

PREDICTIVE INDOOR VENTILATION SYSTEM

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Team 99

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1 Introduction

1.1 Problem

Indoor air quality (IAQ) plays a critical role in human health, comfort, cognitive performance, and building energy efficiency. Individuals spend a substantial portion of their time indoors in environments such as homes, classrooms, offices, and laboratories, where environmental conditions are largely determined by ventilation strategies and building operation. Within these indoor spaces, elevated carbon dioxide concentrations, excessive humidity, and unfavorable temperature conditions frequently occur due to inadequate ventilation, variable occupancy, or static HVAC control policies. People often remain unaware of degraded air quality until symptoms such as fatigue, discomfort, reduced concentration, or respiratory issues are experienced.

Carbon dioxide concentration is widely used as an indicator of ventilation adequacy and occupancy related air quality. Although CO₂ itself at typical indoor concentrations is not considered a primary toxic contaminant, elevated indoor CO₂ levels often indicate insufficient fresh air exchange relative to occupant load. Government indoor air quality guidance documents note that sustained CO₂ concentrations above approximately 1000 ppm are commonly associated with inadequate ventilation and increased occupant complaints, while concentrations below this level generally indicate acceptable ventilation performance.

Humidity is another key variable that influences indoor air quality and health. Excessive indoor moisture levels can promote mold growth, material degradation, and microbial proliferation, which may contribute to respiratory symptoms and long-term building damage. Public health and environmental guidance recommend maintaining indoor relative humidity below approximately 60%, with an ideal comfort range between 30% and 50% to minimize biological growth and occupant discomfort. Temperature conditions also influence occupant comfort and can interact with humidity and ventilation to affect air quality and productivity.

Despite the recognized importance of these environmental parameters, many residential and small scale commercial ventilation systems operate using fixed schedules or manual control. Such reactive or static approaches fail to account for dynamic changes in occupancy, activity levels, or environmental disturbances. As a result, ventilation may be insufficient during peak occupancy periods or excessive during low occupancy periods, leading to either degraded indoor environmental quality or unnecessary energy consumption. These limitations motivate the development of intelligent ventilation systems capable of continuously monitoring environmental conditions and dynamically adjusting airflow in response to evolving indoor air quality states.

1.2 Solution

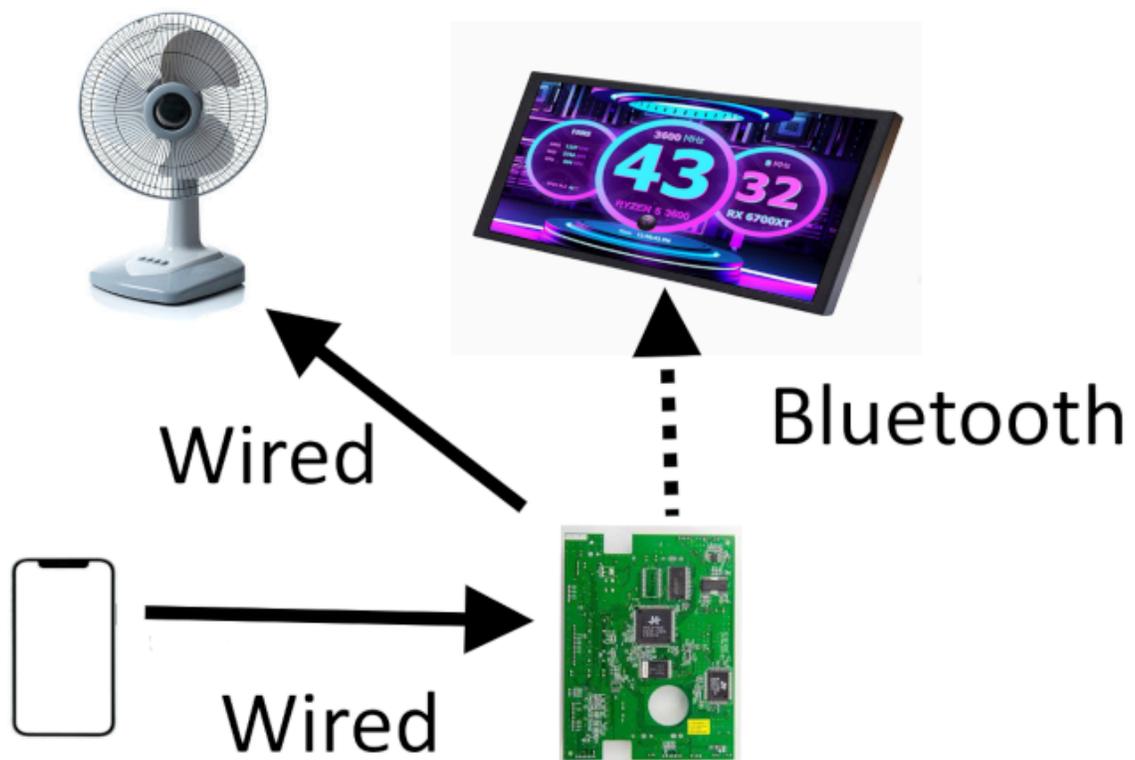
To address the limitations of static ventilation control strategies, this project proposes a predictive indoor air quality monitoring and adaptive ventilation control system. The system integrates environmental sensing, embedded processing, predictive modeling, and active ventilation. Environmental conditions are continuously measured using an integrated sensor module capable of

