Low-cost Real-time IoT-Based Air Quality Monitoring and Forecasting

Hugo Martins[1], Nishu Gupta[2(✉)], M. J. C. S. Reis[3], and P. J. S. G. Ferreira[4]

[1] University of Trás-os-Montes e Alto Douro (UTAD), 5000-801 Vila Real, Portugal
[2] Norwegian University of Science and Technology, Gjøvik, Norway
[3] UTAD/IEETA, Vila Real, Portugal
[4] University of Aveiro/IEETA, Aveiro, Portugal
hugo.m.s.martins@gmail.com, nishugupta@ieee.org, mcabral@utad.pt, pjf@ua.pt

Abstract. The ultimate goal of a "smart city" is improving the quality of life of citizens, optimizing city functions and promote economic growth, through the use of technologies and data analysis. Attention should be placed in how the technology is used rather than on how much technology is available. The "smartness" of a city is measured using a set of characteristics, which includes environmental initiatives. Air pollution, in particular, has a great impact on the quality of life. Here, we will present a low-cost, real-time, compact, lightweight and robust prototype device (hardware and software) capable of measuring, monitoring and forecasting the indoor (closed spaces) air quality. This device produces an Indoor Air Quality Index (IAQI), which is calculated based on the CO_2 and Total Volatile Organic Compounds (TVOC) parameters. The IAQI is used to activate two RGB LED lights, where people can very intuitively be aware of the current and predicted air quality: excellent (green); good (light green); moderate (yellow); poor (orange); and unhealthy (red). The results achieved by the set of conducted tests proved that the device and IAQI are reliable.

Keywords: IoT · Real-time · Alert system · Air quality · Low-cost · Smart cities · Smart environment

1 Introduction

The ultimate goal of a "smart city" is improving the quality of life of citizens. This objective is pursued through the use of technologies and data analysis that aims at optimizing city functions and promote economic growth. Attention should be placed on how the technology is used rather than on how much technology is available. Environmental initiatives are among the most important characteristics used to measure the "smartness" of a city. Air pollution, in particular, has a great impact on the quality of life of citizens.

S. Paiva et al. (Eds.): SmartCity360° 2021, LNICST 442, pp. 307–320, 2022.
https://doi.org/10.1007/978-3-031-06371-8_20

Air pollution can be defined as any form of matter or energy with intensity, concentration, time or characteristics that may make the air inappropriate, harmful or offensive to health, inconvenient to public welfare, harmful to materials, fauna and flora or harmful to the safety, use and enjoyment of the property and the quality of life of the community [1].

The effects of poor air quality are generally not as visible as compared to other more easily identifiable factors. Several epidemiological studies have shown strong correlations between exposure to air pollutants and the effects of morbidity and mortality, caused by respiratory (asthma, bronchitis, pulmonary emphysema and lung cancer) and cardiovascular problems, even when the concentrations of pollutants in the atmosphere do not exceed the legally prescribed air quality standards. The most vulnerable populations are children, the elderly and people with respiratory diseases [2,3].

According to the World Health Organization (WHO) "ambient air pollution accounts for an estimated 4.2 million deaths per year due to stroke, heart disease, lung cancer and chronic respiratory diseases" [4]. What is more intriguing is that almost 91% of the world's population lives in places where the bad air quality levels exceed the limits recommended by the WHO.

Air quality management aims to ensure that socio-economic development takes place in a sustainable and environmentally safe manner. Thus, actions to prevent, combat and reduce pollutant emissions and the effects of degradation of the atmospheric environment are essential. Ideally, actions should be developed that allow for a complete and real-time mapping of air quality. Indoor air quality meters are used to prevent, for example, mildew, or monitor CO_2 levels or detect gas leaks. Whether portable or permanent, this air quality monitoring equipment is essential to ensure the health and safety of people, animals and plants.

There are commercially available air quality monitoring devices that meet various industry standards related to personal safety and are used to detect, measure and monitor relative humidity, ambient temperature, carbon dioxide (CO_2) levels, Volatile Organic Compounds (VOC), carbon monoxide (CO), nitrogen dioxide (NO_2), oxygen (O_2), ozone (O_3) and other flammable, hazardous or toxic gases. Some of these air quality measurement devices feature an automatic calibration function that allows for easy calibration of the gas detector. Some of these devices also have the ability to store measurement values, and can later transfer the measurement data to a computer for more detailed analysis. However, these devices are generally of price, weight and dimensions that can be considered high. On the other hand, these systems do not provide any form of sharing the data resulting from the different readings of air quality, being it on a website or any other form.

