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Low Cost System for Air Quality Measurement Based on Electrochemical and Optical Sensors

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Abstract: In this communication, a comparison between a home-developed low-cost system and reference methods for air quality measurement is performed. For the measurement of the main pollutants, both gaseous (NO_2, NO, O_3, CO) and particulate matter (PM_{10} and $PM_{2.5}$), electrochemical and optical sensors are used, respectively, all from Alphasense brand. In addition, it has been included the sensing of meteorological data that could affect the measurement of pollutants (temperature and humidity). All data collected is stored on an external flash memory connected to the device (microSD). In addition, it is possible to transmit the data in real time using Ethernet, GSM or LoRA. Finally, it incorporates Bluetooth communication in order to communicate with a nearby smart mobile device. The control core of the system is a low power microcontroller from the manufacturer ST (STM32L476). The entire system is powered by a 230 V AC power supply. The equipment includes a pump for air sampling (active sampling).

Reference equipment has been used to perform correlation tasks and preliminary calibrations. This equipment belongs to the air quality protection and research network of Extremadura. The complete system has been tested in real conditions during two months together with the fixed reference stations located in Badajoz and Plasencia (Spain). Its general operation has been positive, with strongly correlated results, although the calibration of the electrochemical sensors should be modified in future work to improve their performance, especially in low-pollution environments.

Keywords: Air quality monitoring, Electrochemical sensors, Particulate matter, Low-cost.

1. Introduction

Nowadays, air pollution and air quality are a major focus of attention. This is due to the scientific evidence of the great negative impact it has on public health [1–3]. In addition, it has been recently demonstrated the great pollution load due to human activity. Containment and restrictions imposed in most countries due to the SARS-CoV-2 pandemic resulted in a significant decrease in air pollution levels [4]. For example, some of the main air pollutants are nitrogen oxides (NOx). These include nitric oxide (NO) and nitrogen dioxide (NO_2) and are formed by the oxidation of atmospheric nitrogen (N_2) naturally present in the air. Nitrogen oxides have great negative effects on the respiratory system, as they

spread to all parts of it due to their low solubility in water [5]. Even though it is true that some NOx emissions are due to natural causes, the largest source of emissions is due to anthropogenic action: the use of fossil fuels and exhaust gases from combustion vehicles [6].

All of these factors highlight the need for massive air quality monitoring. Currently, the reference stations installed make use of techniques of great cost and size. Consequently, the measurement points are too few, so a problem of spatial-temporal resolution arises. Without replacing these existing devices, the use of low-cost devices is born as a partial solution to this problem) [7]. In this way, these systems can alleviate the lack of measurement points, thus being able to obtain a higher resolution map that allows to deal with high levels of pollution [8].

These low-cost systems are mainly based on low-cost gas sensors. These sensors, available in the market, are based on different technologies. The different types of sensors currently deployed are resistive sensors, electrochemical sensors, non-dispersive infrared detectors (NDIR), absorption sensors and photoionization detectors (PIDs) [9]. Recent studies seem to reveal that, within all these technologies, electrochemical sensors have a good performance for the detection and quantification of air pollutants [10]. The sensors contain two or three electrodes, occasionally four, in contact with an electrolyte. The electrodes are typically fabricated by fixing a high surface area precious metal on to the porous hydrophobic membrane. The working electrode contacts both the electrolyte and the ambient air to be monitored usually via a porous membrane. The electrolyte most commonly used is a mineral acid, but organic electrolytes are also used for some sensors. The electrodes and housing are usually in a plastic housing which contains a gas entry hole for the gas and electrical contacts.

The main reason for this choice is that they are selective sensors, with low cross sensitivity. However, their size is large with respect to other type of chemical sensors like resistive ones. Due to the portable, but not personal, nature of the devices presented in this work, the use of electrochemical sensors has been chosen. In particular, the Alphasense A4 model has been selected, mounted on the analogical Front End interface provided by the manufacturer. These sensors have already been used and tested in other research works in different contexts [11–15].

