PREDICTIVE INDOOR VENTILATION CONTROL USING AIR QUALITY ESTIMATION

Arkaprabha Kolay

Noah Rockoff

Gulnaaz Sayyad

Team 99

Abstract

Indoor air quality significantly impacts human health, cognitive performance, and energy efficiency. Elevated CO_2 levels, excessive humidity, and particulate matter often go unnoticed in homes, classrooms, and offices due to limited real-time feedback and fixed HVAC operation schedules. This project proposes a predictive indoor air quality monitoring and adaptive ventilation control system. The system continuously measures CO_2 concentration, temperature, and humidity using integrated environmental sensors. A microcontroller processes real-time data and implements both baseline threshold-based and predictive model-based control strategies. Ventilation fans are activated proactively based on forecasted CO_2 trends and environmental conditions. An LCD interface and software dashboard provide real-time visualization and logging capabilities. The system aims to maintain CO_2 below 1000 ppm for at least 90% of occupied time while reducing unnecessary fan runtime compared to conventional threshold control.

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1. Introduction

1.1 Problem

Indoor air quality is a critical but often overlooked factor in human health, productivity, and well-being. Elevated concentrations of carbon dioxide (CO2), excessive humidity, and high temperatures frequently occur in homes, classrooms, and office spaces due to inadequate ventilation. Because these conditions are not immediately perceptible, people often remain unaware of degraded air quality until symptoms such as fatigue, headaches, reduced concentration, and respiratory irritation appear.

Research has shown that CO2 concentrations above 1000 ppm are associated with measurable reductions in cognitive performance and decision-making ability. Poor humidity control can contribute to mold growth and long-term building damage. At the societal level, degraded indoor air quality affects public health, student performance, workplace productivity, and healthcare costs. From an environmental and economic perspective, most existing HVAC systems operate on fixed schedules or manual settings, resulting in either insufficient ventilation (compromising health) or excessive ventilation (wasting energy).

There is a need for an adaptive ventilation control system that dynamically responds to changing indoor air conditions while minimizing unnecessary energy consumption.

1.2 Solution

This project proposes a real-time indoor air quality monitoring predictive ventilation control system. The system continuously measures CO2 concentration, temperature, and humidity using integrated environmental sensors. A microcontroller processes sensor data and applies both a baseline threshold-based controller and a predictive, model-based control algorithm.

Using a model, the system estimates future CO2 levels and activates ventilation before thresholds are exceeded. This proactive strategy aims to maintain healthier air quality while reducing unnecessary fan runtime.

There will also be an LCD display that will show the user of current sensor readings and will warn if there is a sudden spike in any sensor data.

1.3 High-Level Requirements

The system shall maintain indoor CO_2 concentration below 1000 ppm for at least 90% of occupied operating time during controlled testing.

The predictive control algorithm shall forecast CO_2 threshold crossings within ± 30 seconds of the actual measured crossing time under controlled disturbance experiments.

The system shall activate ventilation when: Humidity exceeds a predefined maximum threshold. Temperature exceeds a predefined maximum threshold.

The system shall operate continuously without unintended resets or sensor communication failures during testing.

The system shall log environmental data and control actions for later comparison between predictive and threshold-based control.
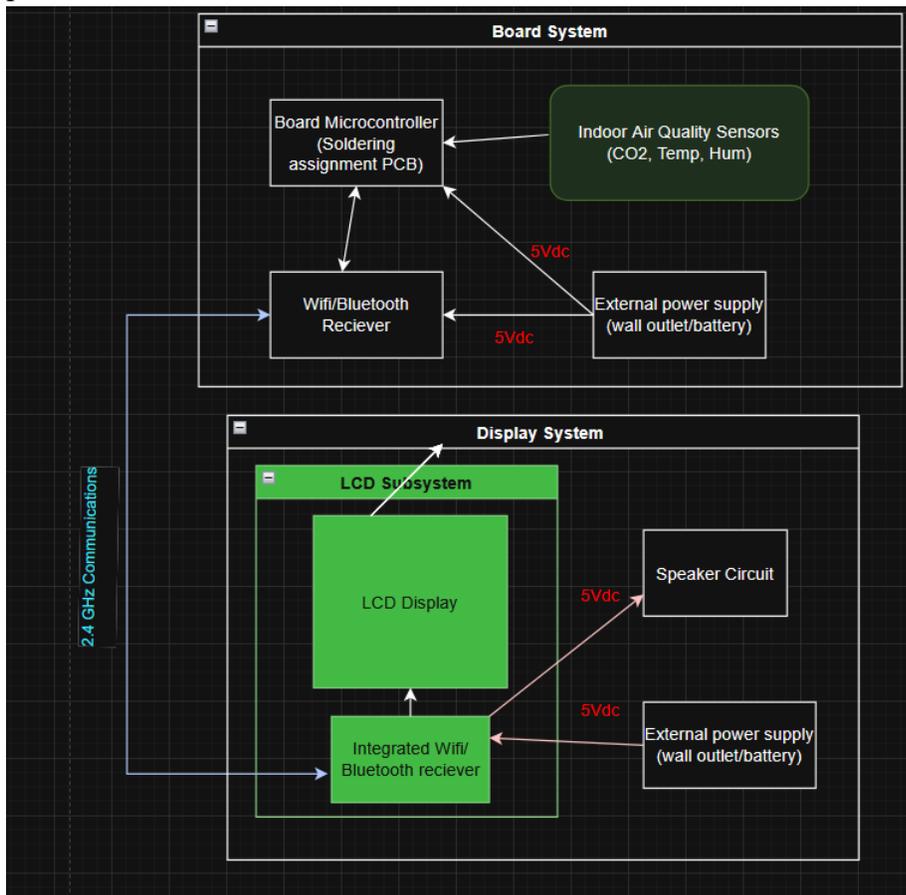
2 Design

