CN20	9	Same device can be used repeatedly and in different environments
CN21	3	Syncs with mobile device for gathering recorded data
CN22	9	Gathered data needs to be able to be exported in a quantifiable way for the public health researcher
CN23	9	Able to install on varying interior home materials
CN24	1	Visually display gas levels
CN25	1	Ability to be left behind for homeowner's use

Table 1: Customer Needs Table. The importance of a customer need is ranked 1, 3, or 9. (9 is greatest importance)

After the customer needs were outlined, the team was able to move to developing specifications for the design (shown in Table 2). The specifications were created to outline what was most important to the final design and how the team could quantitatively measure and check the customer needs. To reach a system level design, the team completed several brainstorming exercises and Pugh selections to determine all major components that should be included in the monitor. These selections included sensors, case materials, basic shape and size of monitor, and a power source.

The team then began to work as two separate teams: one focused on the software and electronics (Electrical Team), and the other focused on the structure of the assembly (Mechanical Team). The Mechanical Team began to assess how the internal parts of the monitor should be organized and how the overall device should be constructed and subsequently assembled. Sensor location within the case was an early question that needed to be answered to ensure that data could be collected reliably from the environment and without endangering any of the electrical components. After speaking with several Mechanical Engineering professors and our faculty advisor, sensor location within the monitor would have no significant impact on sensor readings.

Once the decision had been made on the location of the sensors, the team began work on how to hold the remaining components inside the case and still allow user access to the batteries and be able to retrieve data. The final design incorporates a stack or “sandwich” that allows all of the internal components to be removed as a singular piece. This would allow the device to be easily repaired by a skilled technician, and also allow the device to be installed in different cases if the PVC box chosen for the design was unavailable.

Also discussed were different techniques for mounting and where the sensor would be placed in homes for testing. Velcro and similar adhesives were discussed, along with string and other hanging devices such as S-hooks, screws, or nails. The team felt that multiple methods of hanging the device would allow it to be used in a greater number of home environments.

Test #	Spec. #	Original Spec. #	Importance	From CN	Specification (metric)	Unit of Measure	Marginal Value	Resolution	Ideal Value
#1	S1	S1	9	1	Range of CO levels measured	ppm	Boolean output		Range: 0 - 2000
	S2	S2	9	1, 9	Accuracy of CO measurement	ppm	+/- 100	5	+/- 20
#2	S3	S3	9	2	Size of Particulate Matter captured to measure	µg/m^3	50	5	30
	S4	S4	9	2, 9	Accuracy of Particulate Matter measurement	µg/m^3	+/-10	5	+/-5
	S5	S9	9	6	Operating Humidity range for measurements	%RH	0 to 95%	+/- 5%	0 to 100%
	S6	S10	9	6, 9	Accuracy of Humidity Sensor	+/- %RH	+/- 5%		+/- 0.1%
	S7	S11	9	5	Range of temperatures captured by Temperature Sensor	°C	-5-45°C	1	-15-55°C
	S8	S12	9	5, 9	Accuracy of Temperature Sensor measurement	+/- °C	+/- 2		+/- 0.1
	S9	S25	9	18	Operating Humidity Range for continued monitor use	% Humidity	0 to 95%	+/- 5%	0 to 100%
	S10	S26	9	18	Operating Temperature Range for continued monitor use	°C Temperature	-5-45°C	1	-15-55°C
#3	S11	S13	9	7	Fidelity of time stamp during data measurements	+/- s	10	1	1
	S12	S15	3	10	Frequency of Data measurements taken during operation	Seconds	=60	1	=1
#4	S13	S17	9	12	Hours of Data Stored by Monitor	Hours	120	1	240
	S14	S24	9	17	Amount of time between user-monitor interaction while device is recording (turning it on, syncing, etc.)	Hr	>120	0.5	>240
#5	S15	S18	3	13	style and appearance: % of surveyed researchers who reported the monitor as 5 or better for style on a scale of 1-10	%	50	1	>70
	S16	S29	9	22	software use: % of surveyed potential user that rated the ability to use software as 5 or greater on a scale of 0-10	%	50	1	100
	S17	S32	9	23	installation: % of surveyed researchers who reported the monitor as 5 or better for installation ability on a scale of 1-10	%	50	1%	100
#7	S18	S28	3	21	Time required to sync with mobile device to gather data (Android/iOS)	seconds	10	0.5	5
#8	S19	S30	9	23	Monitor is able to be installed on different surfaces	number of surfaces	1	1	>3
#9	S20	S19	3	14	Footprint of monitor	cm^2	<400	0.5	<115
	S21	S20	3	14	Height of monitor off of mounting surface	cm	<20	0.5	<6.5
#10	S22	S23	9	16	Cost of the monitor to the customer (Public Health Researchers)	$	<$650	$1	<$500
#11	S23	S31	9	20	Device can be used repeatably	number of uses	2	1	>10
	S24	S36	9	20	Lifetime of sensors within the monitor	months	12	1	24
	S25	S37	9	20	Overall life expectancy of the monitor and all of its internal components	months	12	1	24