monitoring CO₂ concentration, temperature, and relative humidity. These measurements provide a real-time representation of the indoor environmental state.

In addition to conventional threshold-based ventilation activation, the system implements a simplified predictive model that estimates future CO₂ concentration trajectories over a short forecast horizon. By identifying anticipated high CO₂ before they occur, the system can activate ventilation proactively, thereby reducing the duration and magnitude of elevated CO₂ exposure.

The integration of sensing, prediction, actuation, and user feedback establishes a closed-loop environmental control system capable of maintaining healthy indoor conditions while reducing unnecessary fan operation and associated energy consumption.

1.3 Visual Aid



1.4 High Level Requirements

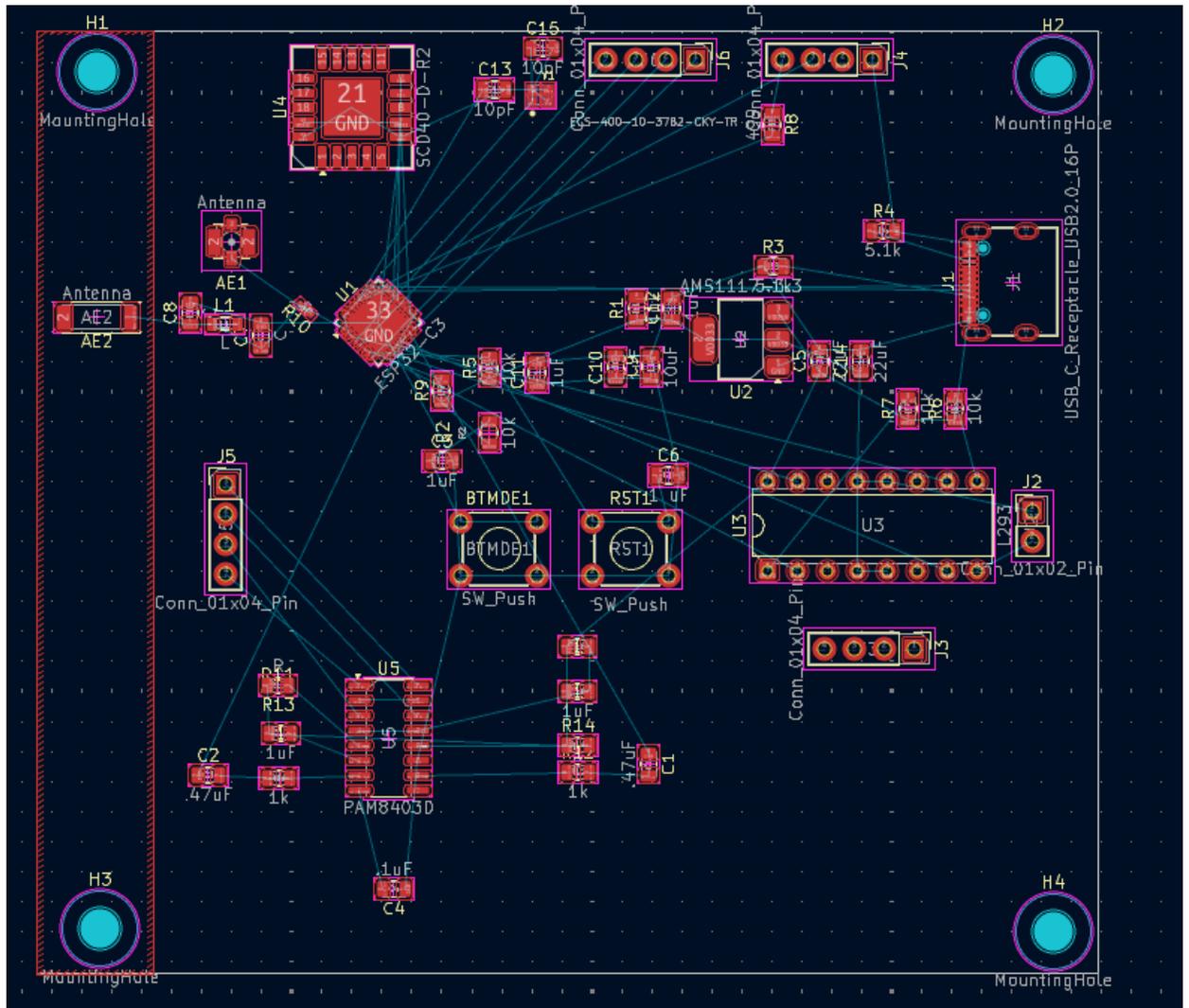
The predictive indoor ventilation control system must satisfy the following high-level requirements to achieve the intended project objectives:

- The system shall maintain indoor CO₂ concentration below 1000 ppm for at least 90 % of occupied operating time during controlled experimental testing.
- The predictive control algorithm shall forecast CO₂ threshold crossings within ± 30 seconds of the actual measured crossing time during controlled disturbance experiments.

- The system shall automatically activate ventilation when temperature or relative humidity exceed predefined environmental thresholds corresponding to unhealthy indoor conditions.
- The system shall operate continuously without unintended resets, sensor communication failures, or data logging interruptions throughout extended experimental evaluation periods.

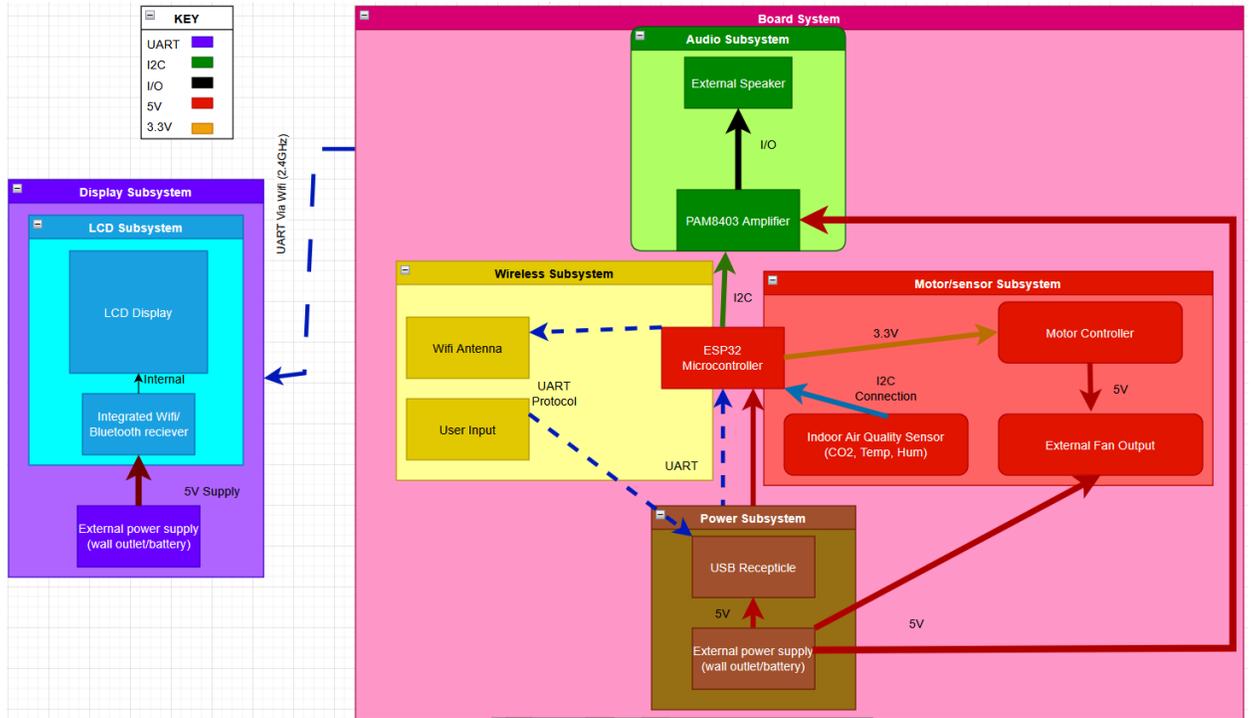
2 Design

2.1 Physical Design

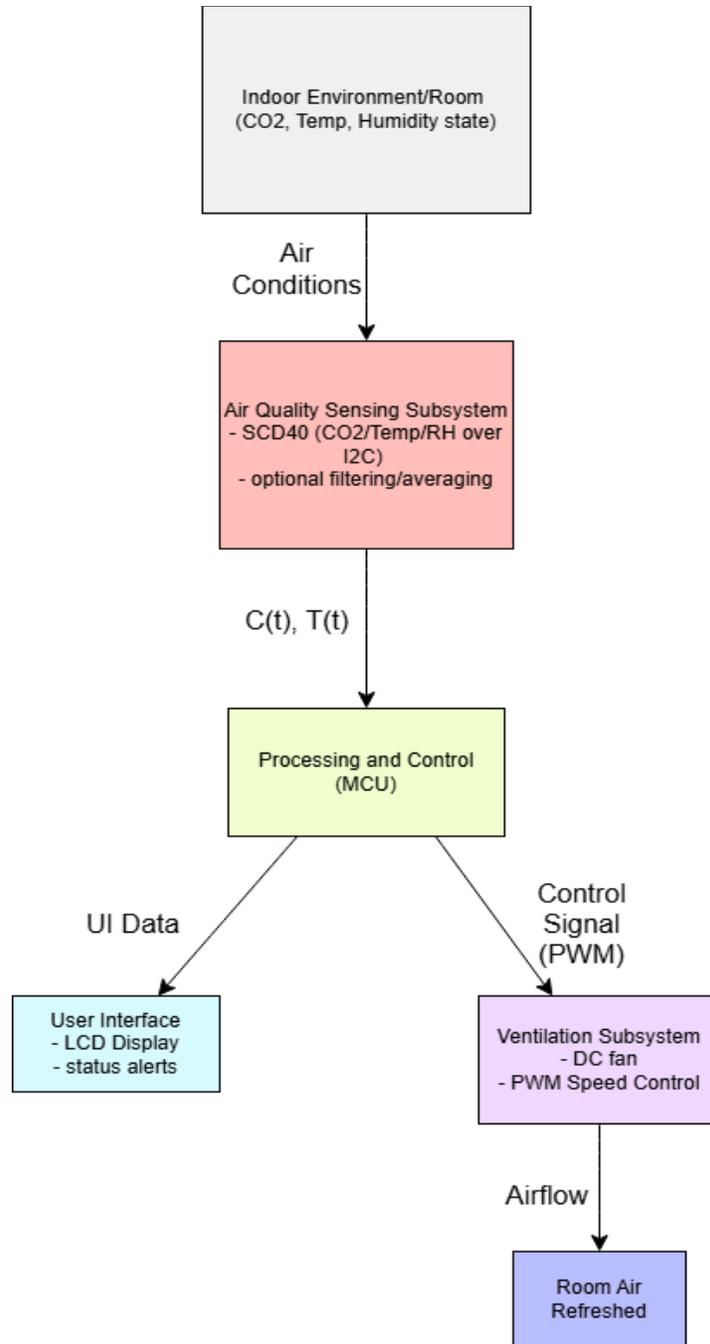


The physical design aspect of the project will consist of the custom PCB, an external fan, and an external screen. There will not need to be any additional physical design as the PCB can be standalone anywhere. The screen will be able to be placed where the consumer wants and the fan will be near the PCB. No housing will be designed or used because we want modularity and the ability to move the screen anywhere and easily swap out the fans.

2.2 Block Diagrams with Subsystem Descriptions



2.2.1 High-level Diagram



2.2.1.1 Indoor Environment / Room

The Indoor Environment represents the physical space whose air quality is monitored and controlled. This includes the CO₂ concentration, temperature, and relative humidity conditions within the room. These environmental variables change over time due to occupancy, human activity, and natural air exchange.

The environment acts as the plant in this closed-loop control system. It provides measurable outputs (CO₂, temperature, humidity) and responds dynamically to ventilation airflow generated by the system.

Inputs: Ventilation, airflow

Outputs: CO₂ concentration, temperature, relative humidity

2.2.1.2 Air Quality Sensing Subsystem

The Air Quality Sensing Subsystem measures the environmental state of the room using the Sensirion SCD40 sensor. The SCD40 communicates with the microcontroller over I²C and provides digital measurements of:

- CO₂ concentration (ppm)
- Temperature (°C)
- Relative humidity (%)

Because sensor readings may contain noise or small fluctuations, optional digital filtering or averaging may be applied before passing the data to the control subsystem. The sensing subsystem does not make control decisions; it only provides accurate and timely environmental measurements to the processing unit.