This paper, which describes the low-cost prototype designed for air quality measurement with the incorporation of electrochemical sensors, is structured as follows. First, the design of the complete device is described, and the electronic design of the control system is briefly detailed. Subsequently, some of the main results obtained in the two measurement campaigns carried out in Badajoz and Plasencia (Extremadura, Spain) are shown. Finally, the main conclusions obtained are listed.

2. Materials and Methods

The main regulated atmospheric pollutants are the targets of this device. Therefore, four electrochemical gas sensors are included to measure CO, NO_2, NO and O_3, and an optical particle-counter sensor to measure PM_{10} and $PM_{2.5}$. For the installation of the electrochemical sensors, the analogue Front End supplied by Alphasense has been incorporated (Fig. 1). The sensor values are read by the microcontroller via an external 24-bit digital-analogue converter with 8 inputs. A high resolution converter is used due to the low voltage changes to be measured. The PM data is measured by the OPC-N3 sensor, also from Alphasense (Fig. 2). This sensor also incorporates humidity and temperature measurements. However, another humidity and temperature sensor has been integrated, as the previous one may not represent the real environmental conditions. The Alphasense OPC-N3 sensor is an optical particle monitor that measures PM1.0, PM2.5 and PM10. It use laser beams to detect particles from 0.35 micron to 40 micron in diameter with 24 bins. Count measurements are converted into mass concentrations of PM1.0, PM2.5 & PM10 using embedded algorithms.



Fig. 1. Analogue Front End with Alphasense A4 electrochemical gas sensors.



Fig. 2. OPC-N3 Particulate matter sensor from Alphasense.

The Nucleo-Board model STM32L476, supplied by ST, is in charge of the control of the whole electronic system. It is an ultra-low power microcontroller, operating at frequencies of up to 80 MHz, based on a high-performance 32-bit core. Data communication is carried out using different technologies. These include low energy Bluetooth, for communication with mobile devices. An Ethernet

module is included to make internet connections. In addition, the design allows other types of wireless connections such as LoRA or GSM. Finally, data storage is performed on a microSD card. Fig. 3 details the main parts of the device in a block diagram. Fig. 4 includes a picture of the designed electronic prototype and points out some of its main elements. The dimensions of the designed electronic printed circuit board are 90 mm × 110 mm. The system is powered at 230V AC with a mains plug. A 5 V converter is included to supply the electronics. In addition, the system is equipped with an electric pump that leads the air from the outside to the sensors. This maintains a constant flow of air in the sensor cell, thus reducing pressure changes that affect the measurements. Besides, the sensor cell is made of metal in order to reduce the effects of electromagnetic noise. These two factors significantly improve the quality of the electrical signals from the electrochemical sensors. Fig. 5 shows a picture of the complete system, detailing the main components. It can be noticed that, for outdoor installation, the complete system has been encapsulated in a watertight plastic box.

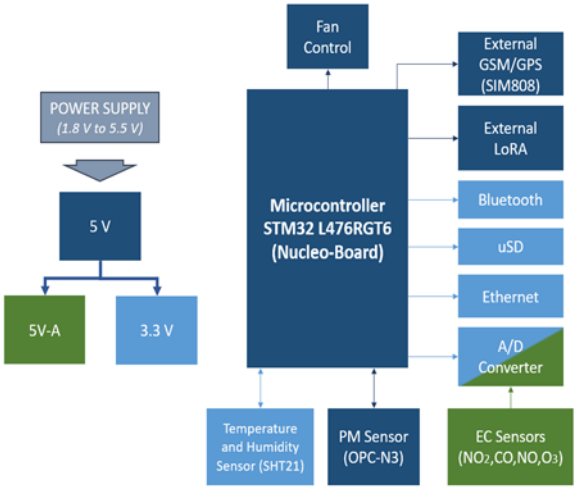


Fig. 3. Block Diagram of the electronic system.