Table 2: Specifications

The Electrical Team simultaneously worked to define what needed to be incorporated into the monitor to reduce power consumption and ensure proper power distribution as well as provide signal processing for the sensors. This work began with attempting to reverse engineer the UCB-PATS monitor. Unfortunately, the UCB-PATS sensor was not in full working condition and was also missing supporting documentation which could not be found online. Due to time constraints, it was decided that reverse engineering would not contribute to a timely, finished product. Several possible 'from scratch' design options were discussed, but after careful power consumption analysis and circuit layouts were made, the team decided to create the electrical system based around an MSP-430 microcontroller.

The Electrical team decided to use a 16-Bit ultra-low power MSP-430 Microcontroller to serve as the brains of the sensor. The hardware and free software that comes with the MSP-430 'LaunchPad' would mean that it would be an easy-to-use and cost effective development option for this application. The microcontroller also came with boards that expanded its functionality to enable more options, which was beneficial in the design and debugging stages.

Using the MSP-430 microcontroller as our foundation, sensors were chosen that could easily communicate with the microcontroller's input and output pins. There are many types of sensors out on the market that come in different forms and sizes, many using different measurement methods to track the same parameters. The major decision in the planning stage was whether to purchase digital or analog sensors. Analog sensors communicate with the microcontroller by sending an electrical voltage along the connection. By measuring where the voltage falls between 0 and the maximum of 3.3 volts, the MSP-430 will have to interpret the voltage as a numerical value. It is difficult to send and maintain an exact voltage so the output would need to be filtered to prevent noise and this final value would need to be regulated to comply with the maximum level that the microcontroller could withstand. Because the number of analog-to-digital usable ports in the MSP-430 relative to usable analog inputs is so high, the temperature and humidity sensor, the CO Sensor, and the particulate matter sensor all required digital outputs to make programming and debugging easier.

The customer expressed the desire to increase the data collection interval, so a period of ten days was selected as the goal for a redesigned monitor. The device would need to remain powered during this period at all times, possibly toggling sensors to conserve power over the duration of data collection. When the sensors are toggled, the period is divided into two sub-periods: operating and standby. During the operating period, all components are drawing power simultaneously to run the microcontroller, the sensors, and other components. Also during this time, the microcontroller is collecting data from the sensors and simultaneously writing this information on the SD card.

This collecting and writing process occurs for only a fraction of a second, but needs to occur at a time interval that can be adjusted between 1 second and 1 minute. During the majority of this downtime, the monitor enters a standby mode to conserve power. An indicator LED on the monitor is always on to indicate that the overall monitor is turned on, although most of the components are off and the voltage regulators are in a standby state. The voltage regulators mitigate the amount of allowable voltage to the sensors to ensure that there is no surge, and always have a current passing through them. Based on the datasheet of these regulators, the standby current of a 5V regulator is 0.0055A, and the standby current of a 3.3V regulator is 0.01A. This would mean that the power consumed by the 5V regulator in standby would be 20mW, while the power consumed by the 3.3V regulator in standby would be 57mW. Though this is significantly less than during the operating period, power loss during monitor operation is inevitable.

