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Optical portable instrument for the determination of CO_2 in indoor environments

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Abstract

A portable device based on a colorimetric sensor to determine the atmospheric level of CO_2 gas is presented in this work. The system is based on a low-cost, low-power System on a Chip (SoC) microcontroller with integrated Wi-Fi. A user-friendly application was developed to monitor and log the CO_2 measurements when the system is connected to a Wi-Fi network. The sensing membrane is directly deposited on the surface of the colour detector, thus reducing the complexity of the system. This sensing membrane is formed by a pH indicator α-naphtholphthalein, tetramethylammonium hydroxide pentahydrate, 1-ethyl-3-methylimidazolium tetrafluoroborate, Tween 20 and hydroxypropyl methylcellulose as the hydrophilic polymer. The system has been fully characterized, obtaining response and recovery times of 1.3 and 2.5 s, respectively, a limit of detection of 51 ppm, and an average resolution of 6.3 ppm. This portable device was applied for the in-situ determination of CO_2 gas in the atmosphere inside classrooms in several secondary schools. The measurements were taken during complete workdays and the results were statistically compared with the same measurements taken using a commercially available non-dispersive infra-red (NDIR) device. No significant statistical differences were found between the results obtained using both devices. A complete statistical treatment of the measurements made with the proposed portable device was carried out. The obtained results show that the concentration of CO_2 gas in some schools was higher than the desired concentration, with regard to influencing the student's health, safety, productivity and comfort. This demonstrates the need to control this parameter to ensure appropriate indoor environmental quality (IEQ).

Keywords: Portable device; colorimetric CO_2 gas sensor; indoor environmental quality; autonomous monitoring.

1. Introduction

Air quality monitoring is essential to ensure a good quality of life. Not only is outdoor air quality important, but also indoor air quality, since nearly everybody spends a lot of time indoors. Poor indoor air quality is mainly caused by inadequate ventilation, as a consequence of not bringing enough outdoor air inside to dilute emissions from indoor sources, as well as not carrying indoor air pollutants outside. High values of temperature and humidity can also increase some pollutant concentrations. Children and young adults are especially vulnerable, because they spend a lot of time in classrooms, usually with a high occupancy. Some research has found negative health effects from prolonged exposure to various gases and particles in schools, which makes it necessary to control and monitor them [1]. Stationary analytical devices used in the routine quality analysis of atmospheric air are expensive and complex to transport and install on site [2]. As an alternative, portable analysers exist to detect and identify specific compounds or groups of compounds present in the air, both indoors and outdoors [3-6]. They are normally equipped with a USB or COM interface for quick and easy communication and data transfer to a desktop computer or laptop, their own rechargeable or replaceable power supply, a built-in cache for storing measurement data and LCD displays [7]. Low-cost devices for data collection and analysis are a very interesting option that can make indoor environmental quality (IEQ) assessment affordable. In this respect, some sensing systems for IEQ control based on an Arduino platform have been developed, basically consisting of an Arduino Uno board, an SD memory card for data storage, and a number of low-cost sensors for temperature, relative humidity, occupancy, lighting, and CO_2 concentration [8]. The integration of wireless communication into these systems reduces the setup time by avoiding the need for additional wires between the sensors and the central data acquisition system, also offering the possibility to collect all the data in one node for storage in a central computer [9, 10]. In addition to these advantages in portable indoor air quality measurement systems, other platforms use the cloud-based VOLTRON software, which can be included in open-source designs. This platform has been used to develop an Xbee agent for the VOLTRON software that enables robust wireless data collection, demonstrating its application in IEQ evaluation in real buildings [11].

The popularity of this kind of portable instrumentation is increasing due to its good performance in terms of short response times, automatic operation for long periods of time, high resolution, low cost and easy operation. In some cases, the instruments are even supplied with self-calibration devices, filling-up systems, auto-regeneration of reagents and independent power supply systems. Moreover, thanks to the on-site use of field portable instruments, errors resulting from sample transport and storage can be eliminated [12]. They are also very useful in process monitoring applications and scenarios that require an emergency response. Ideally, these systems should be noiseless so that they do not bother the building occupants, and can, thus, obtain spatially and temporally representative air pollution data. However, they also have some disadvantages, such as higher detection limits and lower sensitivity than the data obtained in laboratory conditions, a strong influence of environmental factors on the instrument performance and a high possibility of sample contamination in the field.

Among the main gases and pollutants usually monitored for air quality evaluation, CO_2 is undoubtedly one of the most important. In normal conditions, the CO_2 present in the atmosphere is around 300 ppm, which does not pose a threat to human health. Levels up to 1000 ppm are considered permissible in closed spaces [13], and this the typical level found in occupied spaces with good air exchange. However, levels of CO_2 between 2000 and 5000 ppm can cause of headaches, sleepiness, bad concentration, an increased heart rate and slight nausea. Finally, CO_2 levels above 5000 ppm can lead to loss of oxygen, which can cause permanent brain damage [14].