Here, we will present a low-cost, compact, lightweight and robust device to measure, monitor and forecasting the indoor (closed spaces) air quality in real-time. The forecasting is based on a very low computational cost algorithm to determine the first derivative of discrete band-limited signals.

The solution presented here can be used, for example, by the owner of a restaurant, cafe, or bar, to show their customers that the air quality in their establishment is recommended, and that their customers can be accompanied by their children who are not exposing them to polluted environments. On the other hand, being the device compact, lightweight and of small dimensions, it can be easily transported and/or re-positioned. The way in which the device is powered, by a battery and/or a charger, contributes to this flexibility. Please refer to Figs 3 and 4 below, for an overview of the proposed system. This device can be used to create a "social network" where users share their indoor air quality index data. These data can then be used by local, regional and national level authorities to devise measures for improving citizens' life.

2 Air Quality Index and Measures

An air quality index (AQI) is a descriptive scale used to show how polluted the air is. Unfortunately, there is no standard AQI available, and even the research on the health effects of air pollution in short time frames is something not profoundly studied. This is the main reason why air quality indexes are typically only provided for time periods of an hour or longer. Besides, the different indexes used are more effective when measuring outdoor air quality. The concentrations of some air pollutants in indoor environments can be between two to 10 times higher than in outdoor environments. This justifies the need to notify people living in indoor environments, as soon as possible, when air quality deteriorates. By so doing, people can take immediate and direct action to remedy the situation.

The Total Volatile Organic Compounds (TVOC) concept has been established as a practical time and cost-effective method to assess indoor environments for contamination. Table 1 presents the TVOC exposure recommendations issued by the German Federal Environmental Agency [5,6].

Table 1. Total Volatile Organic Compounds (TVOC) exposure recommendation [5,6] (ppb—parts per billion).

Level	Hygienic rating	Recommendation	Exposure	Limit [ppb]
5—Unhealthy	Not acceptable	Use only if unavoidable. Intense ventilation necessary	hours	2200–5500
4—Poor	Major objections	Intensified ventilation. Airing necessary. Search for sources	< 1 month	660–2200
3—Moderate	Some objections	Intensified ventilation. Airing recommended. Search for sources	< 12 months	220–660
2—Good	No relevant objections	Ventilation. Airing recommended	No limit	65–220
1—Excellent	No objections	Target value	No limit	0–65

It is well known that indoor CO_2 levels have a negative impact on cognitive performance as well as human health. Average indoor CO_2 concentrations range from 600 to 1000 ppm (parts per million), but can exceed 2000 ppm with increased occupancy and poor ventilation. Exposure to a value greater than 1000 ppm can lead to decreased cognitive abilities, while levels greater than 2000 ppm have been linked to kidney calcification, inflammation, oxidative stress, bone demineralization, and endothelial dysfunction [7]. Table 2 shows the CO_2 reference levels used in this study.

Table 2. CO_2 reference levels (ppm—parts per million).

Level	CO_2 [ppm]	Meaning
5—Unhealthy	> 5000	Air quality exceeds maximum workplace concentration values
4—Poor	> 2000	Air quality has reached unacceptable levels
3—Moderate	> 1500	Air quality has reached precarious levels
2—Good	> 1000	Air quality has reached acceptable levels
1—Excellent	< 1000	Air quality remains at harmless levels

We also measure temperature because it is an issue of comfort for indoor environments. High temperatures have been found to increase the concentrations of certain pollutants, this case being particularly studied for outdoor environments. Regulating temperature levels minimize the risk of mould growth indoors, thus helping preventing illnesses like the Sick Building Syndrome.

Based on these facts, here we propose to use a real-time air quality index for indoor applications that looks at the average air quality from the last ten minutes as if it had already been measured in the last full hour. Please recall that this averaging operation acts like a low-pass filter, "smoothing" abrupt transitions in the values. Our indoor air quality index (IAQI) is calculated based on the CO_2 and TVOC parameters, being the final value given based on the worst air quality index rating among them, that is,

$$\mathrm{IAQI} = \max\{\mathrm{I}_{\mathrm{CO}_2}, \mathrm{I}_{\mathrm{TVOC}}\}, \tag{1}$$

where $\mathrm{I}_{\mathrm{CO}_2}$ corresponds to the index air quality associated with the CO_2 level and provided by Table 2, and $\mathrm{I}_{\mathrm{TVOC}}$ corresponds to the index air quality associated with the TOVOC level and provided by Table 1.