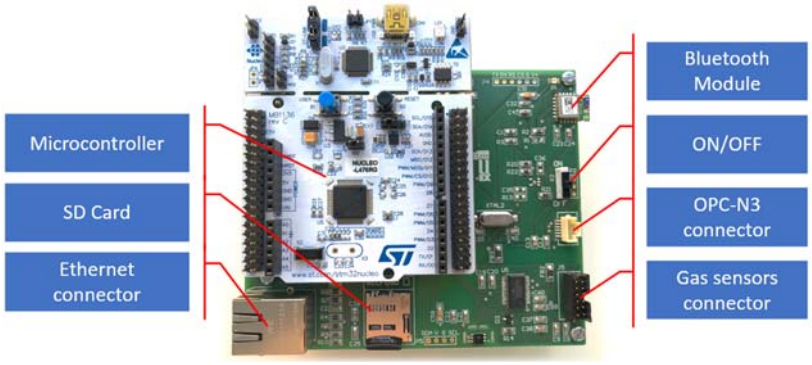


Fig. 4. Electronic system designed.

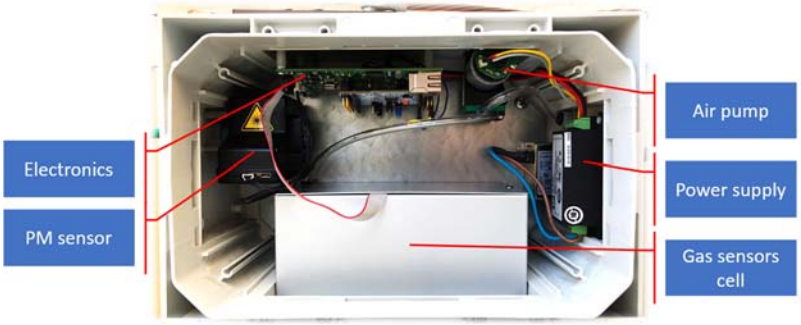


Fig. 5. Complete system developed.

3. Results

The operation of the developed system was successfully tested for two months (August and September 2019) in parallel with the fixed reference stations of Badajoz and for one month (November-December) in Plasencia, in Spain. The data sampling period was 30 seconds, although it was subsequently averaged every 10 minutes for graphical representation and comparison with data from the reference station in μg/m^3. Real-time data was stored in the microSD included in the system. Fig. 6 and Fig. 7 shows pictures of the device installed in the reference stations located in Badajoz and in Plasencia respectively. It can be appreciated that in the location corresponding to Badajoz, the system was slightly protected from rain, while in Plasencia it was exposed to the elements.



Fig. 6. Air quality measurement system installed in parallel with the Badajoz reference station.



Fig. 7. Air quality measurement system installed in parallel with the Plasencia reference station.

3.1. Temperature Calibration

An algorithm of correction has been applied in order to avoid disturbances in the measurements from temperature variations. In particular, the correction factors recommended by the manufacturer have been implemented. These are summarized in Table 1, where it is specified which factor is applied for each gas in different temperature ranges. On the other hand, no humidity and pressure compensation algorithm has been performed, which is a task for future studies.

Table 1. Factors for temperature compensation.

	$T^a<=0$	$0<T^a<=10$	$10<T^a<=30$	$T^a>30$
NO_2	1,09	1,09	1,33	3
O_3	0,75	1,28	1,28	1,28
NO	1,48	1,48	2,02	1,72
CO	1	1	-1	-0,76

3.2. Analysis of the Acquisition System: Humidity and Temperature

Firstly, the humidity and temperature signals from the sensor included for this purpose have been studied. In this way it is studied that the electronic acquisition system is working correctly. For this purpose, the data of the prototype are compared with the values recorded by the reference station located in the same place. These comparative graphs can be seen in Fig. 8, where the blue line represents the values coming from the reference station while the orange line corresponds to the values from the prototype. It can be seen that the correlation is quite precise, so defects coming from the electronic measurement system are ruled out.