The software for this system was designed to accurately read, record, and retrieve information that was being collected by the sensors in this device. Each sensor produces readings in a different way. The temperature and humidity sensor use a synchronous line and a data line to communicate with the controller. This was done by bit-banging on the determined port to send and receive information. The particulate matter sensor constantly produced a Pulse-Width Modulation (PWM) wave that when the ratio of high time to low time was measured, an accurate representation of the particulates in the air could be determined. The CO sensor was calibrated using two potentiometers which are used to determine that level at which the CO sensor would alarm. Instead of providing a value for the amount of CO detected in the air, the CO sensor functions by displaying when CO is present above a configured value.

The user-interface (UI) for this device is a basic command line that connects through a serial terminal. The current software that we use for creating the serial connection is called PUTTY, but any other serial communication software could be used. The UI has the ability to read live data from the sensors, record data for a determined about of time and display data that has been saved on the chip. Future developments for this device would include a software platform that would be able to provide more information on the collected data.

ELECTRICAL SYSTEM

The system requires 9V power supply to operate because of the dropout voltage of the 5V regulator in the system. Because the dropout voltage is 2V, this means that the voltage difference across the regulator should also be 2V. According to the data sheet for the regulator, 9V would be appropriate for the system to ensure that the regulator will never turn off. Initially, a single 9V battery was taken into consideration for the power supply. With the 9V battery the system seemed to operate well, except the working period was undesirably short. This is due to the low battery capacity of the 9V battery. Even combining two 9V batteries in parallel was not sufficient enough to provide enough battery capacity to hold itself for the device’s working period. After research was conducted, it was determined that AA type batteries have a larger power capacity. Unfortunately, AA batteries only carry 1.5V. As a result, in order to achieve 9V, two sets of six batteries in series were combined in parallel. This caused the batteries to occupy more space in the device, but seemed to provide the necessary battery capacity. Using twelve AA batteries, the battery capacity was calculated to be 6000mAh with 335mA effective current. This new capacity is sufficient to provide power for the duration of the working period. After building the monitor physically, the operating current was measured. The operating current was found to be 148mA instead of 335mA, which increased the effective capacity to 6000mAh.

The comparison between the theoretical and actual battery calculations has been listed in the table below. Based on the calculation done for the power consumption and the battery capacity, the duration of battery at continuous operation mode has been calculated.

Battery Type	Voltage of Individual Battery	Capacity	Battery Combination	Effective Capacity	Total Battery Voltage	Time to discharge
Energizer AA (Theoretical)	1.5 V	Rated 2000 mAh at 335mA discharge	Set 6 batteries in series connected in parallel with another set of 6 batteries in series	4000 mAh at 335mA	9.0 V	12.0 hrs (@335mA)
Energizer AA (Actual)	1.5 V	Rated 3000 mAh at 148 mA discharge	Set 6 batteries in series connected in parallel with another set of 6 batteries in series	6000 mAh at 148 mA	9.0 V	40.5 hrs (@148 mA)

Table 3: Battery Comparison between theoretical and actual power consumption

Examining the sensors, the analog output of the CO sensor is driven though an operational amplifier. Using this, the voltage is kept between the 0V to 3.3V range which is then driven into the microcontroller. The input to the CO sensor is active high. Using a transistor the CO input pin value is set. To do this, a NPN transistor is driven by the output pin from the microcontroller. The output pin from the microcontroller supplies a voltage using a resistor at the base, which introduces a current flow. The base to collector current will determine what the input to the CO sensor should be.

After some team discussion and consultation of the sensor data sheets, it was determined that while the electronics will be hot, they are fairly small and will not dissipate large amounts of heat into the monitor. Computational Fluid Dynamics (CFD) calculations or other thermo-analysis was not deemed necessary in order to proceed.

Along the way other alterations had to be made to the project as well. These alterations were typically to keep the scope of the project within our means of designing and prototyping a working monitor by the end of this senior design project. Some of these alterations included the removal of an option to remove data from the monitor via an Android phone or tablet to be transferred through email to a computer. Other alterations were time and safety related such as calibration and testing of the monitor's ability to detect CO, a test which the team determined to be too dangerous without the proper facilities.

During the course of this project there were several assumptions that were made to help us along through the project. Some of these assumptions were that the static that is held by the PVC conduit box. Also assumed, for mounting purposes, is that the difference in the air flow in the testing environment is the same regardless of the position of the monitor relative to the wall or ceiling that it is mounted on.