This means that the higher the value of IAQI the worst the air quality is. For example, if CO_2 is rated as "Excellent", but TVOC level is "Good", then the overall IAQI rating would be "Good".

3 Predicting Air Quality

We will use the numerical differentiation of the CO_2 and $\mathrm{I}_{\mathrm{TVOC}}$ levels provided by the device's sensors, as an indicator of the trend of the air quality in a near future. That is, we will use the slope of the first derivative of the signal provided by the sensors as an estimator of how good or how bad the air will be. It is well known, from elementary calculus courses, that we can predict the shape of a function/signal by recalling that its first derivative simply corresponds to the slope of the (original) signal: where a signal slopes up, its derivative is positive; where a signal slopes down, its derivative is negative; and where a signal has zero slope, its derivative is zero.

The first derivative of a time varying signal corresponds to the rate of change of its amplitude (e.g., $x(t)$) with respect to time (e.g., t), that is, $dx(t)/dt$, which is interpreted as the slope of the tangent to the signal at each point, as illustrated in Fig. 1, for the digital case.

Assuming that the time interval between adjacent samples (points) of a digital signal $x[n]$ is constant, a simple algorithm for computing a first derivative is:

$$x'[n] = \frac{x[n+1] - x[n-1]}{2\Delta T_s} \tag{2}$$

for $1 < n < N-1$, where T_s represents the sampling period ($T_s = 1/f_s$, f_s being the sampling frequency) and N the number of samples of the signal. This is called a central-difference method. Its main advantage is that it does not involve a shift in the time (t or x-axis) position of the derivative [8,9].

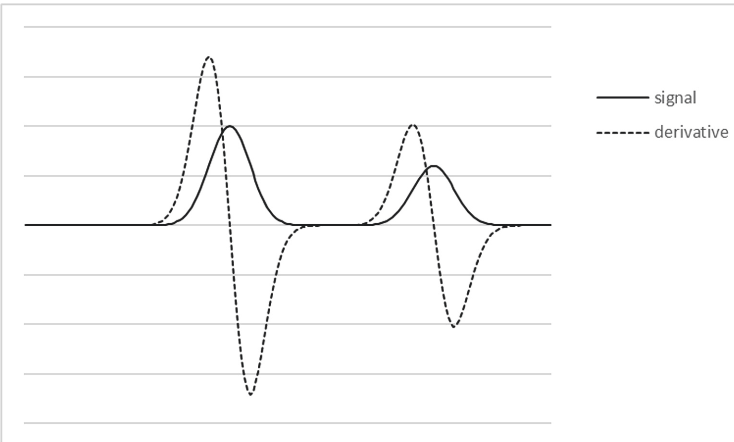

Fig. 1. Plots of a simulated signal $s(t) = e^{-(2(t-4.5))^2} + 0.6e^{-(2(t-8))^2}$, for $t = 1, 1.05, \cdots, 10$, and its derivative.

Figure 1 shows the plots of the signal given by the samples ($t = 1, 1.05, \cdots, 10$) of

$$s(t) = e^{-(2(t-4.5))^2} + 0.6e^{-(2(t-8))^2},$$

consisting of two Gaussian peaks, and its derivative, calculated using Eq. 2. As can be seen, and as expected, the calculation is performed correctly. The method presented here to find the derivative of a signal/function involves only one subtraction and one multiplication/division and it gives us the precision we need for our application proposes. It should also be noted that, in practice, this method needs a delay of one sample.

However, this (derivative) operation is very sensitive to noise. Consequently, in order to minimize the impact of the noise in the IAQI and in the forecasting, we will use a simple low-pass filter, as discussed in the previous section. The IAQI value will correspond to the average value of the last ten minutes of the IAQI values. This operation introduces a time delay of 10 min in the functioning of the device, but in practice it does only mean that the first IAQI value the user sees is only available 10 min after the start of the device. These effects (delay and low-pass filter) can be clearly seen in Fig. 2. This figure presents the plots of a "noisy signal", that we have created by adding 10% of noise to the signal in Fig. 1, a "low-pass" filtered version of this noisy signal, that was computed by using an average filter of the last 20 samples (corresponding to a time of 10 min of operation of the device), and the "derivative" of this low-pass signal. As can be seen, even in the presence of a strong level of noise our proposal continues to produce a reliable IAQI and forecasting of the air quality.

