An AR Visualization System for Carbon Dioxide Concentration Measurement Using Fixed Sensors and Sensors Mounted on Mobile Robots*

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Abstract

Thorough ventilation is one of the measures to prevent COVID-19 infection. CO_2 concentration is frequently utilized as a ventilation guideline. In fact, office buildings, schools and factorys are increasingly introducing systems that display changes in CO_2 concentration values. However, 2D map based visualizations are not enough to understand the progression of indoor air pollution and whether there is a need for ventilation. A 3-Dimensional (3D) measurement is needed to visualize CO_2 concentration in space. However, conventional methods have various problems to achieve a 3D measurement, because a large number of sensors are needed to sense the entire room and explicit knowledge of their location. Therefore, an automated method to measure CO_2 concentration in 3D is also proposed. We propose a three-dimensional (3D) visualization of CO_2 concentration using a head mounted display (HMD). This indoor CO_2 concentration method uses both fixed sensors and mobile sensors with a CO_2 gas sensor module. The visualization facilitates understanding of the temporal changes and spatial distribution of CO_2 concentration. A prototype was developed using Microsoft HoloLens 2 as our Augmented Reality (AR) HMD; an iRobot Roomba 600 Series as our autonomous mobile robot at ground level; a William Mark Air Swimmer Shark as our airship robot to get measurements at higher positions; and a M5Stack Gray, a M5Stick C Plus, and TVOC/eCO_2 gas sensor unit as CO_2 gas sensor modules. Using the position coordinates and measured values of each sensor, a 3D distribution of CO_2 concentration is automatically calculated and visualized using the AR-HMD.

Keywords

Carbon Dioxide, Sensor Networks, Visualization, Augmented Reality, Mobile Robots

1. Introduction

Clean indoor air is essential for human health. Indoor air accounts for more than food and water intake and nearly 60% of the weight of materials consumed by humans in a lifetime [1]. Indoor air quality has a significant impact on the human body. Proper ventilation behavior is important to maintain healthy and comfortable indoor air quality. Inadequate ventilation causes high carbon dioxide (CO_2) concentrations, which have adverse effects on the human body, including headache, drowsiness, carbon monoxide poisoning, and impaired concentration and memory [2, 3, 4]. At the time of this writing, COVID-19 is a worldwide pandemic, and one of the most common risk factors is "closed spaces with poor ventilation" [5]. COVID-19 spread is caused by inhalation of droplets [6]. Therefore, thorough ventilation is considered one of the most effective infection control measures.

CO_2 concentration can be used as a standard for indoor ventilation conditions and is advocated to be less than 1000 [ppm] [7]. In addition, the magnitude of the risk of viral infection is correlated with the indoor CO_2 concentration, and keeping the indoor CO_2 concentration low is a good measure against infection [8]. In fact, the use of CO_2 concentration monitors is increasing in spaces where many people gather, such as office buildings, schools, and factories. However, 2D map based visualizations are not enough to understand the progression of indoor air pollution and whether there is a need for ventilation. This is especially true for some gas such as CO_2 which is not perceivable by the human senses. Therefore, we propose a three-dimensional (3D) visualization of CO_2 concentration using a head mounted display (HMD) to facilitate the understanding of CO_2 concentration in space. Previously, Burgués et al. proposed a method to visualize the temporal variation of 3D gas distributions generated by gas sources located at various locations [9]. To measure the 3D gas distribution, they divided the room into 3D grids, and sensors were placed in each grid. The results show that gas heavier than air does not accumulate near the ground surface, and that the gas distribution changes drastically with time, regardless of height. Additionally, Russel et al. proposed a method

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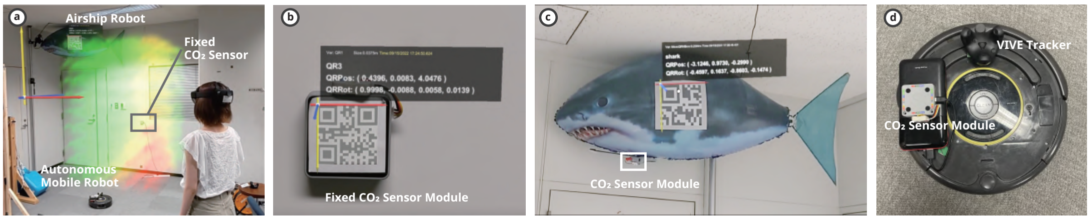

