Wearable Air Quality Monitor

ECE 445 Design Document – Fall 2024

Project # 26

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1. Introduction

Problem:

Air pollution has emerged as one of the most significant health issues of the twenty-first century worldwide. According to the World Health Organization (WHO), 9 out of every 10 individuals on the planet are exposed to polluted air. Typical pollutants are particulate matter (PM2.5), nitrogen dioxide (NO2), sulfur dioxide (SO2), and Formaldehyde. They can all have major health impacts, like respiratory disorders, and cardiovascular issues. Long-term exposure to dirty air has been related to chronic illnesses such as asthma, lung cancer, and heart disease.

People often change residences frequently and when renting a house, they are unaware of potential indoor air hazards. Renters, especially in newly renovated homes or apartments with poor ventilation, may unknowingly be exposed to this toxic chemical, leading to long-term health complications without proper air quality monitoring. Although this issue is quite severe, the public lacks a method to know the real-time air quality in the living environment. The data provided by the government, or the phone apps, is not accurate since the environment is changing. Such as staying in the bedroom, walking down the street when traffic peaks, or passing by a neighbor's house that is being renovated. Moreover, while air quality monitors can help with the issue, they are normally expensive and not portable. They are usually set at a fixed place on the wall and hard to notice. Despite that, these stationery monitors often provide limited information which may cause people to have a false sense of security or may not be fully informed about the varying level of pollution they encounter during the day. Thus, there is a clear need for a more affordable, portable and comprehensive solution that empowers individuals to monitor the air quality in real-time, regardless of their location.

Solution:

We propose a **Wearable Air Quality Monitor** to address the need for affordable, portable, and comprehensive air quality monitoring. This device will track key air pollutants such as **Particulate Matter (PM2.5, PM10)**, **Carbon Dioxide (CO2)**, and **toxic gases like Carbon Monoxide (CO), Nitrogen Dioxide (NO2), and Formaldehyde**. The monitor will connect to smartphones via Bluetooth or Wi-Fi to provide users with real-time data and notifications. We aim to make the device affordable to a wider audience by making the price between $50-80. The wearable nature allows users to monitor air quality wherever they want, and the device will offer guidance for user's behavior, such as wear a mask or avoid outdoor activities when pollution levels are high.

Visual Aid:

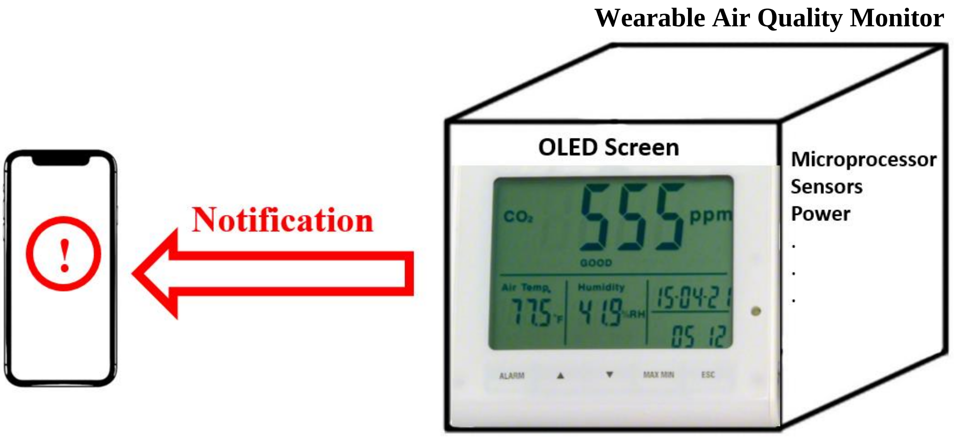


Figure 1: Visual Aid for our Device

Figure 2: Conceptual blueprint (Generated by Midjourney)

Figure 3: Clip at the back of our device for backpack/belt

High-level Requirements:

- The device must be able to detect and measure **PM2.5, PM10**, and **CO2** levels with an accuracy within **±10%** of common market air quality monitors.
- The toxic gas sensors for **CO**, **NO2**, and **Formaldehyde** must trigger alerts when gas concentrations reach harmful levels. We could test this by putting our device in a sealed container, and then fill the container with toxic gas.
- The device must be portable, with less than 500 gram's weight, and should maintain a stable Bluetooth or Wi-Fi connection with a smartphone within a **5-meter's range**.
- See each subsystem for more detailed high level requirements