In closed spaces holding many people, CO_2 levels can exceed those recommended for health reasons, due to the increase of CO_2 from exhaled air. Therefore, it is highly advisable to have a quick way to determine the CO_2 level in closed crowded places [15, 16]. There have been some studies to monitor the levels of CO_2 inside classrooms to determine whether air quality regulations are being complied with, using continuous commercially available CO_2 sensors [17, 18].

This study verifies the feasibility of a portable instrument based on an optical membrane previously developed by us [19] to determine the evolution of CO_2 during activities in secondary school classrooms. The results obtained by our platform are compared with a commercially available device that is used as the gold standard to measure CO_2 concentration.

2. Materials and methods

2.1. Reagents and Materials

Hydroxypropyl methylcellulose (HPMC, Methocel E-5, LV USP/EP premium grade) from Dow Chemical Iberia S.L. (Tarragona, Spain) was used as hydrophilic polymer. 1-ethyl-3-methylimidazolium tetrafluoroborate, α-naphtholphthalein, tetramethylammonium hydroxide pentahydrate (TMAOH), and Tween 20, from Sigma–Aldrich Química S.A. (Madrid, Spain). Sheets of Mylar-type polyester from Goodfellow (Cambridge, UK) were used as support for the membranes.

The standard mixtures to characterize the membranes were prepared using N_2 as the diluting gas, controlling the flow rates of the high purity CO_2 and N_2 gases that enter the mixing chamber with computer-controlled mass flow controllers (Air Liquide España S.A.). The system works at a total pressure of 760 Torr and a flow rate of 500 $cm^3 \cdot min^{-1}$.

2.2. Instruments and software

To compare the experimental results obtained with the portable device developed in this study, the commercial NDIR carbon dioxide gas sensor data logger Perfect Prime CO2000 (EU) (Solomon Smart Ltd, Hong Kong) was used.

To characterize the CO_2 sensing membranes, steady-state luminescence measurements were performed using a Cary Eclipse Varian Inc. (Palo Alto, CA, USA) luminescence spectrometer. The measurements were made using a homemade cell holder composed of two metallic triangular prisms that support the membrane and lead the gas flow towards it. The phosphorescence of the membranes was measured using a gate time (t_g) of 10 ms and a delay time (t_d) of 0.15 ms, with excitation and emission slit widths of 2.5 and 5 nm, respectively, working at λ_{ex} = 537 nm and λ_{em} = 650 nm. All measurements were made in triplicate to check for experimental errors.

Sofware Jasp v.0.8.4 was used in the statistical treatment of the measurements made with the proposed device and with the commercial device.

2.3. Sensing membrane preparation

The sensing membranes for CO_2 were prepared using a cocktail containing 0.02 % of the indicator α-naphtolphthalein, 0.7 % HPMC, 0.84 % TMAOH, 0.38% Tween 20 and, 0.069% 1-ethyl-3-methylimidazolium tetrafluoroborate [20]. The CO_2 sensor was prepared by casting 10 µl of this cocktail in two separate amounts of 5 µL directly on the colour detector sensing surface of the portable instrument. After that, the membrane was left to dry for one day at room temperature.

2.4. System description

The block diagram of the instrument is shown in Figure 1. It consists of two differentiated parts: the sensing module and the microcontroller unit (MCU).

Figure 1

In the sensing module, the CO_2 sensitive membrane is placed on the surface of a digital colour detector model S11059-02DT (Hamamatsu Photonics, Japan), an I2C interface-compatible colour detector sensitive to red (λ_{peak}=615 nm), green (λ_{peak}=530 nm), blue (λ_{peak}=460 nm), and infrared (λ_{peak}=855 nm) radiation. This device codifies the measured incident radiation in four digital words of 16 bits. An LED model SML-010VTT86 (ROHM Semiconductors, Japan) with peak emission at 650 nm is used as light source. This device is aligned with the sensitive membrane and the colour detector at a fixed distance of 2 mm. In order to produce a stable emission, the LED is voltage-biased using a regulator model NCP1117 (ON Semiconductor, USA), which provides a stable voltage of 2 V. A temperature and humidity sensor model SHT15 (Sensirion AG, Switzerland) is included for the compensation of the thermal and humidity dependence of the sensing membrane.

The MCU is embedded in an ESP32 module (Espressif Systems, China). The ESP32 is a low-cost, low-power, Dual-Core 2.4 GHz Wi-Fi Dual-Mode Bluetooth (BT) System-on-Chip (SoC) combo MCU designed for mobile, wearable electronics and Internet of Things (IoT) applications [21, 22]. It features an Xtensa Dual-Core 32-bit LX6 CPU operating up to 240 MHz, 520 kB SRAM, 12-bit SAR ADC up to 18 channels, a built-in Wi-Fi card that supports IEEE 802.11 b/g/n standards, Bluetooth v4.2 BR/EDR and Bluetooth Low Energy (BLE). In addition, the ESP32 module has 40 general purpose I/O pads that can be used to connect external components and sensors. It also includes SPI and I2C interfaces.