Inputs: Room air conditions

Outputs: C(t), T(t), RH(t) via I²C

2.2.1.3 Processing and Control Subsystem (MCU)

The Processing and Control Subsystem is the central controller of the system. It is implemented on a microcontroller and performs the following functions:

- Reads environmental data from the sensing subsystem
- Executes the predictive CO₂ estimation model
- Implements the threshold-based safety controller
- Determines ventilation actuation commands
- Logs data and timestamps for performance evaluation
- Sends real-time data to the user interface

This subsystem integrates both reactive and predictive control. The threshold controller ensures safety by activating ventilation if measured CO₂ exceeds 1000 ppm (or if temperature or humidity exceed defined limits). The predictive model estimates future CO₂ levels 30 seconds ahead and activates ventilation proactively if a threshold crossing is anticipated.

Inputs: C(t), T(t), RH(t), previous CO₂ values

Outputs: PWM control signal, UI data

2.2.1.4 User Interface Subsystem

The User Interface Subsystem provides real-time feedback to the user. It displays:

- Current CO₂ concentration
- Temperature
- Relative humidity
- Fan ON/OFF state

The interface is implemented using an LCD display. It does not influence control decisions but improves usability and transparency by allowing users to monitor environmental conditions and system behavior.

Inputs: Processed sensor data and system status

Outputs: Displayed environmental readings and alerts

2.2.1.5 Ventilation Subsystem

The Ventilation Subsystem consists of a DC fan controlled through a PWM signal generated by the microcontroller. A driver circuit (such as a MOSFET stage) amplifies the PWM signal to supply sufficient current to the fan.

When activated, the fan increases air exchange in the room, reducing CO₂ concentration and assisting in humidity and temperature regulation. The PWM duty cycle determines fan speed, allowing adjustable ventilation intensity rather than simple on/off control.

Inputs: PWM control signal from MCU

Outputs: Airflow

2.2.1.6 Room Air Refreshed (System Output)

This block represents the effect of ventilation on the physical environment. Increased airflow reduces CO₂ concentration and helps regulate indoor environmental conditions. The updated room conditions are then sensed again by the Air Quality Sensing Subsystem, completing the closed-loop feedback cycle.

2.2.1.7 Physical Requirements/Verification

Requirements	Verification
<ul style="list-style-type: none">● The speaker circuit will sound an alarm when CO₂ levels are above 1000PPM,	<ul style="list-style-type: none">● Log when CO₂ levels are above 1000PPM

<p>and the amplifier will allow a range of audio to play.</p>	<ul style="list-style-type: none"> ● Manually simulate high CO2 levels to trip alarm ● Send custom sounds to the speaker to confirm audio range
<ul style="list-style-type: none"> ● The motor subsystem will be able to turn a fan on and off, and control the speed of the fan. 	<ul style="list-style-type: none"> ● Log voltage ranges depending on model output ● Simulate outliers such as no and large CO2 to confirm range of fan. ● Simulate normal operating conditions to have fan adjust speed in real time
<ul style="list-style-type: none"> ● The wireless connectivity will allow data to be exported to a display/other devices 	<ul style="list-style-type: none"> ● Show external devices can connect to wifi ● Gather sensor data on the external display ● Gather sensor data on external device
<ul style="list-style-type: none"> ● The wireless display allows human touch and can display all the data needed 	<ul style="list-style-type: none"> ● Send test data to screen and display given test data ● Touch screen to show the screen accepts touch