2. Design

Block Diagram:

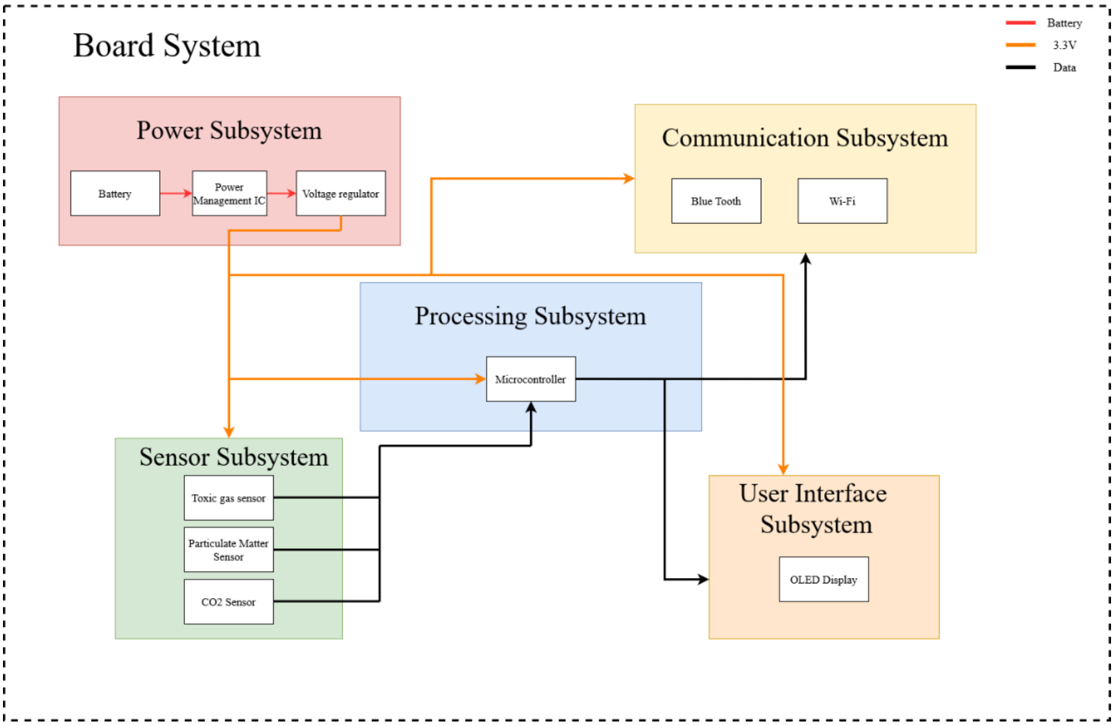


Figure 4: Block diagram for our device

Physical Design (Interior):