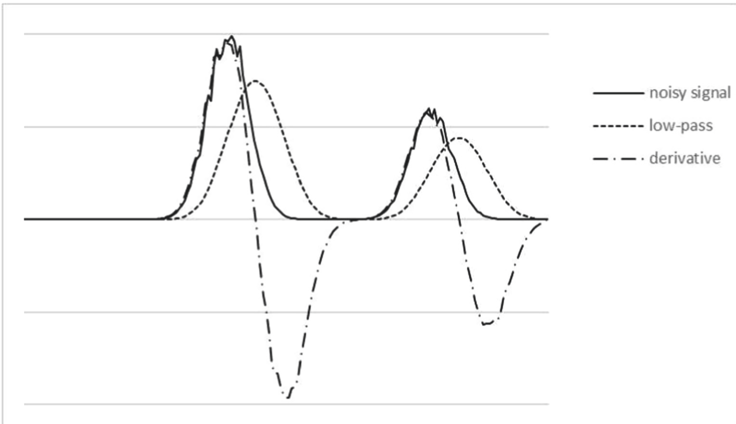

Fig. 2. To the simulated signal in Fig. 1 we have added 10% of noise, resulting in the "noisy signal" plot. Then, we have low-pass filtered this signal, using an average filter of the last 20 samples (corresponding to a time of 10 min of operation of the device), resulting in the "low-pass" plot. Finally, we have calculated the derivative of the low-pass signal, resulting in the "derivative".

Note that both the temperature, CO_2 and TVOC signals resulting from their acquisition/sampling in indoor environments are intrinsically low-pass (it is not expected that these signals have "big changes" within the sampling period of 30 s). Hence, the assumptions that we have made in this section should be correct and proven by the results presented in Sect. 5.

The final predicted IAQI is calculated in the following way. The values of the calculated derivative of the CO_2 and TVOC signals are used with Tables 1 and 2, respectively, to find the air quality indexes given by these derivative signals. To these indexes values we subtract 1, to maintain the current IAQI level as the output of the prediction if the derivative value is low. Then, if the derivative is positive, the index is added to the IAQI level resulting from Sect. 2, and if it is negative, this value is subtracted from the IAQI level resulting from Sect. 2. Finally, if the resulting predicting air quality index value is below 1 it is truncated to 1, and if it is above 5, it is truncated to 5.

It should also be noted that we could use other predicting methods and algorithms like, for example, b-splines or other kernels, both in time or frequency domains [10–13]. However, these other methods will be far more complex and computationally demanding.

4 Description of the Developed Prototype

To fulfill the objectives of monitoring and forecasting the air quality of indoor environments using the principles and methodology described above, we have developed a prototype system consisting of an electronic device and a web/cloud-based server-side application.

The main characteristics of the electronic device are the following ones:

- Compact and lightweight.
- Powered using a USB rechargeable battery, or using a chord charger.
- Measure the temperature, CO_2 and TVOC.
- LED air quality indicator light, with 5 levels: excellent (green); good (light green); moderate (yellow); poor (orange); and unhealthy (red).
- LED air quality forecasting indicator light, with 5 levels: excellent (green); good (light green); moderate (yellow); poor (orange); and unhealthy (red).
- Real-time sending of the measured parameters to a web/cloud-based server application.
- By default, the device is configured to transmit sensor data every 30 s to a web/cloud-based server, but it is re-configurable (time between sensor readings and cloud server address for sending data can be changed).
- The device was developed and implemented in modules, in order to facilitate the incorporation of new sensors in future developments.
- Do not require the installation, calibration and configuration by any type of expert.

Being this device part of a prototype system that aims at monitoring and forecasting the indoor air quality, there is also a web/cloud-based server-side application were a register user can visualize the data, in plot/graph or table form, from any point with Internet access, and access the application using a PC, Tablet or Smartphone. The system is able to generate air quality alerts/alarms (e.g., optionally send SMS), and all the configuration options are carried out based on a web page, with an extremely simple and easy to use interface.