A very user-friendly application has been created using the myDevices Cayenne IoT cloud platform to monitor and log the temperature and CO_2 measurements when the ESP32 module is connected to a Wi-Fi network. MyDevices Cayenne (myDevices, CA, USA) is a solution for building IoT applications based on well-known platforms such as Arduino or Raspberry Pi. Very recently, this platform also added support for ESP32 based development boards, making it possible to programme the ESP32 chip in the Arduino IDE in order to monitor and control this module from anywhere in the world through a very intuitive dashboard. The communication between ESP32 and Cayenne is done by means of a lightweight protocol called Message-Queue Telemetry Transport (MQTT). The Cayenne Cloud acts as the MQTT ‘broker’, which is the mediator between ESP32 and any other devices connected on the network (see Figure 1). The Cayenne platform manages every sensor and actuator client device that wishes to send and receive data using the Cayenne Cloud, so that users are able to monitor and control the ESP32 and their connected devices from anywhere, simply by accessing the Cayenne platform. The dashboard created for our application can be accessed anytime from anywhere via a webpage using any Internet web browser (Figure 2a) or by means of the Cayenne smartphone app (Figure 2b), which is available for both Android and iOS devices. It consists of several custom widgets showing the desired information in real time, that is, the current temperature and humidity and the current CO_2 concentration computed from the colour sensor measurements. The application also saves a history log of every magnitude with timestamps, which can be exported to a file and saved.

Figure 2

3. Results and Discussion

3.1. System characterization

The Perfect-Prime CO2000 commercial sensor data logger was used as the gold standard to measure the CO_2 concentration. Its response was checked when exposed to different known concentrations of this gas. The instrument was proved to be suitable for the study since the measurement range covers the atmospheric levels required for this application.

The sensing membrane for CO_2 used in this study was previously developed on a plastic solid-state sensor membrane containing a luminophore (PtOEP) that presents phosphorescence quenching by the deprotonation form of a non-luminescent pH indicator (α-naphtholphthalein) [23]. The sensing chemistry was placed on the optoelectronic components: LED with the dye and photodetector with the pH indicator. In this study, the design of the portable device is simplified by substituting the membrane containing PtOEP placed on top of the 525 nm LED with an LED that emits that PtOEP at the same wavelength (650 nm). This increases the stability of the sensing area while eliminating a potential source of error. The instrument was calibrated in the range of interest from 100 to 4500 ppm of CO_2 at room temperature by measuring six replicas per point, resulting in a linear response, y = 0.6216x + 14404.9906, with good fit ($R^2 = 0.9985$).

The limit of detection (LOD) was calculated as usual by using LOD = t_0+3s_0, where t_0 is the average blank signal and s_0 is the critical level or standard deviation of the blank, which is determined from eight replicas. The LOD found using this approach was 0.005% CO_2 (51.3 ppm). The limit of quantification (LOQ) was obtained assuming that LOQ = t_0+10s_0, resulting 0.015% CO_2 (153.4 ppm). The resolution of the system was obtained from the fitting function of calibration by taking derivatives in both terms and approximating these derivatives to increments:

$$\Delta CO_2 = \frac{\delta f}{\delta I} \Delta I \qquad \text{(eq. 1)}$$

where *f* is the fitting function and Δ*I* is the error or uncertainty in the determination of the intensity *I*. In this case, this error is taken as the standard deviation of the replicas in each measurement of the calibration (Figure S1). The mean resolution in the range studied was found to be 6 ppm.

The stability of the sensing membranes, both short-term and long-term, is a very important issue for any real application. Stability was studied by means of an inter-day study, using the same sensor for 8 days (n = 15 per day). The inter-day standard deviation was 1.50%, which is in agreement with our previous stability studies of the α-naphtholphthalein membrane, where more than one-year long-term stability of the indicator membrane was demonstrated with no special storage conditions [20].

Reversible operation, quick response time and high photostability are the essential criteria for practical applications of optical sensors. To investigate reversibility and response time, the sensing membranes were exposed to alternating atmospheres of pure CO_2 and pure nitrogen as shown in Figure 3.

Figure 3

The response time between 10% and 90% of the maximum signal was 1.3 s, while the recovery time from 90% to 10% was 2.5 s. In both cases, the signal change was fully reversible and hysteresis was not observed during the measurements. The obtained values are better than in previous studies [24], which is probably due to the inclusion of ionic liquids, as we observed that they produce a significant improvement in recovery and response times and increase the sensor's lifetime [20].

As usual with sensors based on acid-base transduction, the presence of acid gases produces interference. That is the case with acid gases such as SO_2 and HCl, which have a strong interference, as expected. Nevertheless, gases such as CH_4 and O_2 do not produce any change in the signal when in contact with the sensor.

It is also well known that temperature and humidity influence the response of these solid CO_2 gas sensors [25], especially at high values of both parameters. This problem can be solved by knowing the dependence of both variables on the sensor signal in order to introduce correction factors.

To check the influence of temperature, the prototype was put inside a thermal chamber, and calibrations at different temperatures were conducted. Figure 5 shows a decrease in sensitivity while the temperature increases, which is attributed to the reverse dependence of the CO_2 solubility in the pH indicator membrane on temperature [26]. Each curve in Figure 4 can be linearly fitted. The slope m and y-intercept y_0 of these fittings can be related to the temperature in the form:

$$m = -7.99 \cdot 10^{-3} \cdot T + 0.245 \ (R^2 = 0.988) \qquad \text{(eq.2)}$$

$$y_0 = -60.145 \cdot T + 16192 \ (R^2 = 0.976) \qquad \text{(eq.3)}$$

Thus, the correction of the temperature drift in the response of the sensitive membrane is programmed into the microprocessor unit.