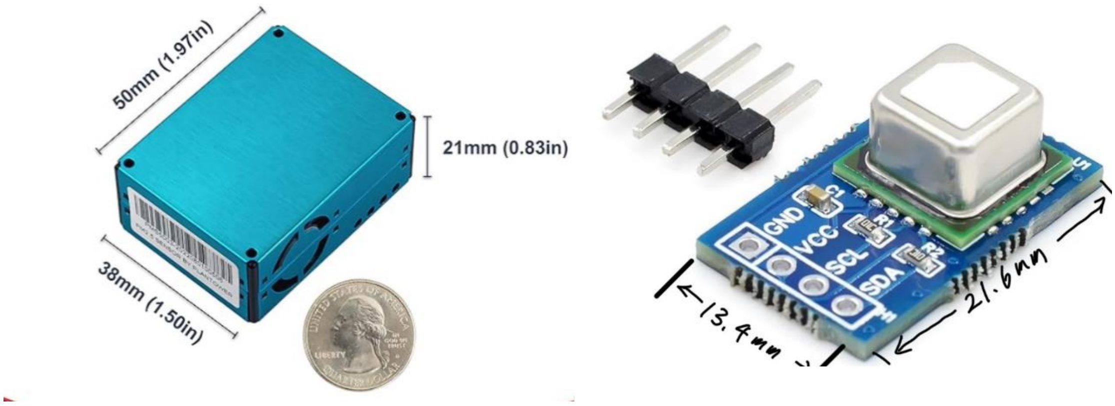


Figure 5: Dimensions for PM2.5/10 (left) and CO2 (right) sensor

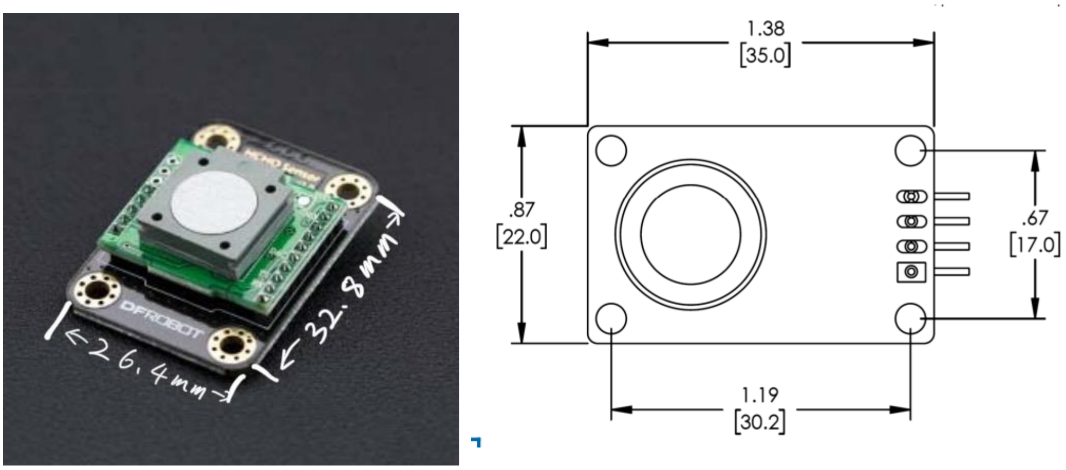


Figure 6: Dimensions for formaldehyde (left) and CO (right) sensor

Sensor Placement:

PM2.5/10 Sensor: Near the side vents for direct air sampling.

CO, CO2, Formaldehyde Sensor: Other side of the vent for direct air sampling

Temperature and Humidity Sensor: At the rear side of our device to avoid contact with battery/microprocessor/human body, ensuring reliability of data.

Processing Unit: Centrally located for heat management and efficient connections to sensors and display, avoid contact with any other components for correct readings.

Battery: Positioned to distribute weight evenly and maximize device longevity

LED Screen: Front side of the device, with air quality data displayed on it.

Exterior:

Figure 7: Conceptual blueprint (Generated by Midjourney)

The wearable air quality monitor is designed as a compact, portable device with a clip at the back. The overall dimensions should be about 18cm x 10cm x 5cm, having a balance between portability and functionality. The size should allow for easy carrying while accommodating all necessary components. The shape should have box-like design with rounded corners for a modern feel, the exterior should be smooth, and minimalist. Finally the material should be 3d-printed lightweight plastic.

Front Face: LED screen with air quality data displayed on it.

Back: Has a durable clip for attaching to backpacks, belts, or other items

Sides: Small, strategically placed vents on both sides of the device for accurate air quality measurements.

Top: An easily accessible power button for turning the device on/off. USB-C or similar ports for convenient charging

Subsystems

1. Sensor Subsystem

The sensor subsystem is the core of our air quality monitor, hence I will focus more on explaining this part. This subsystem is responsible for collecting accurate environmental data. It consists of multiple gas sensors, each designed to measure specific air quality parameters. These sensors are integrated into the main board. Also each position is being calibrated to meet best performance.