2.2.2 Machine Learning Subsystem

2.2.2.1 Subsystem Logic Diagram

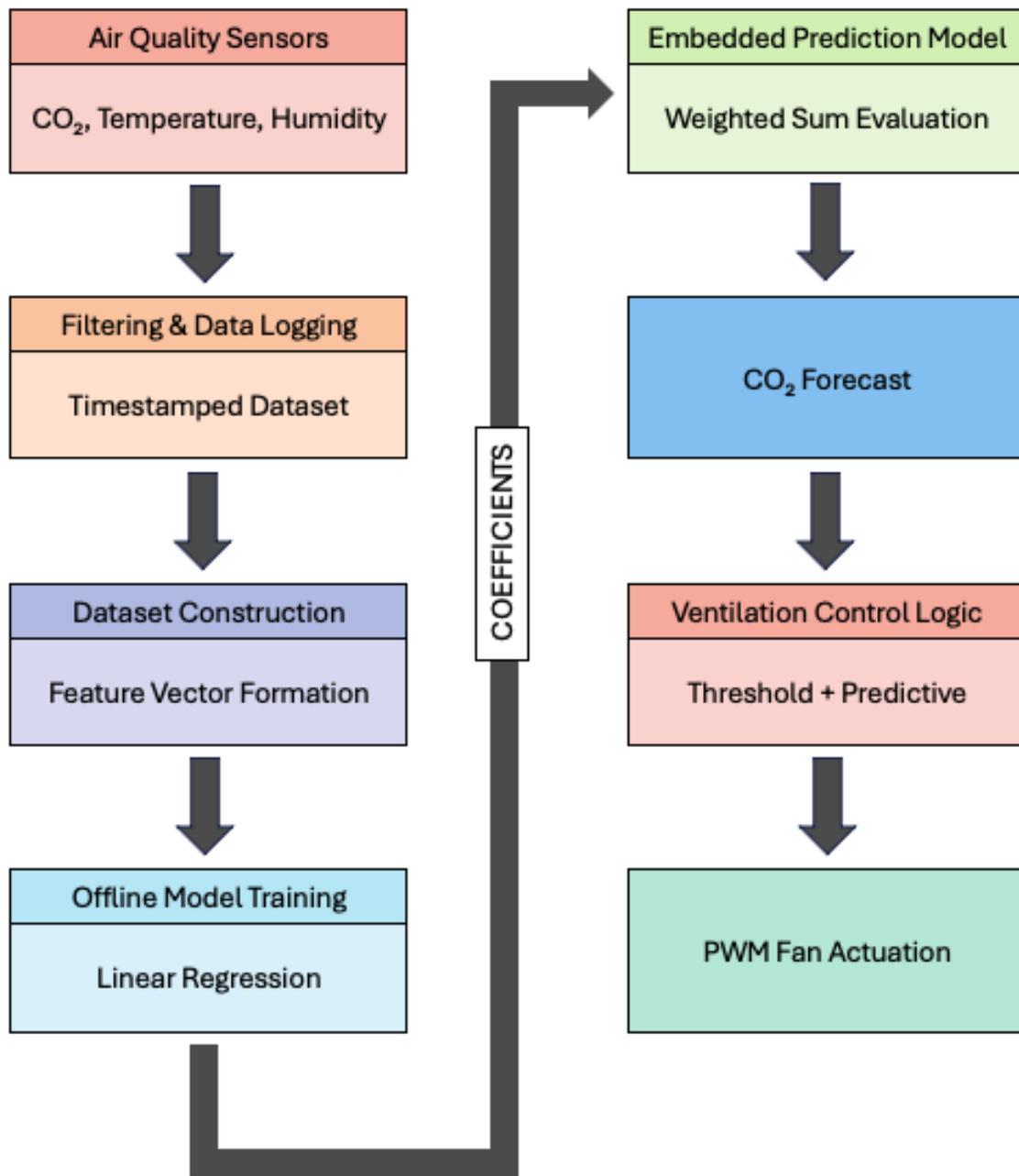


Figure X. Logic Diagram for Predictive Modeling

2.2.2.2 Functional Overview

The Machine Learning Predictive Control Subsystem is responsible for estimating short-term future CO₂ concentration to enable proactive ventilation actuation. Unlike the baseline threshold controller, which reacts only after CO₂ exceeds 1000 ppm, the predictive subsystem estimates future environmental state evolution and initiates ventilation before the threshold is crossed.

Its output is a scalar prediction of CO₂ concentration at a future time horizon Δ . This prediction is passed to the ventilation control logic, which determines whether fan activation is required.

The subsystem performs two distinct operations:

1. Offline training using logged environmental data.
2. Real-time embedded inference using stored model coefficients.

2.2.2.3 Model Formulation

The predictive model is implemented as a multivariate linear regression estimator. For each sampling time step t , a feature vector $x(t)$ is defined as:

$$x(t) = [CO_2(t), T(t), H(t), fan(t), CO_2(t - 1), CO_2(t - 2)]$$

Where:

- $CO_2(t)$ = measured carbon dioxide concentration in ppm
- $T(t)$ = measured temperature in C°
- $H(t)$ = measured relative humidity in %
- $fan(t)$ = ventilation state (PWM-normalized value between 0 and 1)
- $CO_2(t-1)$ and $CO_2(t-2)$ = previous CO₂ measurement

The predicted target is:

$$y(t) = CO_2(t + \Delta)$$

Where Δ is selected to be 30 seconds to align with the ± 30 second threshold crossing requirement.