The configuration options currently available are the sampling rate, i.e., the time elapsed between two consecutive acquisition values, and the web address of the server.

In the near future we also want to develop a mobile application (App) where all these functionalities will be available.

The electronic device has the main logical blocks presented in Figs. 3, and 4 presents a photograph of the prototype device implemented. As can be seen in Fig. 3, the device has one temperature sensor, RBG Leds, one Wi-Fi Antenna, one Wi-Fi MCU, and an air quality sensor.

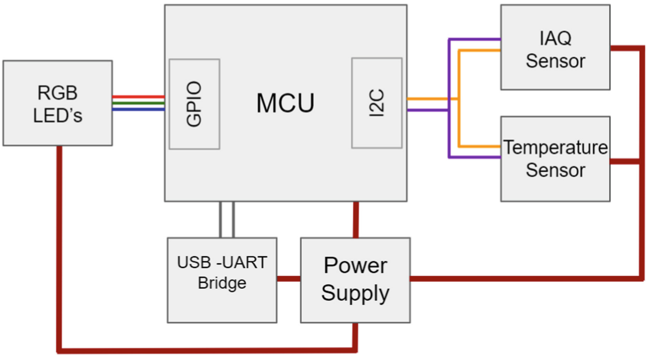

Fig. 3. Main logical blocks of the electronic device to measure the temperature, CO_2 and TVOC values, and produce the measured and forecast IAQI indexes.

To implement the device, we have used the main electronic components listed in Table 3. The main component is an iAQ-Core indoor air quality sensor module, from ams™, to measure VOC levels and CO_2 equivalent and TVOC equivalent predictions. These data are available via I^2C bus. This sensor module gives reliable evaluation of indoor air quality (output of relative CO_2 equivalents (ppm) and TVOC equivalents (ppb)), has high sensitivity and fast response (sensing range of 450—2000 ppm CO_2 equivalents, and 125—600 ppb TVOC equivalents), is of micro size for convenient installation (MEMS metal oxide sensor technology, SMD type package, reflow capable, and module with automatic baseline correction), and has low power consumption (maximum of 66 mW in continuous mode, and maximum of 9 mW in pulsed mode).

The low-power Wi-Fi module ESP32-DEVKITC-32UE from Espressif Systems™ has 802.11 b/g/n (Wi-Fi, WiFi, WLAN), Bluetooth® Smart Ready 4.x Dual Mode Evaluation Board capacities. This component targets at a wide variety of applications, including low-power IoT sensor networks. The ESP32-DEVKITC-32UE integrates a vast set of peripherals, including Hall sensors, capacitive touch sensors, SD card interface, Ethernet, high-speed SPI, UART, I^2S, and I^2C. The high-accuracy temperature sensor MCP9800A0T-M/OT, from Microchip Technology™, has an output type I^2C/SMBus, with a resolution of 11 bit.

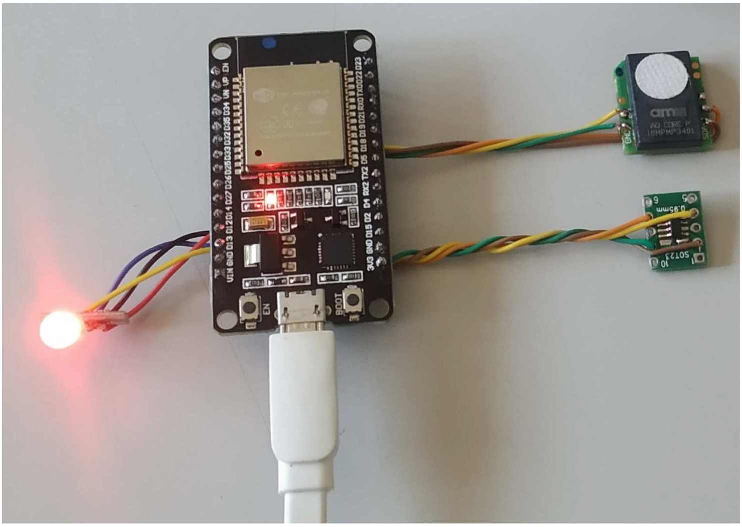

Fig. 4. Photo of the prototype electronic device actually implement.

Table 3. The manufacturers, price, and component's type used in the prototype device presented in Fig. 4. As we can see, the total price is below 35 € (31.01 € to be precise).