Components:

1. PM2.5/PM10 Sensor: PMS5003
   - Function: Measures particulate matter (PM2.5 and PM10) in the air
   - Accuracy: ±10μg/m³ @ 0-100μg/m³; ±10% @ 100-500μg/m³
   - Size: 50mm x 38mm x 21mm
   - Power Consumption: <100mA average
   - Interface: UART
   - Special Features: Built-in fan for active air sampling
   - Power Supply: DC 5V ±0.5V
   - Working Temperature Range: -10~+60°C
   - Working Humidity Range: 0~99%
2. CO2, Temperature, and Humidity Sensor: Hiletgo SCD41
   - Function: Measures CO2 concentrations, temperature, and relative humidity
   - Size: 13.4mm x 21.6mm
   - CO2 Range: 400-5000 ppm
   - CO2 Accuracy: ±5%
   - Temperature Range: -10°C ~ 60°C
   - Temperature Accuracy: ±0.8°C
   - Humidity Range: 0-100% RH
   - Humidity Accuracy: ±6% RH
   - Interface: I2C

    - Power Supply: DC 5V
    - Power Consumption: <0.4mA average
3. Formaldehyde Sensor: DFRobot SEN0231
    - Function: Detects formaldehyde levels
    - Range: 0-5 ppm
    - Resolution: 0.01 ppm
    - Size: 38mm x 28mm x 15mm
    - Power Supply: 3.3-6V
    - Interface: Analog output
    - Working Humidity Range: 15%-90% RH
    - Working Temperature Range: -10~60°C
4. Carbon Monoxide (CO) Sensor: L-com SRAQ-G012
    - Function: Detects carbon monoxide gas
    - Detection Range: 10 - 10,000 ppm
    - Power Consumption: ~10mA
    - Power Supply: 5V±0.2V
    - Working Humidity Range: <95% RH
    - Working Temperature Range: -10~50°C

Operational Requirements:

- Pick the minimum and maximum operating temperature/humidity of each sensor, we decide that our sensor should operate within temperature range of -10°C to 50°C, and humidity range of 15%-90% RH. This would ensure accurate measurements for every data.
- Before put everything into use, we might need to calibrate some of the sensor, particularly for the SCD41, to maintain long-term accuracy.

Integration:

- The PMS5003 & SCD41 sensor is positioned near the sides of the air intake vents to ensure proper airflow for accurate data.

- The temperature/humidity sensor is placed so that it has good air circulation but protected from direct airflow to prevent temperature fluctuations. Also it should avoid contact with the microprocessor and human body.
- The SEN0231 formaldehyde sensor and SRAQ-G012 CO sensor are positioned directly against vents to minimize the response time for toxic gas.

Data Collection and Processing:

- Sensor readings are collected at a constant intervals (e.g., every 15 seconds) to provide real-time air quality data.
- Raw sensor data is processed by the microcontroller to convert readings into human readable data.
- The processed data is then reflect on the device's LED screen and transmitted on to user’s phone.

Alert System:

- The software includes adjustable thresholds for each measured parameters.
- When any parameter exceeds its safe threshold, the device triggers an alert, which will be displayed on the LED screen and sent as a notification to the connected smartphone.

Requirement	Verification
The PM2.5 and PM10 sensors must detect particulate matter levels within ±10% accuracy.	Place the device in a controlled environment with known particulate matter concentrations and compare readings with a commercial sensor. Ensure the error margin is less than ±10%.
CO2 sensor must measure concentrations up to 5000 ppm with ±10% accuracy.	Test the sensor in a sealed container filled with CO2 gas at varying concentrations. Compare the readings with a commercial sensor and verify the accuracy is within ±10%.
CO, NO2, and Formaldehyde sensors must trigger alerts when concentrations exceed safe levels.	Place the sensors in a controlled gas chamber and increase desired gas concentrations. Verify that alerts are triggered at predefined safety thresholds.
All sensors must function accurately in temperatures ranging from -10°C to 50°C.	Test the sensor performance in both low and high-temperature conditions by putting them in fridge/oven, and then verify that readings stay within acceptable error margins.

2. Processing Subsystem

This subsystem processes the data collected by the sensors, performs necessary calculations, and determines whether any air quality thresholds are exceeded. It is the brain of our device and act like a bridge to communicate between user interface and communication subsystems.

Components:

1. Microcontroller (STM32 series): Responsible for processing raw sensor data, convert it into human readable format and interfacing with other subsystems.
2. Alerting Algorithm: Designed to compare the sensor data against known safety limits and alert users when those limits are breached.