3.3. Gas Pollutants Results

Once the behaviour of the acquisition system has been studied, we move on to study whether the gas and particle sensors are working properly. Initially, the correlation study of the gas sensors is carried out. Therefore, we work with the signals corresponding to the pollutants NO_2, NO, CO and O_3. This preliminary test of the behaviour of the sensors is based on visual analysis of the time series of the polluting gases.

In order to carry out this correlation, firstly it is necessary to unify all the units. This requires that the signals from the prototype sensors in ppb are translated into µg/m^3. For this purpose, Eq. (1) is used.

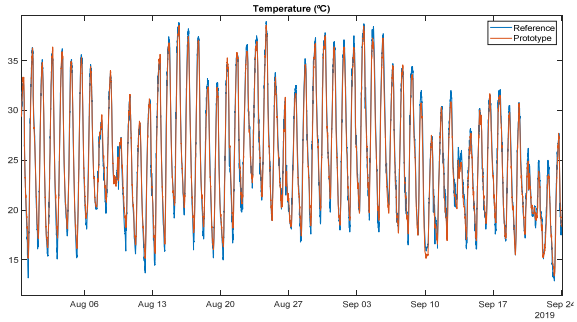
$$\mu g/m^3 = \frac{(ppb) * (atm) * (M)}{(273.15 + °C) * R}, \quad (1)$$

where M is the molecular weight; R=0.082; atm is the pressure.

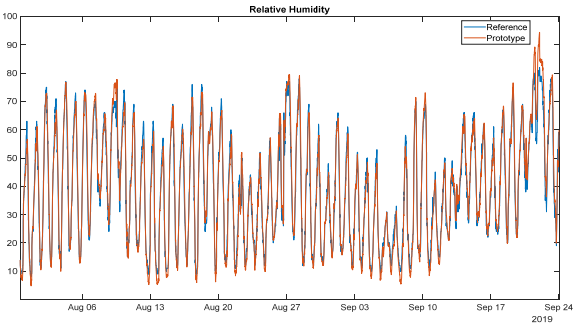
Once all data are compiled in the same unit and time scale (10 minutes), they are represented in the same graph. The O_3 graph is plotted as an example in Fig. 9.

The operation of the ozone sensor seems to be correct, as the signal follows the reference signal quite closely, although its performance could be improved with more accurate temperature and humidity compensation methods. In the case of NO_2 and CO, the results are less accurate, probably because the concentration of these pollutants in Badajoz are quite low, close or below the detection limit of the sensing systems. Fig. 10 shows the comparative graph for CO and Fig. 11 for NO_2, which highlights the above.

However, in the case of the campaigns carried out in Plasencia, the prototype seems to have a better follow-up of the reference signal (shown in Fig. 12). The NO_2 levels are similar in both locations. Therefore, the improvement could be due to the modification of the calibration algorithms from the data previously collected in Badajoz. Nevertheless, as can be observed in Fig. 13, the follow-up for NO measurements is not as adequate. This indicates that there is still a considerable potential for improvement in the calibration systems.



(a)



(b)

Fig. 8. Meteorological data comparison chart.
Blue: reference, orange: prototype.
(a) Temperature; (b) Relative Humidity.

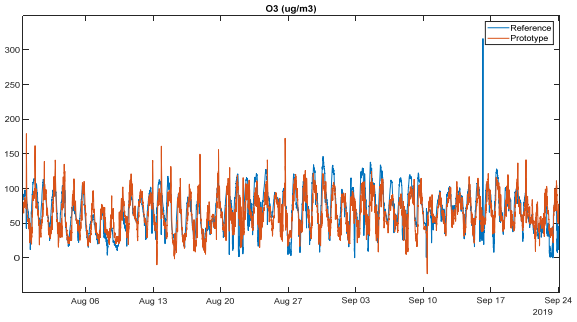


Fig. 9. O_3 time series (Badajoz campaign).
Blue: reference, orange: prototype.

