A Smart Mask for Wireless, Real-Time Monitoring of CO2 and Humidity

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I. INTRODUCTION

Face masks are widely used for health protection in both public and professional settings. However, prolonged usage of masks leads to the buildup of carbon dioxide (CO_2), heat, and humidity inside the mask, which may cause discomfort and adverse physiological effects.

This paper introduces an embedded respiration monitoring device that can be attached to a face mask. The objectives are to measure CO_2, temperature, humidity in real time, alert users when unsafe levels are detected and enable smartphone connectivity for continuous monitoring and control.

II. LITERATURE REVIEW

Existing studies have shown that wearing a mask alters the microenvironment around the face, often leading to negative physiological and cognitive effects. For instance, mask usage has been linked to increased facial skin temperature, intensified sick building syndrome symptoms, and reduced cognitive performance, with these effects worsening over time [1]. Other research highlights a significant rise in CO_2 concentration within the breathing zone when masks are worn, compared to when they are not [2]. Elevated CO_2 levels, have been associated with increased blood pressure and heart rate, while concentrations above 1000 ppm can impair cognitive functions such as decision-making and problem solving. At extremely high levels, CO_2 exposure may cause severe symptoms including dizziness, confusion, and even loss of consciousness [3]. Table 1 shows the CO_2 level and symptoms related with each levels according to [2].

In addition to CO_2 accumulation, increased humidity and temperature inside masks contribute to discomfort during prolonged use. While prior work has established these health and comfort issues, there remains a lack of practical, real-time monitoring solutions that can alert users and provide actionable feedback. This research addresses, this gap by proposing an embedded, mask-mounted device that continuously measures CO_2, humidity, and temperature, while providing real-time alerts.

Table 1

CO_2 concentration (ppm)	Associated symptoms/ effects
500 - 900	Normal CO_2 concentration
> 1000	Drowsiness and loss of attention
> 2200	Undesirable symptoms (fatigue, headache, loss of concentration)
> 2500	Potential to affect decision making
> 5000	Workplace exposure limit

CO_2 levels and associated symptoms

III. MATERIALS AND METHODS

A. Hardware Design

Processing unit – Nordic nRF52832 microcontroller, chosen for its low power consumption and integrated Bluetooth Low Energy (BLE), allowing a smaller form factor.

Sensors – The Sensirion SCD41 was selected as it measures CO_2, temperature, and humidity in a single package and small form factor. And because it relies on non-dispersive infrared (NDIR) technology which is more accurate compared to other technologies.

Power supply – 3.7 V Lithium Polymer battery (200 mAh) with a USB Type-C port for recharging. The device works on 20 mA. With an 200 mAh battery the device works 8.5 ± 0.5 hours with the BLE communication. Without the BLE communication the device can be used for 12 ± 0.5 hours.

Other components – A button (for power on/off and alert control) and a speaker (to notify users if the mobile phone is not connected). An overview of the architecture is shown in figure 2.

As in figure 1 the device is fixed to the mask using a replaceable double tape. The battery, the MCU, button, speaker and the charging port is in the large compartment that's situated outside the mask. A smaller compartment contains the sensors. The smaller compartment is inside the mask and one of the side contains a hole that exposes the sensors. That hole is covered by an PTFE hydrophobic membrane to stop condensation inside the compartment. This doesn't have an impact on the humidity sensor as the sensor itself uses a hydrophobic membrane. The total weight of the device is 55 ± 5 g.

B. Software Design

The microcontroller firmware handles sensor control, data acquisition, alert triggering, and Bluetooth Low Energy (BLE) communication. The firmware follows an event-driven architecture, where sensor readings are taken every 15s and they are collected in an empty buffer and every 1 minute the average value of the data in the buffer is sent to the mobile phone. Apart from that the firmware evaluates the thresholds,

Fig. 1. A prototype of the device.

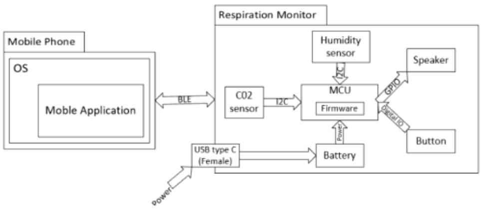

Fig. 2. A block diagram of the architecture.