Requirement	Verification
The microcontroller must process data from all sensors at the same time within 10 seconds.	Simulate real-world scenarios by sending data from all sensors simultaneously. Measure processing time with a stopwatch and ensure the delay is less than 10 seconds.
The microcontroller must trigger alerts within 30 seconds after detecting harmful gas.	In a controlled test, expose the sensors to harmful gas environment. Record the time taken for the microcontroller to trigger an alert and ensure it is less than 30 seconds.
Data accuracy must be maintained after multiple sensor inputs.	Simulate continuous sensor input in real-time and log data over 24 hours. Verify that the data is accurate with no significant variant.

3. Communication Subsystem

The communication subsystem allows the device to interface with a smartphone via Bluetooth or Wi-Fi, transmitting real-time air quality data. It must send notifications when pollution levels exceed the pre-set thresholds within 60 seconds.

Components

1. Bluetooth Module: RN4870/71
    - Function: Transmit data between our device and smartphone
    - Frequency Band: 2.402 to 2.480 GHz
    - Operating Voltage Range: 1.9V to 3.6V (3.3V typical)
    - Power Consumption: ~10mA average
    - Dimensions: 12 mm x 22 mm
    - Special Features: On-board chip antenna with up to 50m range
    - Working Temperature Range: -20°C to +70°C
2. Smartphone App: Displays detailed air quality information and send notifications to guide user’s behavior when necessary.

Requirement	Verification
The Bluetooth must maintain a stable connection within a 5-meter range.	Test the connection in different environments and distances from 1m to 5m, ensuring consistent data transmission.
The system must send air quality notifications to a smartphone within 60 seconds of detecting harmful levels.	Expose the sensors to hazardous air conditions and use top watch to time how long it takes for a notification to appear on the smartphone. Verify that it is under 60 seconds.
The app must accurately display real-time air quality data with the sensor readings.	Compare the readings displayed on the smartphone with real-time data on LED screen from the device. Ensure that there is no difference.

4. Power Subsystem

The power subsystem consists of a rechargeable lithium-ion battery, a voltage regulator, and a power management circuit. The battery is designed to power the device continuously for at least 24 hours on a single charge. The power management should effectively save some energy and ensuring minimal waste.

Components

1. 5V Rechargeable Lithium-Ion Battery: Capacity of 4000mAh, powers all components of the air quality monitor.
2. Power Management Circuit: Integrated lithium-ion battery linear charging and discharging, I2C interface for configuration and monitoring.
3. L7805 voltage regulator: 5V voltage regulator to power the microcontroller and sensors.

Requirement	Verification
The battery must provide power for at least 24 hours on a single charge.	Fully charge the battery, then run the device continuously. Record the operational time to ensure it exceeds 24 hours.
The power management system must prevent overcharging of the battery.	Simulate the battery charging cycle and verify that charging stops once the battery is fully charged. Monitor the battery voltage to ensure no overcharging.
The system must operate efficiently under varying loads.	Test the power consumption under light, moderate, and heavy sensor activity. Measure the efficiency to ensure minimal energy waste.
The power system must provide stable voltages to all components under varying load conditions.	1Use an oscilloscope to monitor the 5V and 3.3V rails while the device cycles through different operational modes. Ensure that voltages remain within ±5% of their nominal values under all load conditions.

5. User Interface Subsystem

The user interface subsystem consists of an LED display that provides real-time feedback to the user. The interface must be easy to read in different lighting conditions and clearly indicate air quality levels, including hazard warnings. Users must be able to access real-time air quality data at a glance, with clear indications of hazard levels for different pollutants.

Components

- LED Display: Receive the data from microcontroller and convert it into visual output of real-time air quality data.
- User Controls: Allows the user to navigate between different settings in mobile app and monitor current air quality status.

Requirement	Verification
The LED display must be visible in both low-light and outdoor conditions.	Test the LED display in dark and bright lighting conditions to ensure readability in both scenarios.
The interface must display current air quality data with hazard indications clearly.	Simulate varying air quality conditions and verify that reading on the screen is the same as output from sensors, and each hazard levels are accurately displayed.
Users must be able to navigate between data intuitively.	Conduct user testing by having participants navigate through the data. Ensure the interface is clear to any new users.
The device must be portable, with less than 500 gram’s weight.	Fabricate the device and weight it, ensure the reading is less than 500g.