Figure 4

The influence of the relative humidity was studied at room temperature (25ºC) in a range between 10 and 90%. The results obtained are presented in Figure 5. As can be seen, the relative humidity has a strong influence on the response of the instrument, which must be corrected by including a humidity sensor in the portable device.

Figure 5

Table 1 shows the comparison of our proposed prototype and different optical CO_2 sensing devices found in the literature.

Depositing the pH indicator on the photodetector improves the results in terms of detection limits and recovery and response times. The main difference with respect to previous studies [23, 24] lies in the composition of the membrane: a different polymer that makes it possible to prepare it in water along with a surfactant to improve the surface tension of the cocktail; a phase transfer agent to improve the stability of the membrane [27]; and the addition of an ionic liquid that increases the lifetime while reducing the response and recovery times [20].

A comparison of response times of the proposed sensor and the dedicated instruments found in the bibliography [23, 24] shows that the detection limits are very similar in all cases. Only when HPTS is used as indicator is the response time somewhat higher than with the rest [32]. The sensor to determine CO_2 in a multianalyte platform [11, 28] has accuracy values of 30 and 50 ppm, respectively, which are considerably higher than those found with our prototype.

3.2 Application to indoor atmosphere

To check the applicability of the instrument to study indoor CO_2 concentration, continuous monitoring was carried out in twelve secondary schools, with the prior permission of the Provincial Delegation of Education of Granada (Spain). Ten secondary schools and two training centres in the region of Granada participated in this study (see Table 2, which presents the characteristics of the different classrooms). The measurements were made on different days, with experimental values of pressure and temperature between 1000 and 1028 hPA, and 15 and 20 ºC, respectively. The data was collected in a similar way in all the buildings where the study was conducted: both the portable device and the commercial sensor were placed on the teacher’s table. Both instruments were left in the secondary schools during the morning from 8:00 h (before the students arrived) until 14:30 h, and from 16:30 h to 21:00 h. In the two training centres, the instruments only measured from 16:30 h. to 21:00 h in the afternoon, the hours when they were in operation. Figure 6 presents an example of the data registered with the portable and the commercial devices over 5 hours of classes in one classroom. As can be seen, both curves show the same trend, which is to be expected in a densely occupied closed classroom with a low ventilation rate [29]. A low indoor environmental quality (IEQ) is observed with CO_2 levels above 2000 ppm throughout the period.

Figure 6

Calibration

In order to check whether the experimental values obtained with our prototype and the reference instrument are equivalent, a simple linear regression was performed. The results obtained partially support this hypothesis (see Figure S1 and Table S1), with R^2 close to 1 (0.902). However, the obtained p-value associated with the independent term is significantly different from zero, the desired value. On average, the developed prototype measures a value only slightly lower than the commercial unit (15 units lower). The fact that the correlation coefficient is close to 1 suggests that the partial lack of adjustment is due to some influential value, as the graph shows. As an alternative analysis to the regression conducted, we applied a Wilcoxon-Mann-Whitney test to verify if the values obtained by both devices are equally distributed, in that the measurements from one are not significantly greater or lesser than those from the other. This was confirmed by the Wilcoxon-Mann-Whitney test (W=3034, p=0.770), hence there is no displacement bias. Additionally, in order to establish whether the dispersion of the means of the prototype and the commercial device are equivalent, the Moses test was carried out (S= 143; p-value = 0.1348). In conclusion, the hypothesis that both dispersions are equal cannot be rejected.

Contrast of means by school

From the measurements obtained with the prototype, a test was done to look for statistically significant differences among the CO_2 average values observed per hour in the different secondary schools. Firstly, we checked for differences between the measurements made during the morning and the afternoon, depending on the measurement schedules. To that end, the t-Student test was used to verify the hypothesis of normality (Shapiro-Wilk test) and homoscedasticity (Test of Equality of Variances, Levene's). The results obtained from the application of the Shapiro-Wilk test in the morning and in the afternoon were W=0.935 and W=0.948, and p=0.002 and p=0.603, respectively. Levene's test recorded F=0.403, df=1 and p=0.528. From the results, it can be concluded that there is no normality in the measurements in the morning. This is possibly due to the fact that the measurements were taken during opening hours, when the CO_2 values are not affected by the personnel in the classroom.

In any case, the hypothesis that CO_2 measurements are equivalent in the morning and the afternoon can be rejected. Therefore, a separate analysis should be made of the data taken in the morning and in the afternoon.

Analysis of differences by school

The calibration of the proposed system was carried out including situational variables: classroom volume, number of occupants and time of day. The calibration graph for both devices including situation variables is presented in Figure S2. The prototype provides values equivalent to the commercial device regardless of the classroom volume, number of occupants and time of measurement. In fact, the correlation coefficient that accompanies the values of the prototype regression is close to 1, as would be expected in a calibration (see Supplementary Information). Additionally, an estimation of the increase in CO_2 levels was made as a function of the time, classroom volume and number of occupants (Figure S3).