Component type	Reference	Manufacturer/Seller	Price (€)
IAQ sensor	IAQ cORE P	ams	20.00
Wi-Fi MCU	ESP32-DEVKITC-32UE	Espressif systems	8.41
Temperature sensor	MCP9800A0T-M/OT	Microchip technology	0.82
Wi-Fi antenna	146153–0150	Molex	1.46
RGB led (x2)	LL-509RGBC2E-006	LUCKYLIGHT	0.32

We have used the values presented in the rightmost column of Table 1 as a reference to control the colors of the RGB LED associated to the current and forecasting air quality: green—Excellent, light green—Good, yellow—Moderate, orange—Poor, and red—Unhealthy.

All the data transferred between the electronic device and the server use the Message Queuing Telemetry Transport (MQTT) protocol. In particular, to upload the temperature, CO_2 and TVOC sampled values to the server and to receive any new configuration parameters, we have used MQTT. Listing 1.1 shows an example of a MQTT message sent from the device to the server.

Listing 1.1. Example of a MQTT message with a JSON object sent by the electronic device to the server to upload the temperature, CO_2 and TVOC sampled values.

```
Topic:
  app/MacAddress/u/uploadSampledValues

Message body:
{
  "uuid":"494c5342-7b17-4eab-a1e1-50fbe796e437",
  "temp": "23.4",
  "co2": "23.6",
  "tvoc": "50"
}
```

5 Results

To assess the developed prototype, we have conducted a set of tests. In the first test, during one day we have installed the electronic device in a room, initially with all doors and windows closed. The test was initiated at 22:34, with the windows opened, with the device placed near a computer. At 12:00 the windows where closed, and at 14:00 they were opened. Next to this room there is a car garage, and a door directly opens to this garage. At 15:48 we started the car's engine, with this door opened. As can be seen the air quality as suffered a great decrease (we can see the peak in the plot). At 16:05 we have closed the windows, at 17:00 the windows where opened and at 22:03 the windows were closed again. The test ended at 22:30. Both the windows and the door were far from the device (more than three meters), but to end the test and disconnect the device we had to move to the vicinity of the device, and thus breathing very close to the sensors (thus increasing the CO_2 levels). As can be seen this influenced the quality of the air. These events are marked with vertical black lines (at the bottom) in the plot in Fig. 5. This figure also shows the values of the temperature, CO_2 and TVOC during the test. The colored horizontal bar shows the colors produced by the light LED, corresponding to the indoor air quality index (green—Excellent, light green—Good, yellow—Moderate, orange—Poor, and red—Unhealthy). The horizontal colored bar at the top of Fig. 6 shows the forecasting air quality values for this test. As can be seen, they are in line with the measured ones, being, as expected, more sever at the moments where the air quality changes abruptly.

In the second test, the device was installed in same room of the first test, near a computer. The test started at 18:45, with all doors and windows closed. At 20:12 we cleaned the computer screens with methanol, and we have not done anything else until the next morning, where we have used some more sprays of methanol close to the device at 09:05, 09:06 and 09:11. At 12:06 we have opened the windows

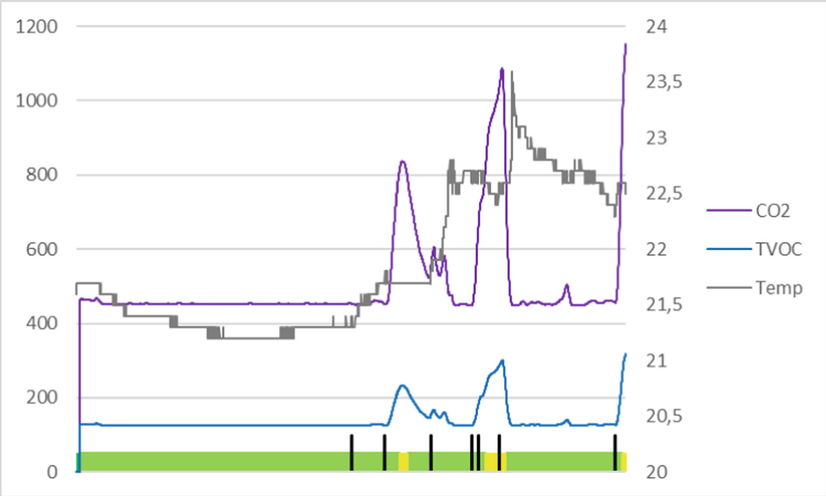

Fig. 5. Plots of the temperature, CO_2 and TVOC values for the first test (please refer to the main text). The vertical black lines (at the bottom) mark the moments where the events have occurred. Also shown by the horizontal colored bar is the color produced by the light LED corresponding to the indoor air quality index (green—Excellent, light green—Good, yellow—Moderate, orange—Poor, and red—Unhealthy). The right vertical axis shows the temperature in Celsius degrees. (Color figure online)

