Multiparametric measuring system for atmospheric monitoring

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Abstract. There are several studies in the literature on monitoring carbon dioxide concentrations in combination with various other parameters to assess indoor air quality. However, no study describes the monitoring of air quality in different locations of the same environment. The characterization of the spatial distribution of atmospheric parameters can contribute to more appropriate analyses, providing customized planning’s for improvements. The present work develops a multiparametric measuring system for real-time monitoring of the spatial distribution of carbon dioxide, temperature, humidity, particulate matter, volatile organic compounds, and barometric pressure. Preliminary results indicate the necessity of multiple-location measurement for appropriate air quality analyses.

Keywords. Indoor air quality, multiparametric, CO2 concentration.

1. Introduction

From the mid-1950s onwards, there has been a great rise in the use of appliances for conditioning the temperature and humidity of indoor environments. The use of air conditioners has resulted in greater exposure of people to air environments with limited renovation. In this condition, individuals may be exposed to pollutants originating mainly from the gases emitted by their own breathing, such as carbon dioxide (CO₂).

Exposure to high levels of carbon dioxide decreases the availability of oxygen in the inspired air and may lead to hypoxemia. Thus, occupants of these environments may not only suffer productivity impairments, but also present symptoms such as irritation of the mucous membranes (eyes, nose, throat), headache, dizziness, fatigue, and, in very critical events, cardiac and neurological disorders, which may result in death. Furthermore, the long-term continuous exposure to these conditions may lead to the development of chronic respiratory and heart diseases, among others [1].

There are several studies in the literature on monitoring carbon dioxide concentrations in combination with various other parameters to assess indoor air quality [10,11,13,14,16,17]. In many cases, air quality monitoring includes humidity and temperature measurements [11,13,14,16,17,18], and some studies include measurements of other quantities as volatile organic compounds (VOC) [10,11,17], particulate matter (PM) [11,17,18], illuminance [16,17], and eventually physiological
measurements such as blood pressure of college environment occupants in [10,13,14], or application of psychometric questionnaires to students of elementary school [18]. The literature, however, describes the monitoring of air quality quantities in a single position of the evaluated environment; no study investigates the space gradients of the parameters' value, measured in several locations of the room. The characterization of the spatial distribution of environmental parameters can contribute to a more appropriate analysis of the environment, providing customized planning/pings to improve the quality of each assessed indoor space. The evaluation of the spatial gradient also enables preventing the incorrect evaluation of the environment, regarding its quality adequacy or inadequacy.

The present work aims at developing a multiparametric measuring system with multiple units, for real-time monitoring of the spatial distribution of indoor air quality, based on measurements of carbon dioxide, temperature, humidity, particulate matter, volatile organic compounds, and atmospheric pressure.

2. Materials and Methods

Aiming at monitoring multiple air quality parameters at different points in an indoor environment, four autonomous measuring units (prototype level), called AirMeas, were developed. All the units measure temperature, air humidity, and carbon dioxide concentration level ($CO_2$). Two of these units measure particulate materials (PM) and volatile organic compound (VOC), and only one measures the barometric pressure.

The design of the measurement system incorporated, in addition to different sensors, a microcontroller, and a transmitter. In this way, each measuring unit can record, store, and transmit (Wi-Fi) measurement results to a digital platform. Through the Internet, one can access the information concentrated in the platform, regarding all autonomous units. Thus, an operator or an automated system can analyze in real-time the measured parameters to define the air quality in a given environment, allowing the execution of control actions.

The prototypes were built on a universal printed circuit board. Figure 1(a) shows the unit that incorporates sensors of $CO_2$ concentration, temperature, humidity, volatile organic compound (VOC), and particulate materials (PM). Two systems were built in this complete configuration, the AirMeas-33-1 and the AirMeas-33-2. Figure 1(b) presents the unit arrangement measuring only $CO_2$ concentration, temperature, and humidity levels. In this configuration, two other prototypes were developed, AirMeas-30-1 and AirMeas-30-2. In all the four developed units, the data is acquired at a frequency of 10 s and an external 5 V dc power is required.

![Figure 1](image)

**Figure 1.** Multiparametric measuring system. In (a) the AirMeas-33-1 model, while in (b) the AirMeas-30-1 model. The components are identified as: 1 - $CO_2$ Sensor, 2 - VOC Sensor (CCS811), 3 - VOC Sensor (IAQ coreP), 4 - Temperature and Humidity Sensor, 5 - Controller / Transmitter and 6 - Particulate Matter Sensor, 7 Atmospheric Pressure.