The regression model is expressed as:

$$CO_2(t + \Delta) = w_0 + w_1 CO_2(t) + w_2 T(t) + w_3 H(t) + w_4 fan(t) + w_5 CO_2(t - 1) + w_6 CO_2(t - 2)$$

The coefficients w_0 through w_6 are computed offline by minimizing the squared error cost function:

$$J(w) = \sum (CO_{2_i}^{\hat{}} - CO_{2_i})^2 \text{ using ordinary least squares estimation.}$$

2.2.2.4 Interpretation of Coefficients

After offline training, the coefficients are stored in microcontroller flash memory as floating-point constants. During real-time operation, the prediction is computed at each sampling interval using multiply–accumulate operations:

w_0 : Bias / baseline offset

- Constant correction term that accounts for systematic offsets in the prediction.

w_1 : Current CO₂ influence

- Determines how strongly present CO₂ concentration predicts future CO₂ concentration.
- The largest coefficient and represents persistence in room air dynamics and mixing behavior.
- If CO₂ is high now, it is likely to remain high in the future.

w_2 : Temperature effect

- How temperature influences CO₂ evolution.
- Temperature can affect air density, mixing, and occupancy behavior.
- Magnitude is smaller than the CO₂ coefficient but still contributes to prediction accuracy.

w_3 : Humidity effect

- Humidity serves as a proxy for occupancy and ventilation conditions.
- Human presence often increases both humidity and CO₂ levels.
- This coefficient allows the model to leverage correlated environmental information.

w_4 : Fan state effect

- This coefficient represents the impact of ventilation on CO₂ concentration.
- It is typically negative because fan operation removes CO₂ from the indoor environment.

w_5 and w_6 : Previous CO₂ (trend information)

- Captures short-term temporal dynamics by incorporating the previous CO₂ measurement.
- Allows the model to represent rising or falling trends and provides momentum awareness in prediction.

2.2.2.5 Requirements and Verification

Requirements	Verification
<ul style="list-style-type: none"> The predictive model shall estimate CO₂ concentration 30 seconds ahead with mean absolute error less than a defined tolerance during disturbance experiments. 	<ul style="list-style-type: none"> Log predicted and measured CO₂ values during controlled candle disturbance tests. Compute mean absolute error and root mean square error. Confirm error remains within tolerance bounds.
<ul style="list-style-type: none"> The predictive subsystem shall forecast threshold crossings within ± 30 seconds of measured crossing events. 	<ul style="list-style-type: none"> Induce controlled CO₂ rise events. Confirm absolute timing difference ≤ 30 seconds.
<ul style="list-style-type: none"> The predictive subsystem shall not suppress ventilation when CO₂ exceeds 1000 ppm. 	<ul style="list-style-type: none"> Force CO₂ above 1000 ppm while predictive output is artificially biased low. Confirm threshold controller activates ventilation regardless of prediction.

2.3 Tolerance Analysis

The predictive indoor ventilation system depends on accurate sensing, consistent timing, and reliable fan actuation. Because real hardware is never perfectly accurate, this section analyzes how measurement errors, timing variations, and actuator limitations affect overall system performance. The goal is to ensure that these imperfections do not prevent the system from meeting the high-level requirements defined in Section 1.4.

2.3.1 Sensor Measurement Tolerance

The system uses the Sensirion SCD40 sensor to measure CO₂ concentration, temperature, and relative humidity. According to the manufacturer datasheet:

- CO₂ accuracy: $\pm(50 \text{ ppm} + 5\% \text{ of reading})$
- Typical response time: about 60 seconds
- Measurements are internally compensated using temperature and humidity sensing.

This means the sensor reading is never exactly equal to the true room value.

We can describe the measured CO₂ value as:

$$C_{\text{measured}} = C_{\text{true}} + \text{error}$$

Where:

- C_{true} = actual CO₂ concentration in the room
- error = sensor uncertainty and noise

2.3.2 Sampling Time Tolerance

The system samples sensor data periodically. Let:

- T_s = time between measurements
- Δ = prediction horizon (30 seconds)

These are related by:

$$\Delta = N * T_s$$

Where N is the number of samples ahead being predicted. Example: If measurement occur every 1 second, then $N = 30$, meaning the model predicts 30 samples into the future.

If sampling intervals vary too much, the prediction horizon becomes incorrect.

For example:

- intended prediction: 30 seconds ahead.
- actual timing drift: ± 0.1 s each sample

After 30 samples:

$$30 * 0.1 = 3 \text{ seconds error}$$

This is still much smaller than the allowed ± 30 s requirement, so the system remains acceptable.

2.3.3 Fan Actuation and Airflow Delay

Even after the controller turns the fan on, CO₂ does not immediately decrease.

There are two delays:

1. Fan spin-up time - motor needs time to reach speed.
2. Air mixing time - fresh air must reach the sensor location.

We define total response delay as:

$$T_{response} = T_{fan} + T_{mix}$$

The sensor itself has about a 60s response time; extremely fast control changes would not provide meaningful benefits.