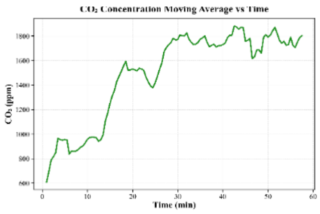

Fig. 3. CO_2 level (in parts per million) vs time (in minutes).

and alerts are triggered via the onboard speaker or BLE notifications when necessary.

The mobile application was developed using the Flutter framework for cross-platform support and faster prototyping. BLE communication was implemented with the *flutter_reactive_ble* library, which manages device discovery, connection, and data exchange. The app provides a real-time dashboard to visualize CO_2, temperature, and humidity, allowing users to set custom threshold values, and manages device permissions (Bluetooth, location). Additional UI libraries were used to design an interactive and user-friendly interface.

The device implements standard BLE security features including AES-128 encryption and device bonding. And there is a 5-minute connection timeout and a single-device pairing limit to help reduce attack surface. But the system is still susceptible to man in the middle (MITM) attacks and eavesdropping attacks.

To reduce power consumption, the system uses multiple low-power modes. Deep sleep is enabled when the device is idle, disabling all peripherals except the real-time clock. When active but not connected via BLE, the device enters light sleep, lowering the CPU clock (from 64 MHz to 8 MHz) and shutting down unnecessary modules. Apart from that the sensor sampling rate is 0.25 Hz and data is sent once per minute to reduce the need of BLE communication.

IV. RESULTS AND DISCUSSION

A. Testing Environment

Experiments were conducted in an indoor setting to evaluate CO_2 accumulation while wearing a KN95 mask. There were 5 trials in an indoor room with windows and the door open and while a fan was working. The average room CO_2 level was 600±50 ppm.

B. CO_2 Levels Inside the Mask

In all the trials the CO_2 concentration increased rapidly. Within 15 minutes, average CO_2 levels reached 1000 ± 50 ppm, and after 1 hour, levels rose to 2000 ± 50 ppm, demonstrating significant accumulation over time. These findings align with previously reported data [2], confirming that prolonged mask use can create conditions of elevated CO_2 exposure. The data recorded on one male volunteer can be seen in figure 3. The dips in the graphs were unpredictable from trial to trial.

C. Temperature and Humidity

Inside the mask, temperature increased by 2.5 ±0.5 °C compared to ambient conditions, and relative humidity rose by (17.5 ± 2.5) % within the first 30 minutes. Continued usage led to further gradual increases. (Figure 4 and figure 5 shows the recorded data for the same trial that recorded data for the CO_2 levels)

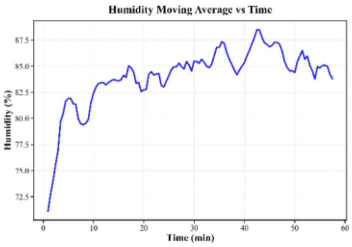

Fig. 4. Relative humidity vs time (in minutes)

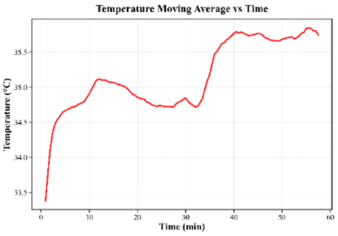

Fig. 5. Temperature (in Celsius) vs time (in minutes).

D. Device Performance

The mask-mounted device successfully captured real-time CO_2, temperature, and humidity data. Alerts were triggered when CO_2 levels moving average exceed 1500 ppm or humidity rose above 80%. And the thresholds for humidity and the temperature could be controlled by the mobile app.

E. Discussion

The developed device delivers the intended functionality by continuously monitoring CO_2, temperature, and humidity inside the mask and notifying users when threshold values are exceeded. But in the trials users complained about the strain in back of the ears where the masks hold on, due to increase in the masks weight.

V. CONCLUSION

Experimental results confirm substantial CO_2 buildup, rising temperature and humidity inside KN-95 masks, highlighting the potential for discomfort and cognitive effects during prolonged use. The developed system addresses this issue by providing continuous monitoring, customizable thresholds, and smartphone integration, there by filling a gap in wearable health monitoring solutions.

VI. FUTURE WORK

Future work will focus on implementing MITM protection, encrypted data storage, reducing the device size and improving its ergonomics to enhance user comfort and overall experience.

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