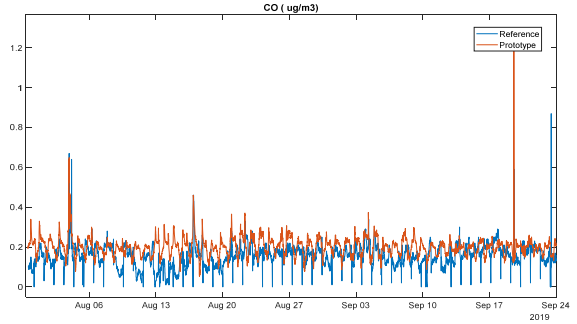


Fig. 10. CO time series (Badajoz campaign).
Blue: reference, orange: prototype.

It should be noted that the loss of signal observed at the end of November is due to a power failure caused by the heavy storms.

With respect to the O_3 measurements in the Plasencia campaign, shown in Fig. 14, the designed prototype still has an acceptable follow up of the reference signal.

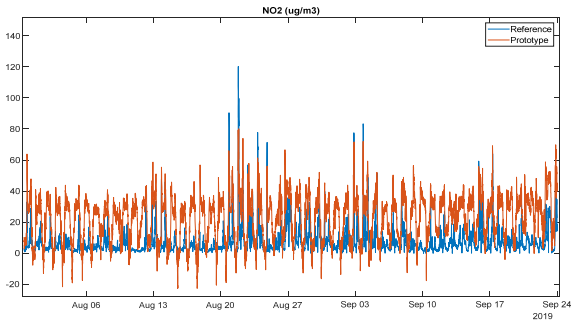


Fig. 11. NO_2 time series (Badajoz campaign).
Blue: reference, orange: prototype.

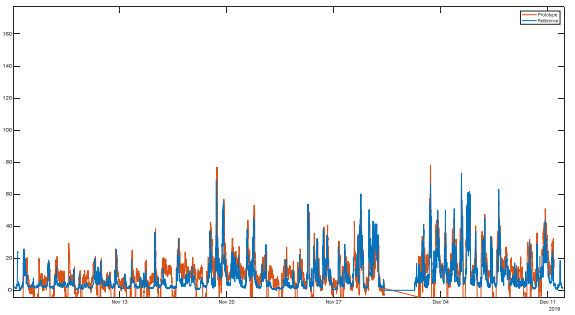


Fig. 12. NO_2 time series (Plasencia campaign).
Blue: reference, orange: prototype.

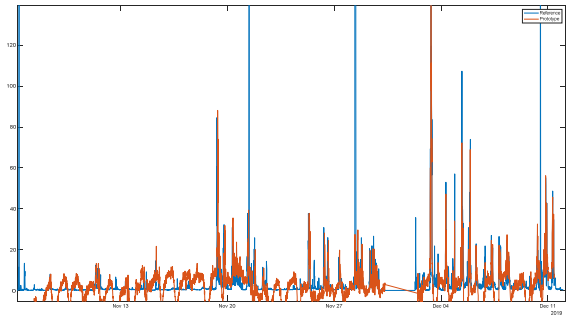


Fig. 13. NO time series (Plasencia campaign).
Blue: reference, orange: prototype.

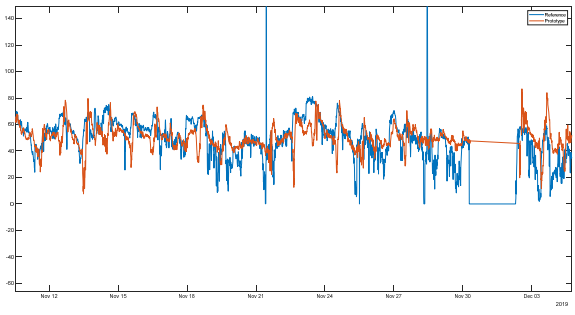


Fig. 14. O_3 time series (Plasencia campaign).
Blue: reference, orange: prototype.