Figure 1: (a) Proposed AR visualization System for carbon dioxide concentration, (b) Fixed CO_2 sensor module, (c) Airship robot with a CO_2 sensor module, and (d) Autonomous mobile robot with a CO_2 sensor module.

for measuring 3D gas distribution using a mobile robot equipped with a telescopic sensor head [10]. The results showed that the gas was concentrated near the ceiling, even though the gas source was located on the floor. This supports the idea that the dispersion of gas heavier than air is influenced by convection. This indicates that 3D measurement is necessary even for CO_2, which is heavier than air. However, conventional methods require manual registration of each sensor's position beforehand. In addition, conventional methods can only measure the position of a fixed sensor, and a large number of sensors are required to sense the entire room.

To address these issues, we aim to achieve high-density 3D measurement and visualization without requiring laborious manual labor. Therefore, we propose an augmented reality (AR) visualization system for indoor CO_2 concentration (see Fig. 1) using both fixed sensors and sensors mounted on mobile robots that have the following characteristics:

- Automatic localization of fixed CO_2 gas sensors in 3D.
- Automatic localization of CO_2 gas sensors mounted on mobile robots in 3D.
- Interpolation of the measurement to estimate dense distribution.
- AR visualization of CO_2 concentration distribution.

2. Related Work

2.1. CO_2 concentration measurements

Numerical fluid dynamics models such as CFD simulations are often used to analyze atmospheric gases. However, there is a large discrepancy between the predicted CO_2 concentration by CFD simulation and the measured value by sensors [11]. Therefore, we measure changes in CO_2 concentration in the real environment.

Various methods have been proposed for indoor environmental measurement using mobile robots. For example, Jin et al. used an autonomous mobile robot equipped with sensors for indoor environment monitoring [12]. However, it does not account for inaccessible areas to the autonomous mobile robot. Therefore, we propose a measurement method that combines fixed sensors and mobile robots with sensors.

2.2. CO_2 concentration indication system

Sone proposed a system that displays changes in indoor CO_2 concentration on a time-series graph [13]. The purpose of the system is to encourage users to voluntarily ventilate their room by looking at the measured values on the display, and to close the windows when the ventilation is sufficient. However, as a result, no change in the user's ventilation behavior was observed. We expect that using AR to superimpose the gas distribution directly in the air will encourage users to take action.

2.3. AR visualization systems

Duan et al. proposed a system that combines an optical see-through HMD, a motion capture camera, and a laser gas detector to visualize gas distribution in the real environment [14]. Their system visualizes in real-time by mapping the detected gas information on the floor surface to the color and size of the visualization model. Kataoka et al. proposed an AR system for real-time measurement and visualization of 3D sound fields, that are invisible to the human eye, which combines SLAM (simultaneous localization and mapping), an optical see-through HMD, and acoustic measurement technology [15]. By superimposing the measured sound field information on the real environment, it is possible to present information coherent with the environment. In this study, we use AR to superimpose objects that represent the observed CO_2 concentration on the real environment.