There is an increase that only lessens during recess, at 11:00 h, probably due to classroom ventilation. The small decrease observed at 21:00 h may be due to the smaller number of measurements taken at that time. Considering average values, the value of the increase produced in the concentration of CO_2 is about 240 concentration units per hour. Special consideration must be given to the disparity of measurements per school, which are presumably due to the difference in the quality of the window closures. Table 3 summarizes the results obtained regarding the amount of CO_2 gas measured with our prototype and the commercial system, specifying the observation time (time of measurement) for each school.

4. Conclusion

A simple, low-cost, portable device for CO_2 gas monitoring in indoor environments has been presented. The proposed instrument is based on an optical sensor using a water solution of a pH indicator, α-naphtholtalein. The chemistry used in previous designs was simplified by eliminating the need to use a different sensing area containing the platinum complex (PtOEP) luminophore. Instead, an LED emitting at the same wavelength was used and the sensor membrane was directly placed on the top surface of the colour detector. Thus, a simple, portable, electronic device based on a low-cost, low-power SoC microcontroller with integrated Wi-Fi was designed. The system includes temperature and humidity sensors for drift correction. The information collected about the CO_2 is automatically logged and can be accessed in real time via a webpage or smartphone application. This portable instrument was applied to determine the concentration of CO_2 gas in several secondary schools, taking measurements simultaneously with a commercially available device. The results were statistically compared, concluding that there are no significant differences between the results found with both devices. The application of this methodology to evaluate air quality in the secondary school classrooms showed that in 5 out of the 12 schools studied, approximately 42% have CO_2 values above 2000 ppm, which are above the normal values established for this gas for health reasons. In conclusion, the results obtained are very promising, indicating that the developed device could compete with classic commercially available portable instruments.

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Conflict of interest

The authors declare that there are no conflicts of interest with regard to this study.

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Table 1. Comparison of performance of proposed instrument for CO_2 with literature.

Instrument type	Sensing membrane	Dynamic Range (%)	LOD (%)	t_{90}-t_{10} (s)	Remarks	Ref.
Dedicated	PtOEP/PVCD-αNTTLN /EC	0-100	-	31-117	Coated photodetector-coated LED	[23]
Dedicated	α-naphtholphthalein /EC	<100	0.0066	11 - 55	PEDD technique	[24]
Dedicated	NDIR	-	0.0004	-	Dual element detector	[30]
Dedicated	m-cresol purple/ hydrophobic membrane	0.005- 11.5	-	0.1-	LED-photodiode	[31]
Multianalyte Platform	K-30	0-1	-	-	Platform VOLTTRON	[11]
Multianalyte Platform	T6615 CO_2	0-0.5	-	120	IoT system	[28]
Multianalyte Platform	HPTS	2-5	-	48-76	Optical Fiber sensing array	[32]
Dedicated	α-naphtholphthalein / HPMC/IL	0.005-0.5	0.005	1.3 – 2.5 s	PEDD technique	Current study

αNTTLN: α-naphtholphthalein;PtOEP: Platinum octaethylporphyrin complex; PVCD: poly(vinylidene chloride-co-vinyl chloride); EC: ethyl cellulose; PEDD:paired emitter-detector diode; NDIR: non-dispersive infra-red; HPTS: 1-hydroxy-3,6,8-pyrene trisulfonic acid trisodium salt; HPMC: hydroxypropylmethylcellulose; IL: ionic liquid;

Table 2. Characteristic of classrooms under study.

High school center	Classroom dimensions (m)	Volume (m^3)	Number of students
1	7.69×8.01×2.88	177.86	32.0
2	10.38×6.31×3.19	209.29	28.0
3	7.73×7.828×2.94	178.04	26.0
4	8.67×6.69×3.73	216.79	31.0
5	8.20×7.09×4.33	251.87	28.0
6	12.18×4.40×3.32	178.00	17.0
7	9.20×5.29×3.19	155.25	29.0
8	8.50×6.79×3.10	179.48	25.0
9	6.28×9.20×3.00	174.00	12.0
10	7.35×7.66×3.18	179.05	32.0
11	8.40×7.02×2.91	171.64	34.0
12	17.50×6.62×2.90	335.96	43.0

Table 3. Comparison of average results found with the proposed prototype and with the commercial device

High School	**$[CO_2]$ prototype (ppm)**	**$[CO_2]$ commercial (ppm)**	**t**	**P**	**N**
1	824 ± 247	1020 ± 177	-1.71	0.11	7
2	1350 ± 4923	1552 ± 459	-0.74	0.50	6
3	1259 ± 257	1142 ± 264	0.80	0.50	6
4	2600 ± 486	2580 ± 460	0.07	0.94	6
5	1125 ± 362	1035 ± 449	0.41	0.70	7
6	1366 ± 469	1513 ± 499	-0.60	0.60	7
7	2423 ± 646	2668 ± 630	-0.70	0.52	6
8	2182 ± 1228	2102 ±1169	0.07	0.95	7
9	2625 ± 1024	2723 ± 796	-0.20	0.85	6
10	3133 ± 872	3025 ± 834	0.22	0.83	6
11	4255 ± 361	4252 ± 434	0.01	0.99	6
12	5311 ± 1053	5419 ± 1767	-0.13	0.90	6

Figure captions

Figure 1. Block scheme of the portable device.