RESULTS

This design process led the team to come up with a final system design that included two sheets of acrylic, one to hold the sensors, to act as a UI, and a PCB to act as a central hub for all of the electrical components. These square "levels" were then held together and aligned by placing 4 threaded rods in each corner, with rubber tubing to act as spacers and secured with nuts to hold the 'core' components. This core was then fastened to the case exterior by using four screws that attach it to two sides of the box, utilizing L-brackets fastened to the acrylic pieces to create a mating surface.

The goal in mind, while determining the power distribution, is to make the system more efficient. According to the customer's needs, the system should be able to complete one working period, of a length of ten days, using one set of batteries. During the operating period the total operating current used by the system is 335mA, consuming 3.015W of power. If the system happens to operate continuously without any interval, the battery selected would keep the system in operating state for 9 hours. Rather than operating in a continuous on state, the monitor gathers data at a preset interval. The operating period has been estimated to be a fraction of a second, where rest is the standby period until the next operating period has been initiated. The time interval between the start of the two operating periods, or the approximate length of the standby period, is one second. This assures that the system would supply power efficiently for the ten days of working period.

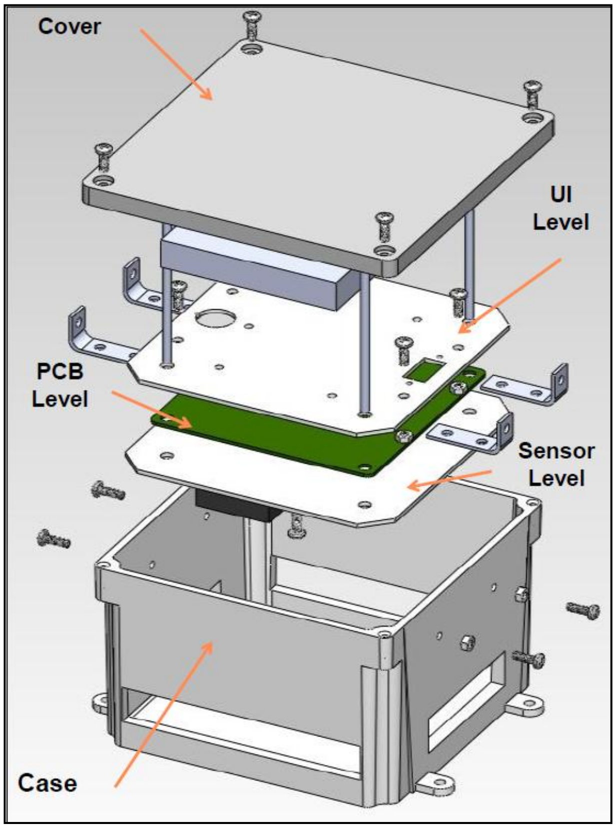

Figure 1: Final Design

Once built, the monitor was tested to assure that the finished product was capable of meeting the specifications that were developed from the customer needs. The specifications that are related to each of the tests are shown in Table 2 and a more detailed description of each of the tests is shown in Table 3. Overall, each of the tests that were conducted was successfully completed. Tests number 1 and 6 were not completed due to safety concerns and concerns about the fragile nature of the sensors in the monitor.

The environmental test was conducted by exposing the monitor to varying humidity, temperature, and CO levels. The measurements with the monitor were taken in defined intervals and were synchronized with a timer in order to verify that the data gathered was consistent with the present weather conditions. Gathered results were transferred from the monitor to a computer, where it was uploaded to excel and the resulting plot is shown in Figure 2.