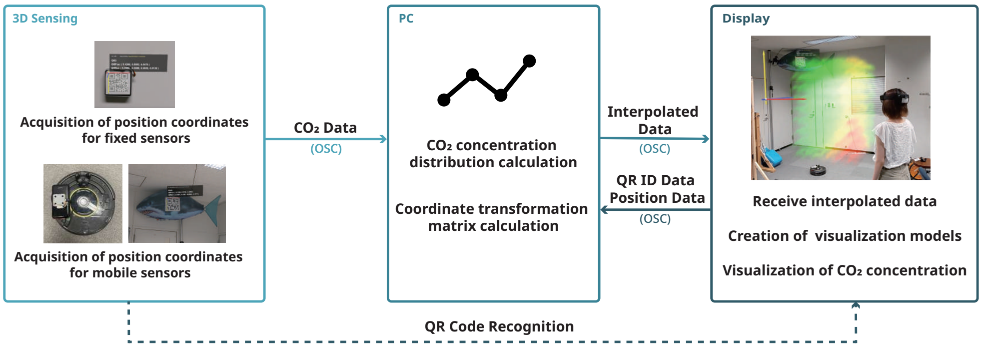

Figure 2: System overview. The position coordinates and measured values of all sensors are sent to the PC, and the CO_2 concentration distribution is calculated. The CO_2 concentration distribution is sent to and visualized by the AR-HMD.

3. Proposed System

In this study, we build an AR visualization system for CO_2 concentration using both fixed and mobile sensors. Figure 2 shows the system configuration. The system automatically calculates the distribution of CO_2 concentration in a room using the position coordinates and measured values of fixed and mobile sensors that patrol the room. We use UDP-based OpenSound Control (OSC) to communicate the measurement. The visualization model corresponding to the calculated CO_2 concentration is displayed in the form of AR in real-time using an AR-HMD. We believe that many people will be wearing AR glasses in the future. This system can be used for daily sensing of CO_2 concentration in offices and other indoor spaces. The system can also be used to stimulate ventilation behavior, to help optimize furniture placement, and to improve the layout of air conditioning equipment such as circulators and air purifiers.

CO_2 concentration is measured using a set of CO_2 gas sensor modules, which consist of a microcomputer and a CO_2 gas sensor. The CO_2 concentration distribution in a room can be estimated by linear interpolation from the position coordinates and measured values of fixed sensors (Fig. 1(b)) plased at various locations in the room and the mobile sensors that patrol the room. As a mobile sensor, we can use a CO_2 sensor module mounted on a moving object such as an airship robot (Fig. 1(c)) and an autonomous mobile robot (Fig. 1(d)). The position of the sensors can be acquired either by an AR marker attached on the sensor and a built-in camera of the AR-HMD, or by an external motion tracker. Assuming that the AR-HMD can estimate its self position by SLAM, each marker's position can easily be acquired by simply looking at its AR marker. One observation is enough for fixed sensors. In the case of mobile sensors, the position can be continuously acquired while the user is looking at the corresponding marker. While the user is not looking at the corresponding marker, the CO_2 concentration distribution is calculated using the last measurement. An external motion tracker can be attached on a mobile sensor if continous measurement is desired while the user is not looking at the marker. Automatic acquisition of the position coordinates of each sensor enables automatic calibration of sensor placement. The visualization space is divided into a voxel grid, and the CO_2 concentration at each grid point is calculated by linear interpolation from the position coordinates and measurements of each sensor. We render a particle-based smoke-like visualization model based on the calculated CO_2 concentration. The color of the visualization model continuously corresponds to the CO_2 concentration value. For example, low CO_2 concentrations can be represented by green and high concentrations by red. The visualization model is displayed in the real environment in real-time using the AR-HMD.

4. Implementation

4.1. Sensing

We implemented a prototype system using several CO_2 gas sensor modules those fixed in various indoor locations and those mounted on an autonomous mobile robot (iRobot Roomba 600 Series) and an airship robot (William Mark Air Swimmer Shark). The CO_2 gas sensor modules consist of a M5Stack Gray (120 $[g]$) and a TVOC/eCO_2 gas sensor unit (SGP30). The CO_2 concentration is measured at a sampling rate of 1 Hz. The microcomputer for the CO_2 gas sensor module mounted on the airship robot is a M5Stick C Plus (21 $[g]$) to reduce weight. TVOC/eCO_2 gas sensors mainly measure volatile organic compounds and hydrogen (H_2). The eCO_2 concentration is calculated