Figure 2. Screen captures of the created dashboard using Cayenne platform accessed via (a) webpage and (b) the Android application.

Figure 3. Response and recovery times of the developed portable device with alternate atmospheres of CO_2 from 0% to 100%.

Figure 4. Thermal dependence of the sensing membrane from 5 to 35 ºC.

Figure 5. Influence of humidity on the response of the instrument.

Figure 6. Example of CO_2 measurements in one morning during a class session in a high school classroom.

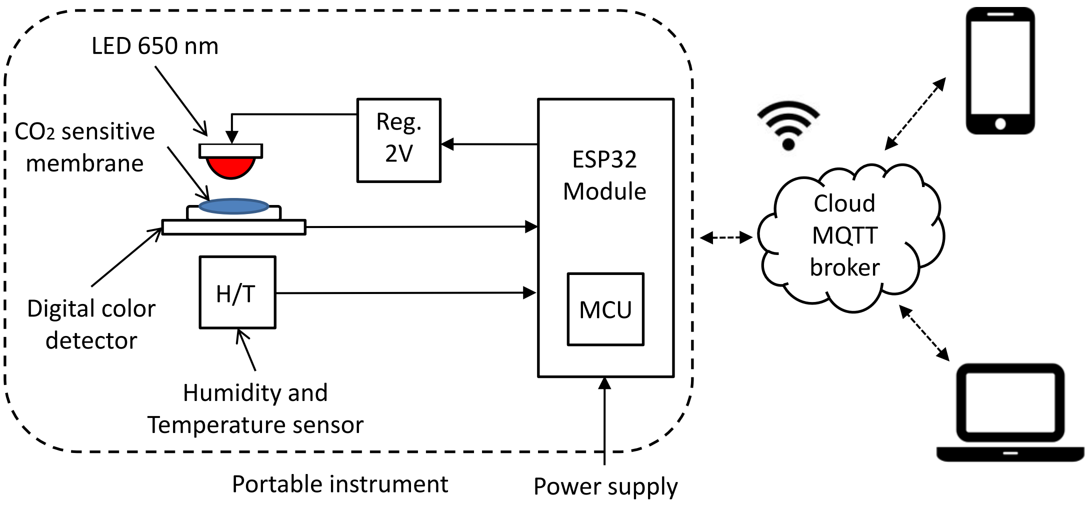
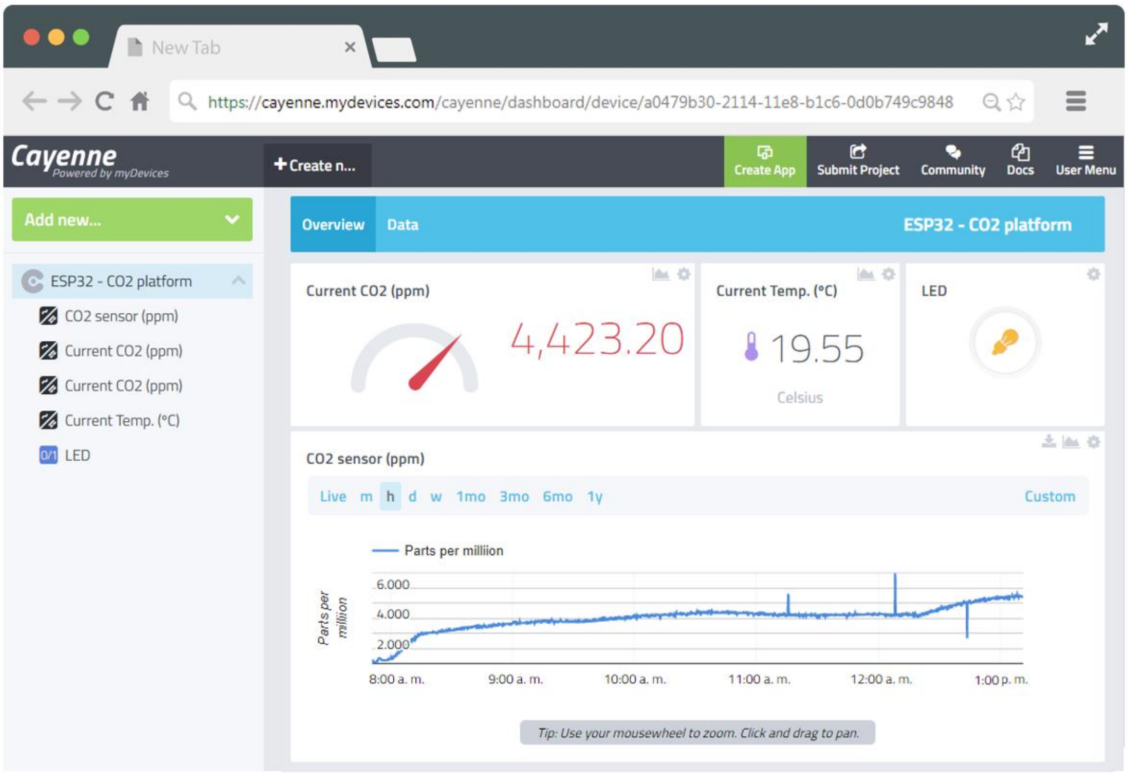
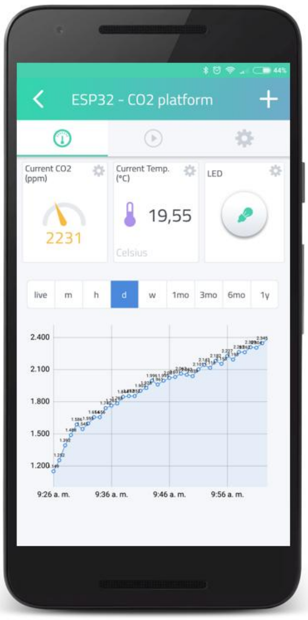