Tolerance Analysis:

The Wearable Air Quality Monitor is designed to meet specific requirements such as long battery life, lightweight construction, and precise sensor functionality. The following tolerance analysis addresses the critical aspects that could impact the performance of the device.

Ensuring 24-Hour Operation without Recharging:

To ensure the device can operate continuously for 24 hours without recharging, we must calculate the total power consumption of all subsystems and compare it with the battery's capacity.

- **Power consumption of Components:**
    - PM2.5/PM10 Sensor (PMS5003): ~100mA at 5V → 0.5W
    - CO2 Sensor (Hiletgo SCD41): ~0.4mA at 5V → 0.002W
    - Formaldehyde Sensor (DFRobot SEN0231): ~3.6V at <50mA → 0.18W
    - CO Sensor (L-com SRAQ-G012): ~10mA at 5V → 0.05W
    - Bluetooth Module (RN4870/71): ~10mA at 3.3V → 0.033W
    - Microcontroller (STM32 series): ~100mA at 3.3V → 0.33W
    - OLED Display: ~30mA at 3.3V → 0.1W
- **Total Power Consumption:**
  Note that the PM2.5/PM10 sensor and the Formaldehyde sensor have a limited operational lifetime, approximately 12 months due to the consumption of internal materials. We want to optimize their usage to extend their lifespan. These sensors degrade over time because they rely on consumable elements to detect pollutants, and continuous operation would accelerate the depletion of these materials. To mitigate this, we will implement a power-saving strategy where the sensors only operate cyclic, at a defined interval, instead of continuously sampling the air. This approach will significantly reduce unnecessary wear on the sensors, ensuring their functionality for a long period. Additionally, the intermittent operation will reduce overall power consumption, contributing to the goal of 24-hour device operation on a single battery charge.

We decide the operating cycle for PMS5003 and Formaldehyde Sensor to be: ON for 30 seconds, Stand By for 1 minutes. PM2.5/10 and Formaldehyde tends to be invariable for a short period of time, and hence periodically sleep these two sensors will not dramatically affect the performance of our device.

$$P_{total} = 0.5\mathrm{W} \times \frac{30}{30+60} + 0.002\mathrm{W} + 0.18\mathrm{W} \times \frac{30}{90} + 0.05\mathrm{W} + 0.033\mathrm{W} + 0.33\mathrm{W} + 0.1\mathrm{W} = 0.742\mathrm{W}$$

- **Battery Capacity**:
  We are using a **4000mAh** lithium-ion battery rated at **5V**. The total energy stored in the battery is:

$$E_{battery} = 4000mAh \times 5V = 20Wh$$

- **Operating Time**:
  To calculate the operating time:

$$\mathrm{t} = \frac{E_{battery}}{P_{total}} = \frac{20Wh}{0.742W} \approx 27hours$$

Note that all the operating current are peak current, and for most of the time the actual current is lower than peak, hence the total operating time is at least 27hours. Which prove that we could easily meet the requirements of "operate continuously for 24 hours".

Ensuring the Weight is Within 500g

The device's weight is critical to ensure portability. We calculate the total weight by adding up the weights of all components and ensure that the device stays under 500g.

- **Weight of components**
  - PM2.5/PM10 Sensor (PMS5003): ~40g
  - CO2 Sensor (Hiletgo SCD41): ~2g

- Formaldehyde Sensor (DFRobot SEN0231): ~5g
- CO Sensor (L-com SRAQ-G012): ~25g
- Bluetooth Module (RN4870/71): ~3g
- Microcontroller (STM32 series): ~15g
- Battery (Lithium-Ion 4000mAh): ~90g
- OLED Display: ~10g
- 3D Printed Plastic & Other Materials (Voltage regulator): ~ 200g

$$W_{total} = 40\text{g} + 2\text{g} + 5\text{g} + 25\text{g} + 3\text{g} + 15\text{g} + 90\text{g} + 10\text{g} + 200\text{g} = 390\text{g}$$

Even with some uncertainty in the case's weight, we comfortably meet the weight limit of 500g. This gives us huge flexibility to add any additional components or reinforce the casing if necessary. Additionally, lightweight alternatives for the casing such as carbon fiber could further reduce the weight if needed.