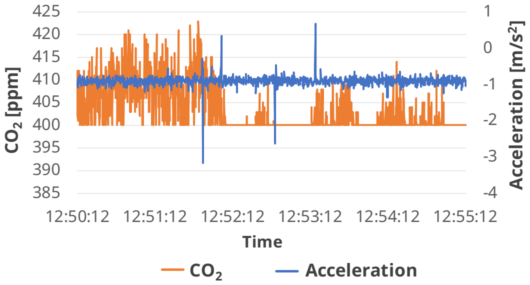

Figure 3: CO_2 concentration and microcontroller vertical acceleration measured by an autonomous robot during a 5-minute run.

based on the H_2 concentration. The minimum measurement value of the sensor is 400 [ppm]. Figure 3 shows example CO_2 concentration and acceleration of the microcomputer measured while the autonomous robot was running on the floor for five minutes. The measured CO_2 concentration did not change significantly even when the acceleration changed significantly due to collision.

4.2. Localization of fixed sensors

AR markers (QR codes) attached to the CO_2 gas sensor modules are detected by the built-in camera of the HMD to obtain the position coordinates of fixed sensors placed at various locations in the room. We use a Microsoft HoloLens 2 as an AR-HMD. Automatic acquisition of sensor position coordinates enables automatic calibration of sensor placement.

4.3. Localization of mobile sensors

If only fixed sensors are used, a large number of sensors are required to achieve spatially high-density 3D measurements. We thought that high-density 3D measurement could be realized by having a mobile robot mounted with sensors patrol the room. The positions of the mobile robots are tracked either by a QR code or by an HTC VIVE Tracker (for the autonomous robot). In the case of QR codes, the position can be continuously acquired while the user is looking at the QR code attached to the mobile robot. It is discrete data, but can be measured over a wide range. If continuous measurement is desired while the user is not looking at the QR code, an external motion tracker can be attached on the autonomous mobile robot. CO_2 concentration distribution can then be calculated with higher accuracy.

Regarding the calibration of the position sensing, first, the coordinate system of the tracker is aligned with that of the HMD. The position coordinates of the tracker in the coordinate system of the HMD are obtained by reading the QR code attached to the tracker with the built-in camera of the HMD. Four trackers with QR codes attached are used for calibration. A transformation matrix is calculated from the position coordinates in the HMD coordinate system and the position coordinates in the tracker coordinate system. The position coordinates of the tracker in the coordinate system of the HMD are calculated using the transformation matrix and obtained automatically.

4.4. Estimation of CO_2 concentration distribution

The visualization space is divided into a voxel grid, and the CO_2 concentration at each grid point is calculated by linear interpolation from the position coordinates and measurements of each sensor. The weighted average method is used to estimate the value of each grid point from irregularly distributed measurements [16]. The weight w_p, which is inversely proportional to the square of the distance r_s from each grid point (x_i, y_j, z_k) to the measurement point by the fixed sensors (x_s, y_s, z_s), is given by Eq. 1:

$$w_s = \frac{1}{(r_s^2 + \alpha^2)^s} \tag{1}$$

where α and s are parameters that specify the weights. The smaller α, the higher the data sufficiency, and the larger s, the more pronounced the difference in weights between the far and near points. The weight w_m, which is inversely proportional to the square of the distance r_m from each grid point (x_i, y_j, z_k) to the measurement point by the mobile sensors (x_m, y_m, z_m), is decreased exponentially over time and is forgotten after a certain time. The exponential decay of the weights is given by Eq. 2:

$$w_m(t) = \frac{1}{(r_m^2 + \alpha^2)^s} e^{-\lambda t} \tag{2}$$

where t is time and λ is a positive number called the decay constant. The larger λ is, the faster w_m decreases. Finally, the CO_2 concentration estimation at the grid point f_{ijk} is given by Eq. 3 where F_s is the measured value by the fixed sensor and F_m is the measured value by the mobile sensor:

$$f_{ijk} = \frac{\sum_{s=1}^{N} w_s F_s + \sum_{m=1}^{M} w_m(t) F_m}{\sum_{s=1}^{N} w_s + \sum_{m=1}^{M} w_m(t)} \tag{3}$$