LED 650 nm
CO_2 sensitive membrane
Reg. 2V
ESP32 Module
MCU
Digital color detector
H/T
Humidity and Temperature sensor
Portable instrument
Power supply
Cloud MQTT broker

Figure 1


New Tab
https://cayenne.mydevices.com/cayenne/dashboard/device/a0479b30-2114-11e8-b1c6-0d0b749c9848
Cayenne
Powered by myDevices
+ Create n...
Create App
Submit Project
Community
Docs
User Menu
Add new...
ESP32 - CO2 platform
CO2 sensor (ppm)
Current CO2 (ppm)
Current CO2 (ppm)
Current Temp. (°C)
0/1 LED
Overview
Data
ESP32 - CO2 platform
Current CO2 (ppm)
4,423.20
Current Temp. (°C)
19.55
Celsius
LED
CO2 sensor (ppm)
Live m h d w 1mo 3mo 6mo 1y
Custom
Parts per million
Parts per million
6.000
4.000
2.000
8:00 a. m.
9:00 a. m.
10:00 a. m.
11:00 a. m.
12:00 a. m.
1:00 p. m.
Tip: Use your mousewheel to zoom. Click and drag to pan.

(a)


ESP32 - CO2 platform
Current CO2 (ppm)
2231
Current Temp. (°C)
19,55
Celsius
LED
live m h d w 1mo 3mo 6mo 1y
2.400
2.100
1.800
1.500
1.200
9:26 a. m.
9:36 a. m.
9:46 a. m.
9:56 a. m.

(b)