The microcontroller selected for the integration of these sensors is the ESP32 model, produced by Espressif Systems (device 5 in figure 1). It is widely used in IoT applications, and, thus, provides digital
interfaces adopted by various types of sensors, speeding up their integration. Besides, this microcontroller provides a Wi-Fi (IEEE 802.11) interface that enables wireless connection to a local area network. This functionality simplifies the installation of multiple detection devices in the same wired environment, needing a power-supply spot or a battery.

2.1. Processing and transmission of data
The integration software between the sensors and the microcontroller was developed through the Arduino integrated development environment, which allows the use of robust open-source libraries with numerous applications for sensing and controlling peripheral devices, as well as having protocols for data transmission used in IoT.

In this project, MQTT (Message Queuing Telemetry Transport) is used as a data transmission protocol. This protocol is widespread in IoT applications due to its low computational consumption, allowing it to run on restricted processing devices such as microcontrollers. The protocol also has a message acknowledgment system, which allows data retransmission in case of unavailability of the wireless network. In this way, the data measured with the sensors arranged in the AirMeas models is not lost in case of local network instability, being retransmitted once the wireless connection is stable.

After the microcontroller (ESP32) internal initialization, it connects to a local network through a router and accesses the internet to adjust its internal time clock (RTC). This action ensures synchronization of the various devices available for monitoring. After this initial procedure, the sensors initialization routines are performed, where parameters such as resolution, acquisition rate, among other settings are adjusted. Every 20 seconds, the microcontroller interrogates the sensors and transmits the measured values to a cloud-available MQTT server.

A Google cloud virtual machine instance receives data from ESP32 modules via the MQTT protocol. The operating system of this instance is the Debian Linux distribution. Commonly employed, this distribution supports various applications such as databases, web servers, among others.

The open-source platform for creating graphical interfaces Grafana has been selected for viewing sensor data. This platform allows high-quality graphics and indicators to be created through a web application, allowing data visualization through browsers, smartphones, tablets, among others, without the need to install any visualization software. The platform also supports several accessible databases, including InfluxDB that was selected for this application. InfluxDB is an open-source database specific to time series. This tool supports a large number of reading and writing operations required by monitoring and visualizing data. It also allows the creation of data retention policies and has a simplified installation process. The integration between the Grafana and InfluxDB tools promotes the development of robust applications for time series manipulation and visualization. Enables automatic data aggregation based on display screen resolution, enabling efficient database queries, regardless of point granularity or length of time required for viewing.

An application developed in Python runs on the virtual machine instance and receives data from remote devices via the MQTT protocol. Upon the arrival of data, the application validates these values and stores them in the InfluxDB database (Figure 2).
2.2. Sensors characterization and preliminary measurements in an indoor environment
Temperature and humidity sensors were calibrated using a Votsch model VCL 4010 climate chamber. The test consisted of placing the measuring units inside the climate chamber, which was programmed to condition a range of temperatures and humidity during 1 hour, for air conditions inside the climate chamber to reach equilibrium. Three test conditions were determined for temperature (20 °C, 30 °C, and 40 °C). For each of these thermal conditions, the humidity was varied in four levels (40 %, 50 %, 60 %, and 70 %), totaling 12 distinct conditions.

Although the CO₂ concentration sensor was still not calibrated, a characterization assay was performed in which the four developed units were placed within an airtight chamber. Thus, as the CO₂ level was kept almost static, the response of the four sensors could be compared among them, in controlled conditions. The test was performed in a laboratory space maintained without human occupancy, for 33 hours. The standard deviation of the four temporal recordings was analyzed to select the most stable sensor as a CO₂ concentration reference for mutual comparison. Thus, a correction factor for the other three sensors was obtained, allowing the comparison between the CO₂ levels recorded by each measuring unit. As the other sensors (VOC, PM, and pressure) were not yet characterized, their results will not be discussed in this paper.

Preliminary tests, using the calibrated temperature and humidity sensors and the adjusted CO₂ sensors, were performed to evaluate these parameters in an indoor environment. The sensing system was distributed in a researcher room (PUC-Rio), as shown in Figure 3, consisting of two compartments (room A and room B) connected by a door. The exit door and the air-conditioning system, which operates in a closed cooling cycle, are located in room B (Figure 3).
3. Results

In the calibration test of the AirMeas measuring system (Figures 1a and 1b), the mean square error of each sensor (temperature and humidity) was calculated for the range of 20 °C to 40 °C and humidity concentrations from 40 % to 70 %. Table 1 presents the mean square error, combined mean standard uncertainty, and expanded uncertainty values associated with temperature and humidity measurement for each of the sensors analyzed.