4.5. Visualization of CO_2 concentration distribution

We render a particle-based smoke-like visualization model based on the calculated CO_2 concentration. The visualization model is displayed in the real environment in real-time using the AR-HMD as shown in Fig. 4. This method is considered semi-transparent volume rendering. It is similar to a traditional splatting technique, but instead of splatting, the smoke particles are assigned a color based on the CO_2 concentration and opacity. The size of each voxel is 20 x 20 x 20 cm and the spatial resolution is coarse, so simply filling the image with a single color will result in noticeable jaggies. In addition, low transparency reduces the visibility of the real environment, while high transparency reduces the visibility of the visualization. For these reasons, we decided to use particles for visualization. The color of the smoke particles is continuously mapped to the CO_2 concentration, for example, green for low and red for high. The transfer function can be changed by a configuration file depending on the user preference. The latency for the CO_2 gas sensor measurements to be reflected in the visualization model is approximately 887 ms.

4.6. User evaluation

Ten participants in their twenties experienced the prototype system for about five to ten minutes. Afterwards, a 10-question questionnaire was administered, consisting of four questions to investigate awareness of ventilation, five questions to evaluate the system, and free-response questions. In a survey on ventilation awareness, 80% of respondents indicated that ventilation is important. However, 90% of the respondents did not know that CO_2 concentration should be kept below 1000 [ppm] to maintain good indoor air quality. This suggests that a means of communicating the need for ventilation is needed. A Likert scale of 5-points was adopted for the evaluation of this system. The questions are shown in Table 1. The distribution of the survey results is shown in Fig 5. From the responses collected for Q1, Q2, Q3, and Q4, it can be concluded that all four categories of visual clarity of high concentration areas, visual clarity of differences in concentration distribution, increased awareness of indoor air quality, and increased awareness of ventilation show positive trends. The results of Q5 suggest that AR visualization may be a more effective means of communicating the need for ventilation than conventional methods such as displaying numerical values on a 2D display. The following are the main opinions and impressions obtained from the free writing. Most participants appreciated the system for ease of understanding the CO_2 concentration distribution. Some participants also gave us an idea for better visualization and additional functions which encouraged further work.

- It is easy to see where the CO_2 concentration is high or low, and to feel the gradual change.
- I felt that the visual representation of CO_2 concentration emphasized the dangerous state of my location more than the 2D display.

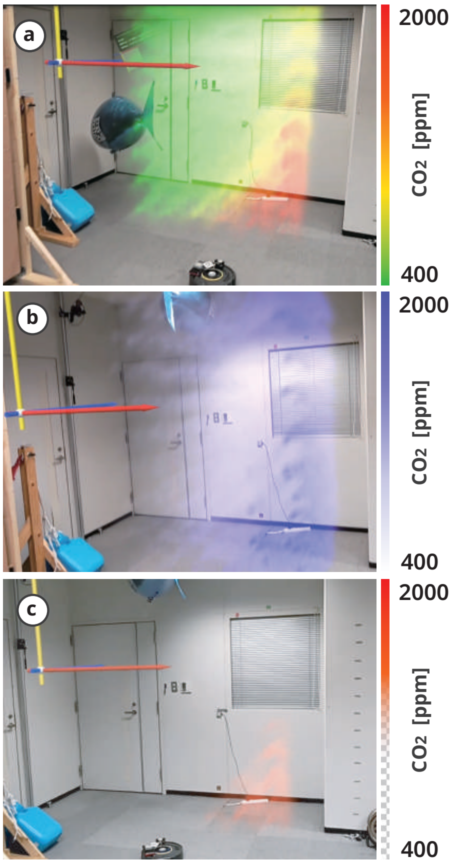

Figure 4: Example visualization models of CO_2 concentration distribution. (a) Four colors, (b) One color with different intensity, (c) High CO_2 concentration only.

- I felt that the AR visual display would encourage feelings of wanting to ventilate without knowing the standard for carbon dioxide concentration.
- It is better to display visualization objects only in areas of high CO_2 concentration to promote ventilation behavior.
- The visualization model in the foreground was easy to see but difficult to perceive from some viewpoints because it was difficult to perceive depth.
- I would like to see a correspondence chart between colors and actions to be taken.