Figure 2

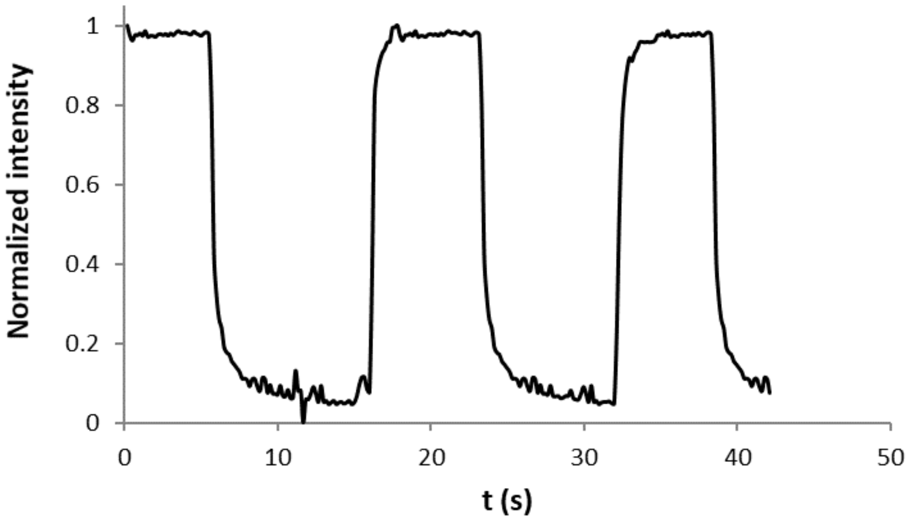


Figure 3

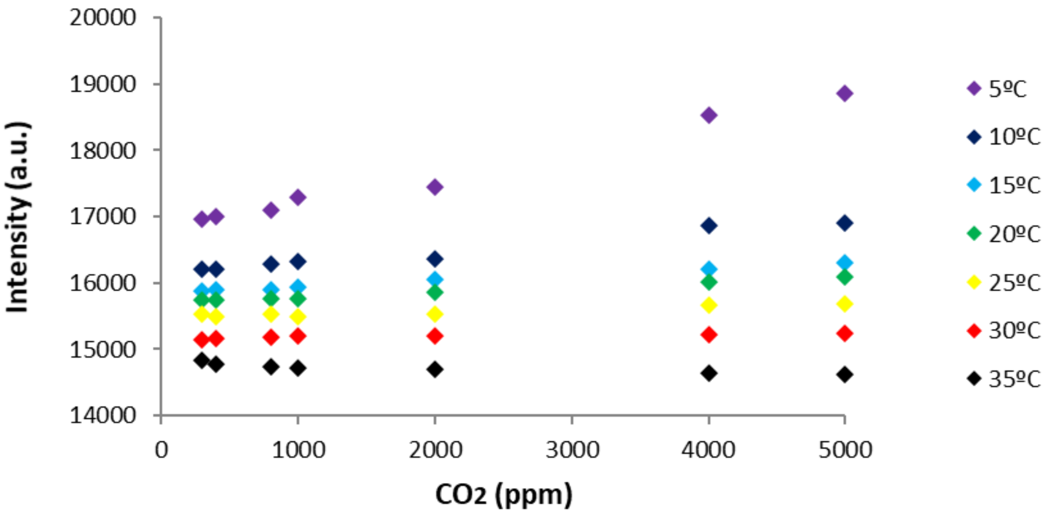

20000
19000
18000
17000
16000
15000
14000
Intensity (a.u.)
0
1000
2000
3000
4000
5000
CO2 (ppm)
5ºC
10ºC
15ºC
20ºC
25ºC
30ºC
35ºC

Figure 4

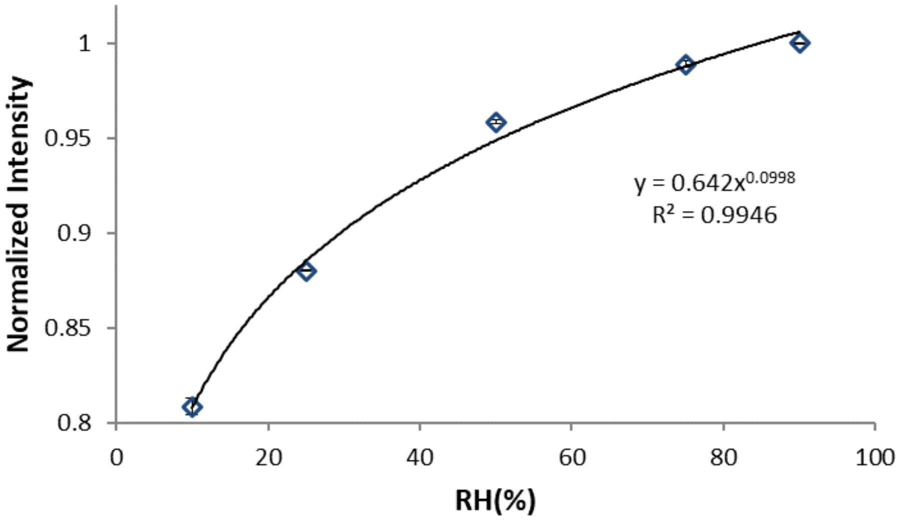

Normalized Intensity
1
0.95
0.9
0.85
0.8
0
20
40
60
80
100
RH(%)
$y = 0.642x^{0.0998}$
$R^2 = 0.9946$

Figure 5

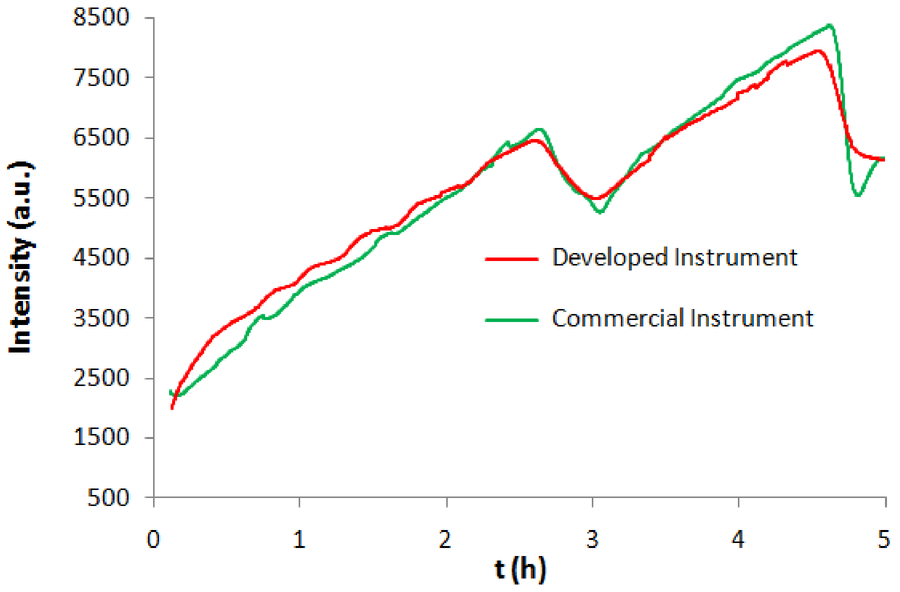

8500
7500
6500
5500
4500
3500
2500
1500
500
Intensity (a.u.)
0
1
2
3
4
5
t (h)
Developed Instrument
Commercial Instrument

Figure 6

Author Agreement

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Supplementary Material

***Graphical Abstract (for review)**