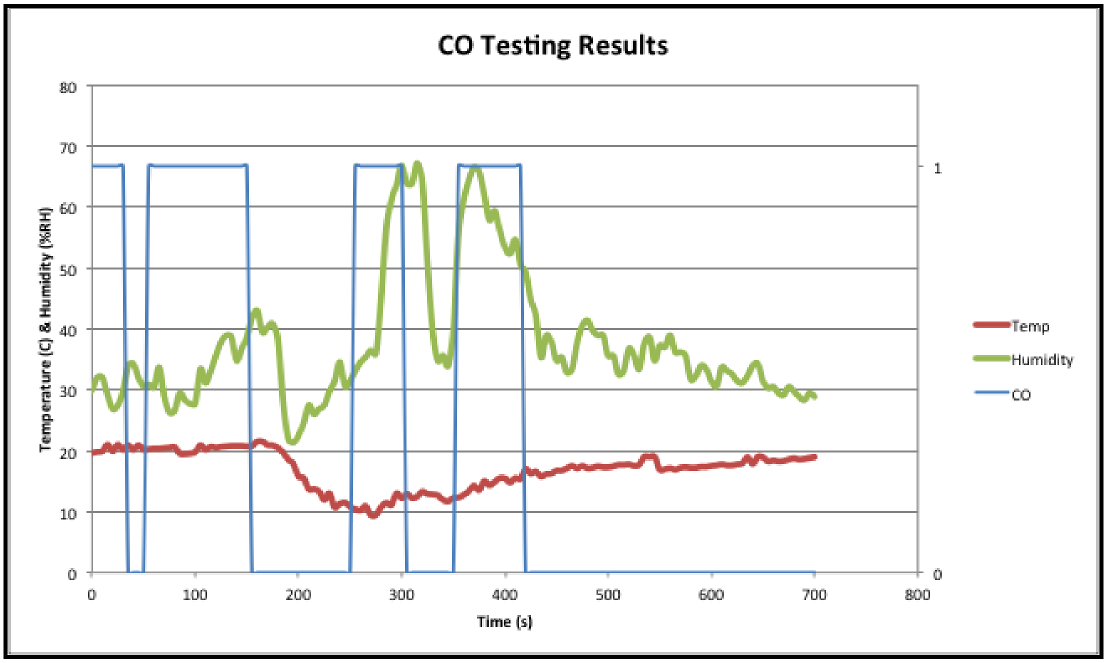

Figure 2: Environmental testing results

Test #	Title	Results	Comments
1	CO Sensor Calibration	*(not conducted)*	Test was not conducted due to lack of safe testing facilities and the potential health hazards to team members
2	Environment	*(Passed)*	
3	Microcontroller Sensor Communication	*(Passed)*	The reading and acknowledgement means that a single reading can be done in 13 ms (77 readings per second)
4	Monitor Endurance	*(Passed)*	While the monitor failed a live test due to software issues, the theoretical life span of the batteries is 9.1 days
5	Survey	*(Passed)*	There were 21 surveys completed to compile data on the style and usability of the Indoor Air Quality Monitor. All of the survey points resulted in a average between 7.6 to 8.3 (on a scale of 1 to 10).
6	Drop	*(not conducted)*	The drop test was not completed at this time due to the fragile nature of the sensors within the monitor
7	Computer Interfacing Time	*(Passed)*	The monitor transfer a complete set of data in approximately 6.5 seconds
8	Mounting	*(Passed)*	The team was able to test and document 5 different ways of mounting the monitor to various surfaces
9	Footprint and Height	*(Passed)*	The footprint and height of the monitor are 229.3 cm^2 and 10.95 cm respectively, which falls into our specifications of 400 cm^2 and 10 cm
10	Cost Analysis	*(Passed)*	The total cost of the monitor is $435 (parts and labor)
11	Reusability	*(Passed)*	The expected lifetime of the monitor (determined by individual component life expectancy) is approximately 2.28 years