5. Limitations

The color assignment of the visualization model is set to be heuristically easy to see, referring to the recom-

Table 1
Questionnaire for user evaluation.

	Question	**Responce Type**
Q1	I was able to recognize the location and range of high CO_2 concentrations.	5-Point Likert (1:Strongly Disagree; 5:Strongly Agree)
Q2	I was able to visually recognize the difference between areas of low and high CO_2 concentrations.	5-Point Likert (1:Strongly Disagree; 5:Strongly Agree)
Q3	I increased my interest in cleaner indoor air.	5-Point Likert (1:Strongly Disagree; 5:Strongly Agree)
Q4	I increased my awareness of ventilation.	5-Point Likert (1:Strongly Disagree; 5:Strongly Agree)
Q5	Which do you think is a more effective means of indicating the need for ventilation compared to the method of displaying values on a 2D display?	5-Point Likert (1:2D Display; 5:AR)

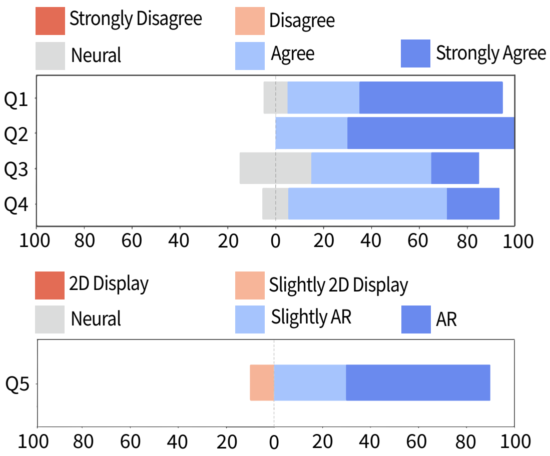

Figure 5: User evaluation results.

mended standard of the Ministry of Health, Labor and Welfare, Japan. However, since it is unclear whether this is the optimal color mapping, we plan to experts for their opinions. Another problem that is always present in volume rendering is that the depth information is difficult to understand due to the information in the foreground. We are considering performing thresholding to display only the darker areas, or adding a fog effect to display only a certain amount of the nearby area.

6. Conclusion and future work

We have proposed an AR visualization system for indoor CO_2 concentration distribution using CO_2 sensor modules, mobile robots, and an AR-HMD. In our system, the position coordinates of fixed sensors and mobile sensors that patrol the room are obtained using a built-in camera of the AR-HMD, enabling automatic calibration of sensor placement. The CO_2 concentration distribution in a room is estimated by linear interpolation from the position coordinates and measured values of every sensor. The visualization model corresponding to the automatically calculated CO_2 concentration is displayed in the real environment in real-time using the AR-HMD. We built a prototype using a Microsoft HoloLens 2 as an AR-HMD, a William Mark Air Swimmer Shark as an airship robot, an iRobot Roomba 600 Series as an autonomous mobile robot, and several CO_2 gas sensor modules that consist of a M5Stack Gray, a M5Stick C Plus and a TVOC/eCO_2 gas sensor unit. A preliminary evaluation revealed that the participants found the system useful and promising.

High-precision interpolation results can be obtained as the number of sensors used increases. We plan to conduct a scalability test to see how many sensors can be connected to our system. In the future, we plan to evaluate the accuracy of linear interpolation under multiple conditions, such as the number of sensors used, and when measurements are taken with only fixed sensors or only mobile sensors. In addition, we will evaluate the accuracy of the linear interpolation in the case of long-term measurement. We use a William Mark Air Swimmer Shark as the airship robot and an iRobot Roomba 600 Series as the autonomous mobile robot, but we currently do not control their movement. Our system is intended to be used in an environment where humans coexist with the robot, so it is necessary to implement an automatic patrol method for mobile robots that is compatible with an environment where humans coexist.

In the future, we will improve the color mapping for better visibility and encouraging ventilation. Our system can be used as a platform to visualize not only CO_2 but also other gases by changing the sensors mounted on the measurement modules. In the future, we will also support other sensors, such as an anemometer to change the decay rate of mobile sensor readings, and to visualize human movement and involvement over time.

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