3.4. Particulate Matter Results

Finally, the OPC-N3 sensor (for measuring particulate matter) also shows good performance. The concentration values provided by the prototype are lower than those of the reference station in a small range, but nevertheless the trend is correctly followed. Fig. 15 shows the comparison between reference and the prototype measurements in PM_{10}, and Fig. 16 in $PM_{2.5}$.

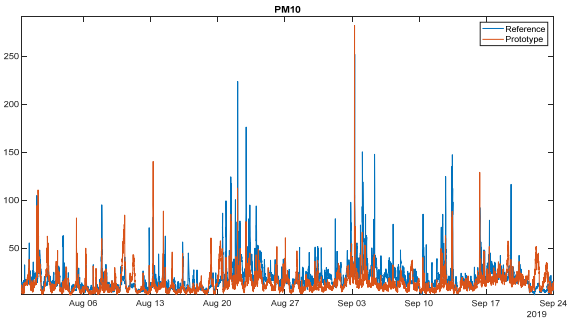


Fig. 15. PM_{10} time series (Badajoz campaign). Blue: reference, orange: prototype.

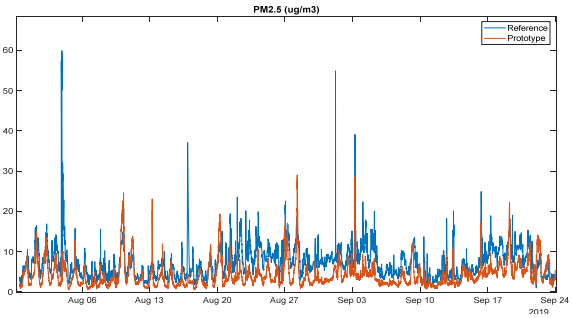


Fig. 16. $PM_{2.5}$ time series (Badajoz campaign). Blue: reference, orange: prototype.

The data from the PM sensor does not include any processing or calibration process. The information from the sensor has been directly represented in $\mu g/m^3$.

During the beginning of the campaign carried out in Plasencia, the particle sensor displayed a good performance. However, during the storms that took place in November, water leaked into the measuring system. Therefore, the particle count is triggered from then on and after the blackout, the sensor does not work again. This effect can be seen in Fig. 17.

4. Conclusions

A portable and low-cost system has been designed for the measurement of the main air pollutants. For this purpose, electrochemical (gaseous pollutants) and optical (PM) sensors have been included in the design. The device was tested for 3 months in two locations (Badajoz and Plasencia) by comparing its results with those given by a reference station, to study its operation. The system worked correctly during the field campaigns, demonstrating that the electronics and design of the device are suitable for atmospheric pollution monitoring under real conditions.

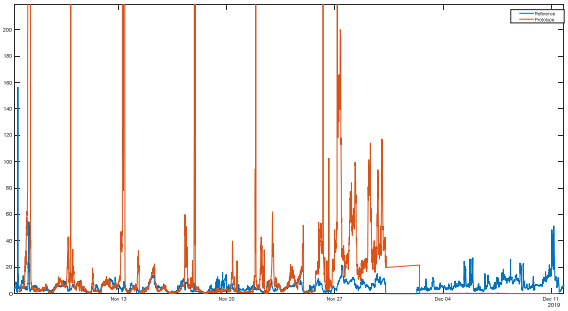


Fig. 17. PM_{10} time series (Plasencia campaign). Blue: reference, orange: prototype.

Promising results were obtained for some compounds and PM, whereas other (NOx) gave a weaker performance, probably due to the low concentration of these pollutants in Extremadura. The first calibrations carried out seem to slightly improve the performance of the system as shown by the measurements of NO_2 made in Plasencia.

However, further in-depth calibration work must be carried out. As a result, further measurement campaigns will also have to be carried out in places with higher levels of contamination. In addition, moisture correction algorithms must be implemented. Finally, in future work, the equipment design will be revised in order to avoid rain or other climatological effects affecting the operation of the system.

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