Table 3: Summary of tests

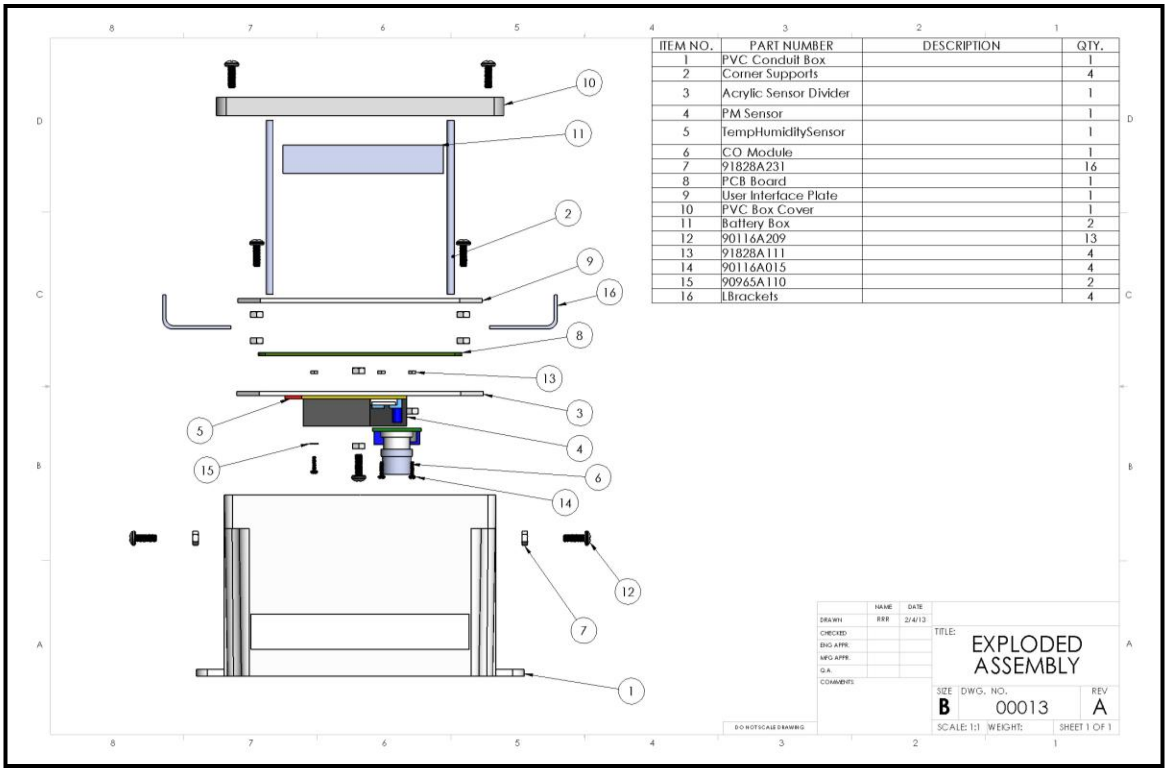

Figure 3: Exploded view of monitor with the bill of materials.

CONCLUSIONS

While the final goal of this project in the end became a high level pass at what can be done to create better research tools for health researchers, it is reasonable to produce, in low volumes, air quality monitors that record more data at a cheaper price than the UCB-PATS. We were able to successfully build 2 separate prototypes that functioned and were used in the different test. We were able to easily manufacture the different components with the available machining capabilities.

One of failures one this project were lack of complete testing. There was not the capability to control a testing environment with all of the different factors that are able to be precisely controlled. Another failure of the project was not completing an independent software program that is able to display and analyze the data collected by the monitor. The memory card was not fully integrated into the electronic circuit and therefore the storage capacity of the monitor was limited to what the microcontroller could store.

FUTURE IMPROVEMENTS

While this monitor may not be completely field-ready, the system design was validated allowing for future work to be more focused on specific sub-systems of the monitor. It is the opinion of the team that future iterations of this project should focus on several key aspects that show potential to greatly increase the level at which the monitor can operate. These aspects include, but are not limited to, the battery life of the monitor, the accuracy and precision of the PM data collected, and the type of CO data collected.

Alterations involving the battery life should look at power consumption of the device as a whole and ways to limit what is consumed as well as optimizing power usage by optimizing circuitry as well as software design.

While the Shinyei PM sensor that was chosen for use in this iteration of the monitor is an optical sensor based on the number of particles that pass through a beam of light over a specified period of time, alternatives for this method such as ionization type sensors should be explored.

The current CO sensor that is used in the monitor is not capable of measuring continuous data or even measuring but rather outputs a Boolean signal as to whether or not a predetermined level of CO has been exceeded. Future teams should look to either remove the sensor from its breakout board to enable the CO sensor to capture more detailed data or to replace the current sensor with one that has more desirable function.

Lastly affecting almost every aspect of this project was the team's inability to properly test the monitor. It is the team's collective thought that the monitor should be able to be tested in an all-inclusive manner where temperature, humidity, PM, and CO can accurately and precisely be varied to simulate home environments for the monitor. No testing facility available to the team has this capability and it has the potential to have the greatest impact upon the project if more data can be collected so that the monitor's performance can be looked at more objectively to find areas of improvement.

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10) Microcontroller, http://www.ti.com/lit/ug/slau144i/slau144i.pdf

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