2.1 Air Quality Sensing Subsystem

Components:

• Sensirion SCD40 (CO_2, temperature, humidity via I²C)

Function:

The sensors continuously monitor environmental conditions and transmit data to the microcontroller. The environmental state vector is:

$$x(t) = [CO_2, \text{T(t), RH(t)}]$$

Sensor data is filtered before use in control decisions.

2.2 Processing and Control Subsystem

The microcontroller performs:

- Sensor data acquisition
- Digital filtering
- Threshold comparison
- Predictive modeling of CO_2 dynamics
- PWM signal generation for fan control
- Data logging

A simplified CO_2 concentration model is used:

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

If the predicted concentration exceeds 1000 ppm within a short forecast window, ventilation is activated before the threshold is crossed.

The system also compares predictive control performance against a baseline threshold controller.

2.3 Ventilation Subsystem

- DC fan
- PWM speed control
- MOSFET driver circuit implemented on custom PCB

Fan speed is dynamically adjusted based on predicted and measured air quality conditions.

2.4 User Interface Subsystem

LCD Displays:

- CO_2 concentration
- Temperature
- Humidity
- System state (Fan ON/OFF)

Provides immediate user feedback in the event of rapid environmental changes.

3. Design Verification

3.1 CO2 Disturbance Testing

Candles or controlled flame sources will be used near the CO_2 sensor to artificially elevate CO_2 concentration.

Metrics evaluated:

- Detection latency
- Prediction accuracy
- Activation timing
- Comparison between predictive and threshold control

Success: Prediction within ±30 seconds of threshold crossing.

3.2 Humidity and Temperature Testing

Controlled environmental changes will be introduced to verify:

- Ventilation activation when humidity exceeds set limit.
- Ventilation activation when temperature exceeds set limit.
- Stable operation without oscillatory behavior

3.3 Energy Efficiency Comparison

Fan runtime will be logged under:

- Baseline threshold control
- Predictive control

Success criterion:
Predictive control reduces runtime or estimated energy consumption by a measurable percentage while maintaining safe CO_2 levels.

4. Costs
Make sure that any tables of costs are numbered, given titles, and cited directly in the text.

4.1 Parts

Table 1 Parts Costs

Part	Manufacturer	Retail Cost ($)	Bulk Purchase Cost ($)	Actual Cost ($)
SCD40 CO2, Temperature and Humidity Sensor Breakout I2C	7Semi	$31.40	NA	$51.30 post tax + shipping
DIS05035H LCD Display	Elecrow	$31.39	$25.40	$38.38 post tax + shipping
Speaker + amplifier	Monk Makes	$11.45	**NA**	$20 post tax + shipping
Total				

5. Conclusion

5.1 Ethical considerations

This project aligns with the IEEE Code of Ethics, particularly the principles emphasizing the responsibility of engineers to prioritize public health, safety and welfare, and to be honest and realistic in stating claims based on available data. Because this system monitors environmental conditions that may influence health related decisions, it is ethically important that performance claims regarding prediction accuracy and energy savings are supported by experimental validation. Any predictive control results must be reported transparently, including limitations and uncertainty.

Although the system primarily collects environmental data rather than personal data, ethical data handling practices must still be followed. Logged air quality data should be stored securely and used only for performance evaluation or system improvement. If the system were expanded in the future to include remote connectivity, appropriate safeguards would be necessary to prevent unauthorized access. Finally, predictive algorithms must be rigorously validated before users rely on them to make ventilation or health-related decisions, preventing a false sense of security due to modeling inaccuracies.

5.2 Safety

- Electrical isolation between sensing and power circuitry

- Proper MOSFET heat dissipation

- Controlled flame use during testing under supervision

- Avoid direct exposure to particulate sensors during disturbance testing

5.3 Societal Impact

Improved indoor air quality can enhance cognitive performance, reduce health risks, and lower energy consumption. Scalable deployment of predictive ventilation systems could contribute to improved public health outcomes and sustainable building management practices.