![Figure 3. Schematic floor plan of the indoor environment used for the testing with the developed measurement system distributed in four different positions. Only one of the sensors, AirMeas 30-2, is situated in the place of highest ventilation, in which the exit door and the air conditioner are located.](image)

| Sensor     | Temperature RMSE | uc   | U   |
|------------|------------------|------|-----|
| AirMeas 33 | 0.0875           | 0.0019 | 0.0038 |
| AirMeas 33 | 0.9834           | 0.0015 | 0.0029 |
| AirMeas 30 | 0.1112           | 0.0015 | 0.0030 |
| AirMeas 30 | 0.1554           | 0.0014 | 0.0029 |

| Sensor     | Humidity RMSE   | uc   | U   |
|------------|-----------------|------|-----|
| AirMeas 33 | 1.2051          | 0.0218 | 0.0436 |
| AirMeas 33 | 1.2551          | 0.0216 | 0.0433 |
| AirMeas 30 | 1.2835          | 0.0230 | 0.0459 |
| AirMeas 30 | 1.6406          | 0.0215 | 0.0430 |

Despite the reduced measurement uncertainty values of the analyzed sensors, there is a systematic error, whose correction was employed to enable a comparative analysis of the results obtained by distributing the sensors in the space of an indoor environment.

Figure 4 presents the results of the test for characterizing the CO₂ concentration sensors, performed in an airtight chamber. The four sensors presented a systematic difference between their recorded values (Figure 4). Figure 4 (a) presents the results before incorporating the adjustment to compensate for differences, and 4 (b) the records after the correction. All devices behaved equivalently over time, as
seen in figure 4 (a), with their values progressively stabilizing along an initial period until they reached constant levels of CO₂ concentration.

Figure 4. Record of CO₂ concentration obtained by the four developed units when positioned in a hermetically sealed chamber. In (a), records without offsetting their systematic differences, and in (b) records after adjustment.

Figure 5 presents the results obtained from the sensors distributed at different points of the internal space of a research environment, as shown in Figure 3. The records of CO₂ concentration, temperature, and humidity, obtained by the four units, are presented, respectively, in figures 5 (a), 5 (b) and 5 (c).

When closing the door between the two compartments of the environment, around 16 h and 30 min (Figure 5), the only sensor positioned in the compartment without the human presence (AirMeas-30-2, green registration) and located near the air conditioner and the exit door, showed a reduction in CO₂ concentration, temperature, and humidity values. On the other hand, these same quantities measured by the sensors of the other three units, positioned in the environment in the presence of the researcher, showed an increase in their values. With the reopening of the passage between Room A and Room B, just before 20 h, there is an abrupt rise in CO₂ concentration and humidity, with a more gradual temperature increase, recorded by AirMeas-30-2, located in Room B. In turn, the other sensors located in the compartment with human occupancy and less ventilation (Room A) present the opposite behavior.
Figure 5. Time records of $\text{CO}_2$ concentration in (a); temperature in (b); and humidity in (c); obtained by the four developed measurement units, distributed in a two-compartment indoor environment.

Figure 6 shows the volatile organic compounds (VOC) and the barometric pressure results recorded at the same time interval presented in figure 5. These VOC detectors are positioned in the unit Airmeas33-1, which is the closest to the human location during experiments. Both VOC sensors (figure 6a) show an increase in their values during the period in which the door between the two-compartment indoor environment is closed. The VOC sensor CCS881 presents a less evident variation due to automatic compensation of its value according to the temperature and humidity (figure 6a). An increase of barometric pressure, in figure 6b, is not associated with the indoor ventilation variations, but with a transition of local weather conditions occurring during the measurements. Particulate matter was monitored and showed small changes only when re-opening the inside room door.

Figure 6. Records of VOC concentration in (a); barometric pressure in (b).
These preliminary results indicate the possibility of using the developed system to analyze the spatial distribution of the measured parameters and the effect of conditions such as ventilation, area, human occupation and their location in space, on the indoor air quality.

4. Conclusions
A multiparametric measurement system have been developed for real-time monitoring of the spatial distribution of indoor air quality. Each unit of the system include sensors for measuring carbon dioxide, temperature, humidity, particulate matter, volatile organic compounds, and atmospheric pressure. In all the developed units of the system, figures 1(a) and 1(b), a digital platform implemented allowed analyzing, in real-time, the evolution of the measured quantities.

Preliminary results from the assessment of the spatial variation of carbon dioxide levels, temperature, humidity measured in a two-compartment indoor research environment indicate the need of multiple-site monitoring of the environment to achieve a proper analysis of its air quality. Particular conditions may lead to acceptable results in some regions of internal space and off-limits in other locations in the same environment. Spatial monitoring makes it possible to identify the most critical locations, thus enabling the development of more efficient initiatives to adjust the levels of atmospheric quantities of interest.

In the present study, the measurement units of the system were arranged in a plane at the same height relative to the ground. As future work, the effects of the positioning of the sensors along the ambient volume will be investigated by analyzing the quantities measured at different distances from the ground.

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