and closed them at 14:02. At 14:50 we used a soldering iron in a PCB board, and cleaned the PCB board at 15:00 using methanol. At 15:44 we have opened the windows and closed the windows at 17:15. At 17:35 we started using heated tobacco (Heets) until 17:36. The windows were then opened again at 19:17, and then the test was ended. These events are marked with vertical black lines (at the bottom) in Fig. 7, along with the registered temperature, CO_2 and TVOC values. Once again, the colored horizontal bar shows the colors produced by the light LED, corresponding to the indoor air quality index (green—Excellent, light green—Good, yellow—Moderate, orange—Poor, and red—Unhealthy). The equivalent horizontal colored bar at the top of Fig. 8 shows the forecasting air quality values for this test. As can be seen, once again, they are in line with the measured ones.

As can be seen, globally, the device and the system correctly follows the changes in the air quality, and it also correctly forecasts the air quality.

Although the device was designed so that it can be battery powered, we have only conducted tests with the device being directly powered through the power-grid. Hence, we did not collect any data concerning battery life, discharging/charging cycles, among other.

Fig. 6. Plots of the CO_2 and TVOC derivatives values for the first test (please refer to the main text). The vertical black lines (at the bottom) mark the moments where the events have occurred. Also shown by the horizontal colored bar is the color produced by the light LED corresponding to the forecasting of the indoor air quality index (green—Excellent, light green—Good, yellow—Moderate, orange—Poor, and red—Unhealthy). As can be seen, the predicted values are in line with the measured ones (Fig. 5), being, as expected, more sever at the moments where the air quality changes abruptly. (Color figure online)

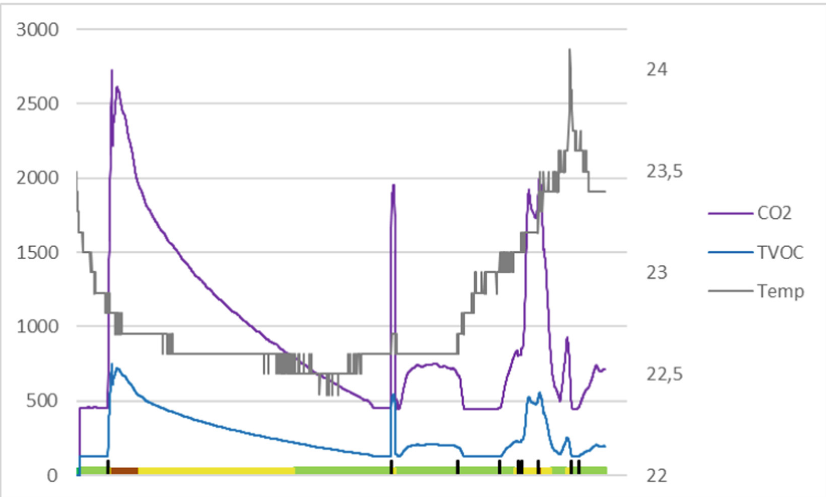

Fig. 7. Plots of the temperature, CO_2 and TVOC values for the second test. The vertical black lines (at the bottom) mark the moments where events have occurred. Also shown by the horizontal colored bar is the color produced by the light LED corresponding to the indoor air quality index (green—Excellent, light green—Good, yellow—Moderate, orange—Poor, and red—Unhealthy). The right vertical axis shows the temperature in Celsius degrees. (Color figure online)

Fig. 8. Plots of the CO_2 and TVOC derivatives values for the second test. The vertical black lines (at the bottom) mark the moments where events have occurred. Also shown by the horizontal colored bar is the color produced by the light LED corresponding to the forecasting of the indoor air quality index (green—Excellent, light green—Good, yellow—Moderate, orange—Poor, and red—Unhealthy). As can be seen, the predicted values are in line with the measured ones (Fig. 7). (Color figure online)

6 Conclusions

We have presented a real-time device (hardware and software) capable of measuring, monitoring and forecasting the indoor air quality. This device is able to measure the temperature, CO_2 and Total Volatile Organic Compounds (TVOC). It produces an Indoor Air Quality Index (IAQI), which is calculated based on the CO_2 and TVOC parameters. Then, the IAQI is used to activate two RGB LED lights, where people can very intuitively be aware of the current and predicted air quality: excellent (green); good (light green); moderate (yellow); poor (orange); and unhealthy (red).