Ventilation Design

Figure 8: Conceptual ventilation design

Proper sensor placement and vet design within the casing is another crucial factor to ensure that sensor readings are accurate. The vent should be designed with enough clearance to ensure proper airflow without obstruction. Testing in environments with variable airflow will confirm whether the sensor is placed in the optimal position.

Environmental Tolerance and Sensor Accuracy

One of the main performance challenges is ensuring that the sensors function accurately under varying environmental conditions, such as temperature and humidity.

- **Environmental Tolerance**:
  - The sensors must operate effectively between -10°C to 50°C and in humidity ranges of 15%-90% RH.
  - Accuracy under Temperature Variations:
    - Sensors such as the PM2.5/PM10 sensor are sensitive to temperature changes. We will perform a tolerance analysis to ensure that the sensors maintain accuracy within ±10% even at temperature extremes. Testing the device in fridge/oven will verify its resilience.
  - Humidity Impact:
    - High humidity levels can affect sensors like formaldehyde and CO sensors. We might be able to adjust the readings based on current humidity level. During testing level we could create a controlled environment with a fixed CO or formaldehyde concentration, and then vary the humidity levels to record sensor reading for CO. After that plot a graph showing sensor output vs. humidity for each fixed gas concentration. Finally we hope we could find a mathematical formula to reduce the error reading caused by extreme conditions.
  - Sensor Calibration:
    - Routine calibration will be necessary to maintain the device's accuracy over time, particularly for the CO2 sensor. We should include some recalibration options to keep sensor outputs consistent.
- **Sensor Accuracy**:
  - To ensure sensor accuracy within ±15% across the -5°C to 50°C temperature range:
    - Create a controlled testing environment.
    - Test each sensor at 5°C intervals across the range.
    - Compare readings to calibrated commercial instruments.

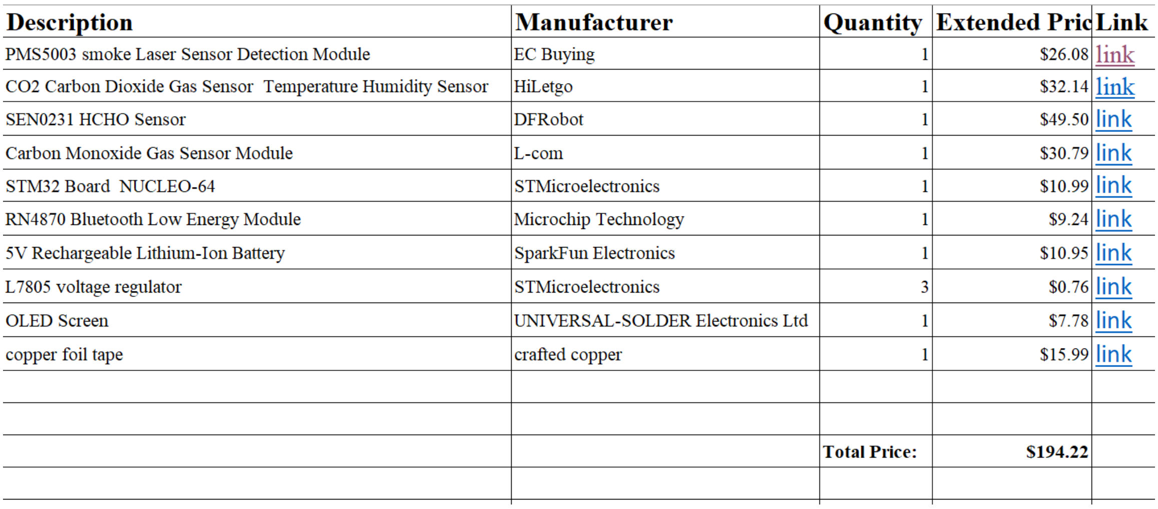
If a commercial air quality measurer state that its accuracy is within ±5%, then we approximately need to make sure our data is ±5% compare to commercial instrument.

$$\text{Percent Error} = \frac{|Measured\ \ value - Commercial\ \ instrument\ \ value|}{Commercial\ \ instrument\ \ value} \times 100\%$$