Therefore, the chosen prediction horizon (30s) is appropriate because it is comparable to the physical response speed of the sensing system.

2.3.5 Logging and Verification Timing

To verify the requirement that predictions occur within ± 30 seconds of threshold crossing, the system logs:

- measured CO₂
- predicted CO₂
- fan state
- timestamps

If timestamps are inaccurate, prediction accuracy could appear worse than it is.

To avoid this, timestamps are generated using the microcontroller system timer with approximately 1-second resolution, which is sufficient compared to the ± 30 s requirement.

3 Cost and Schedule

3.1 Cost Analysis

3.1.1 Labor Cost

A reasonable hourly salary for a newly graduated electrical or computer engineer is estimated at \$40 per hour.

$$\text{Labor cost per member} = (\$40 \text{ per hour}) * 2.5 * (\text{hours worked})$$

Assuming around 60 hours of total project work per team member:

$$40 * 2.5 * 60 = 6000$$

Thus, the labor cost per team member is \$6,000. With three members, the total estimated labor cost is \$18,000.

3.1.2 Parts Cost

Table 1 Parts Costs

Part	Manufacturer	Retail Cost (\$)	Bulk Purchase Cost (\$)	Actual Cost (\$)
SCD40 CO2, Temperature and Humidity Sensor Breakout I2C	Digikey https://www.digikey.com/en/products/detail/sensirion-ag/SCD40-D-R2/13684008	\$20	NA	\$51.30 post tax + shipping
DIS05035H LCD Display	Elecrow	\$31.39	\$25.40	\$38.38 post tax + shipping
Speaker + amplifier	Monk Makes https://www.digikey.com/en/products/detail/diodes-incorporated/PAM8403DR-H/4033372	\$20	NA	\$20 post tax + shipping
Total				\$109.68

3.1.3 Total Project Cost

$$\$18,000 + \$109.68 = \$18,109.68$$

The total project cost is approximately \$18,109.68. This includes cost of the parts and labor costs.

3.2 Schedule

Week	Task	Responsible Member
Week 1	Finalize hardware architecture, complete schematic design, order remaining components	Entire Team
Weeks 2-3	PCB Fabrication, sensor integration, microcontroller data acquisition development	Noah Rockoff, Arka Kolay

Weeks 4-5	Ventilation driver circuit implementation and predictive algorithm development	Gulnaaz Sayyad, Arka Kolay
Week 6	Full system integration, UI Implementation, preliminary debugging	Noah Rockoff, Gulnaaz Sayyad
Week 7	Verification Testing, performance comparison, final refinement	Entire Team

4 Discussion of Societal Impact, Engineering Standards, Ethics, and Safety Considerations

4.1 Societal Impact

The predictive indoor ventilation control system aims to improve indoor air quality awareness and management in residential, educational, and workplace environments. By continuously monitoring CO₂ concentration, temperature, and humidity and enabling proactive ventilation control, the system can help maintain healthier indoor conditions that support comfort, cognitive performance, and general well-being. Additionally, predictive activation of ventilation reduces unnecessary fan runtime compared to static schedules, contributing to improved energy efficiency and more sustainable building operation.

4.2 Engineering Standards

The system design is informed by commonly referenced indoor environmental and engineering standards. Ventilation practices and environmental monitoring approaches are influenced by guidance from organizations such as ASHRAE, which provide recommendations related to ventilation effectiveness and indoor environmental quality. Electrical design decisions follow general embedded system safety practices, including proper voltage regulation, and component operating limits.

4.3 Ethical Considerations

This project aligns with engineering ethics principles emphasizing honesty, transparency, and prioritization of public welfare. System performance claims regarding predictive accuracy and ventilation improvement will be supported by experimental validation to avoid overstating capabilities. Although the system primarily records environmental data, responsible data handling practices will be followed, and collected information will be used only for system evaluation and development purposes. Additionally, predictive outputs will be presented as estimates rather than guarantees to ensure realistic user expectations.

4.4 Safety Considerations

Safety considerations include electrical safety, mechanical safety, and safe testing practices. Electrical safety is addressed through appropriate voltage levels, current-limited circuitry, and adherence to component specifications. Mechanical safety is maintained by securely mounting components and ensuring guarded operation of the ventilation fan. Controlled disturbance experiments will be conducted under supervised conditions to avoid unsafe environmental exposure. The system also incorporates fallback control behavior to maintain safe operation in the event of predictive model failure.

5 Citations

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