The total price of the device is estimated to be clearly below 35 €. The device is also capable of forecasting the air quality within relative small periods of time.

We believe that this proposal can be used to improve the quality of life of citizens in the context of "smart cities".

The results achieved by the set of tests conducted proved that the device, server-side application and IAQI are reliable. Although not final, the results achieved are highly motivating.

It should also be noted that the IAQI can be used to automatically control the indoor air quality if, for example, connected to an air cleaner.

In a near future, it is also intended to carry out precision tests, preferably with certification by a specialized laboratory. Additionally, and in terms of the future evolution of the device and the complete system, it is also intended to carry out outdoor tests, in order to study the possibility of measuring, monitoring and forecasting the air quality in uncontrolled environments. Concerning forecasting, we want to test the use of other techniques and algorithms, balancing their usage with computational complexity and, ultimately, power consumption.

We believe that this device can be used to create a "social network" where users can share their IAQI data. These data can then be used by local, regional and national level authorities to devise measures for improving the life of citizens.

References

1. Vallero, D.: Introduction. In: Vallero, D. (ed.) Fundamentals of Air Pollution, 5th edn. p. 1. Academic Press, Boston (2014). https://doi.org/10.1016/B978-0-12-401733-7.02001-6, https://www.sciencedirect.com/science/article/pii/B9780124017337020016
2. Chau, T., Wang, K.: An association between air pollution and daily most frequently visits of eighteen outpatient diseases in an industrial city. Sci. Rep. **10**, 2321 (2020). https://doi.org/10.1038/s41598-020-58721-0
3. World Health Organization–Europe: Noncommunicable diseases and air pollution. Tech. rep., World Helth Organization, Denmark (2019)
4. World Health Organization. https://www.who.int/teams/environment-climatechange-and-health/air-quality-and-health/ambient-air-pollution. Accessed 03 July 2021
5. Sensirion: Indoor air quality and volatile organic compounds. Tech. rep., Sensirion The Sensor Company, Staefa, Switzerland (2017)
6. Umweltbundesamt: Beurteilung von innenraumluftkontaminationen mittels referenz- und richtwerten. Bundesgesundheitsbl **50**, 990–1005 (2007). https://doi.org/10.1007/s00103-007-0290-y
7. The Guardian: Indoor carbon dioxide levels could be a health hazard, scientists warn. https://www.theguardian.com/environment/2019/jul/08/indoorcarbon-dioxide-levels-could-be-a-health-hazard-scientists-warn.Accessed 07 July 2021
8. Krishna, B.T., Rao, S.S.: On design and applications of digital differentiators. In: 2012 Fourth International Conference on Advanced Computing, ICoAC, pp. 1–7 (2012). https://doi.org/10.1109/ICoAC.2012.6416802
9. Mitra, S.K., Kuo, Y. (eds.): Digital Signal Processing: A Computer-Based Approach. McGraw-Hill, New York (2006)
10. Ferreira, P.J.: New algorithms for band-limited interpolation and extrapolation: a synthetic view. In: Proceedings of EUSIPCO, Tampere, Finland, 2000. Zenodo, December 2015. https://doi.org/10.5281/zenodo.37308, https://doi.org/10.5281/zenodo.37308
11. Reis, M.J., Ferreira, P.J., Soares, S.F.: Linear combinations of b-splines as generating functions for signal approximation. Digital Signal Process. **15**(3), 226–236 (2005)
12. Unser, M., Aldroubi, A., Eden, M.: B-spline signal processing .i. theory. IEEE Trans. Signal Process. **41**(2), 821–833 (1993). https://doi.org/10.1109/78.193220
13. Unser, M., Aldroubi, A., Eden, M.: B-spline signal processing .ii. efficiency design and applications. IEEE Trans. Signal Process. **41**(2), 834–848 (1993). https://doi.org/10.1109/78.193221