Cost Analysis

The total cost for ordering parts before shipping is $194.22 plus 5% shipping cost 9.71 plus 10% sale tax 19.42. We assume a salary of $40/hr x 2.5hr x 45 = $4500 per team member. So the total cost is:

$$\text{Total cost} = \$4500 \times 3 + \$194.22 + \$9.71 + \$19.42 = \$13723.35$$



Description	Manufacturer	Quantity	Extended Pric	Link
PMS5003 smoke Laser Sensor Detection Module	EC Buying	1	$26.08	link
CO2 Carbon Dioxide Gas Sensor Temperature Humidity Sensor	HiLetgo	1	$32.14	link
SEN0231 HCHO Sensor	DFRobot	1	$49.50	link
Carbon Monoxide Gas Sensor Module	L-com	1	$30.79	link
STM32 Board NUCLEO-64	STMicroelectronics	1	$10.99	link
RN4870 Bluetooth Low Energy Module	Microchip Technology	1	$9.24	link
5V Rechargeable Lithium-Ion Battery	SparkFun Electronics	1	$10.95	link
L7805 voltage regulator	STMicroelectronics	3	$0.76	link
OLED Screen	UNIVERSAL-SOLDER Electronics Ltd	1	$7.78	link
copper foil tape	crafted copper	1	$15.99	link
		Total Price:	**$194.22**	

Figure 9: Lists of components and costs

Schedule

Week	Task	Person Responsible
September 30th - October 7th	Order parts for prototyping	Everyone
October 7th - October 14th	Start board assembly	Zonghan
	Prototype sensors for PM2.5, PM10, and CO2	Ziheng
October 14th - October 21st	Research transceiver communication	Xin
	Continue board assembly	Everyone
October 21st - October 28th	3D print sensor enclosures	Ziheng, Xin Yang
	Finalize 3D prints	Zonghan
	Second Round PCBWay Order 10.22	Everyone
October 28th - November 4th	Establish transceiver communication	Xin
	Gather timing data	Ziheng
	Third Round PCBWay Order 10.29	Everyone
November 4th - November 11th	Finalize communication protocol	Everyone
	Finish PCB design	Zonghan
	Fourth Round PCBWay Order 11.5	Everyone
November 11th - November 18th	Complete board assembly	Everyone
	Prepare for Mock Demo	Everyone
	Conduct integration testing with final components	Everyone
	Fifth Round PCBWay Order 11.12	Everyone
November 18th - November 25th	Perform bug fixes	Everyone
November 25th - December 2nd	Prepare for final demo	Everyone
December 2nd - December 9th	Assemble final prototype	Everyone

Figure 10: Schedule for project

Ethics and Safety

We adhere to the principle stated by IEEE Code of Ethics. As according to I.1 of Code of Ethics we should “hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices, to protect the privacy of others, and to disclose promptly factors that might endanger the public or the environment”. By designing an air quality monitor, we intend to improve the well-being of users by providing an indication of air quality surrounding them, enabling them to avoid environments that may lead to health issues due to the prevalence of pollutants. Hence, as stated in I.5 and promised in our proposal before, we must make experimental data transparent, and be honest about inaccuracies, in order to avoid giving users false negative alarm, which may result in inhaling excessive pollutants if the monitor overestimated the quality of the air. The concern raised from proposal is what’s the way to minimize inaccuracies of measurement for our device, which will surely be addressed during the design procedures by improving the sensor system as best as we could.

The safety issues involve mainly two aspects: danger due to the testing environment as well as danger due to electricity usage. As it is required to test our monitor in environment with air pollution, we need to make the lab environment sealed and controlled to avoid affecting the safety and health of others. For members who will conduct testing within such environments, we promise to provide them with measures such as pollutant-resistant masks. Danger due to electricity usage is able to affect not only our team members developing the device, but also users of our final product. The monitor, especially the power system that uses batteries, may be susceptible to damage and even burning due to over-heating, suppression, and over-charging. We will surely include design procedure to test the durability of our power system and our device after assembling it, through putting the power system in circuit with current, and adjusting voltage and resistance. Any safety issue discovered will be seriously addressed, which may involve changing battery or re-design our systems. We believe that these are the best measures to sufficiently protect both users and developers from unsafe conditions caused by your project.

By adhering to these ethical and safety guidelines, we aim to develop a product that not only provides value to users but also apply to the ethical conduct.

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