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MOBILE & WIRELESS HEALTH

Monitoring Indoor Air Quality for Enhanced Occupational Health

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Abstract Indoor environments are characterized by several pollutant sources. Because people spend more than 90% of their time in indoor environments, several studies have pointed out the impact of indoor air quality on the etiopathogenesis of a wide number of non-specific symptoms which characterizes the "Sick Building Syndrome", involving the skin, the upper and lower respiratory tract, the eyes and the nervous system, as well as many building related diseases. Thus, indoor air quality (IAQ) is recognized as an important factor to be controlled for the occupants' health and comfort. The majority of the monitoring systems presently available is very expensive and only allow to collect random samples. This work describes the system (iAQ), a low-cost indoor air quality monitoring wireless sensor network system, developed using Arduino, XBee modules and micro sensors, for storage and availability of monitoring data on a web portal in real time. Five micro sensors of environmental parameters (air temperature, humidity, carbon monoxide, carbon dioxide and luminosity) were used. Other sensors can be added for monitoring specific pollutants. The results reveal that the system can provide an effective indoor air quality assessment to prevent exposure risk. In fact, the indoor air quality may be extremely different compared to what is expected for a quality living environment. Systems like this would have benefit as public health interventions to reduce the burden of symptoms and diseases related to "sick buildings".

Keywords Indoor air quality · Occupational health · Air quality monitoring · Sick buildings · Wireless sensor network · ZigBee · Gas sensors

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Introduction

Indoor environments are characterized by several pollutant sources and health problems related to poor indoor air quality have reached increasing importance in the last years [1]. Besides, the concentration of indoor air pollutants seems to be 2–5 times higher than the concentration of outdoor pollutants [2, 3]. Furthermore, according to the United States Environmental Protection Agency [3], human exposure to indoor air pollutants may occasionally be more than 100 times higher than outdoor pollutant levels, because a home's interior accumulates and concentrates pollutants given off by finishes, furnishings and the daily activities of the occupants [4]. Actually, indoor air pollutants have been ranked among the top five environmental risks to public health. Thus, indoor air quality (IAQ) is recognized as an important matter to be addressed for the occupants' health and comfort. This issue is even more important if we take into consideration that, today, most people spend more than 90% of their time in artificial environments [1].

In 1983, the World Health Organization (WHO) used the term "Sick Building Syndrome" (SBS) to the clinical features that we could find in building occupants as a result of the indoor air pollution [2]. Several studies have highlighted the impact of indoor air quality in the etiopathogenesis of many non-specific symptoms and clinical findings that characterize SBS. The clinical picture of this syndrome is wide as it may involve the skin (with xerosis, pruritus), the upper and lower respiratory tract (such as, dysphonia, dry cough and asthma), the eyes (ocular pruritus) and the nervous system (for example, headache and difficulty in concentration) [5, 6].

Moreover, besides the signs and symptoms of this syndrome, there are diseases which may be associated with indoor environments, namely, Legionnaire's disease, extrinsic allergic alveolitis, asthma and atopic dermatitis [5, 6]. For instance, concerning atopic dermatitis, it is a chronic and inflammatory skin disease and one of the most common allergic diseases in children. Its incidence is increasing and, although it is associated with genetic factors, there is strong evidence of a role for environmental factors, namely indoor air pollutants. This is particularly important in industrialized countries, where children spend most of their time indoors [7]. Among the air pollutants linked with the exacerbation of atopic dermatitis are the volatile organic compounds [8], which are considered the most common contaminants of indoor air [6]. Globally considered, in atopic dermatitis, indoor air pollutants may induce oxidative stress, leading to skin barrier dysfunction or immune dysregulation [8].

Thereby, the symptoms and diseases associated with the "sick buildings" are a problem with growing importance in public health and have also been correlated with lower productivity and higher absenteeism. The etiology of the SBS and the building related-diseases may include chemical contaminants (both from outdoor and indoor sources), biological agents, psychological factors, electromagnetic radiation, absence of sunlight, humidity, bad acoustics, poor ergonomics and inadequate ventilation [6].

Ventilation is used in buildings to create thermally comfortable environments with acceptable IAQ by regulating indoor air parameters, such as air temperature, relative humidity, air speed, and chemical species concentrations in the air [9]. Numerical solutions are most suitable for studying the airflow pattern and contaminant particle transport inside occupied areas. Thus, many investigators have studied the behaviour of airflow and pollutant concentrations through numerical modelling. Pitarma et al. [9], for instance, present some numerical predictions of pollutants dispersion in a ventilated room by mixing ventilation.

An indoor air quality assessment system helps in the detection and improvement of indoor air quality. Local and distributed assessment of chemicals concentrations is significant for safety (gas spills detection, pollution monitoring) and security applications as well as for to effectively control heating, ventilation and air conditioning (HVAC) system for energy efficiency [10]. In fact, the indoor air quality measured in the built environment provides a continuous stream of information for seamless controlling of building automation systems, and provides a platform for informed decision making [11]. However, the monitoring systems presently available are normally very expensive and only allow to collect random samples.

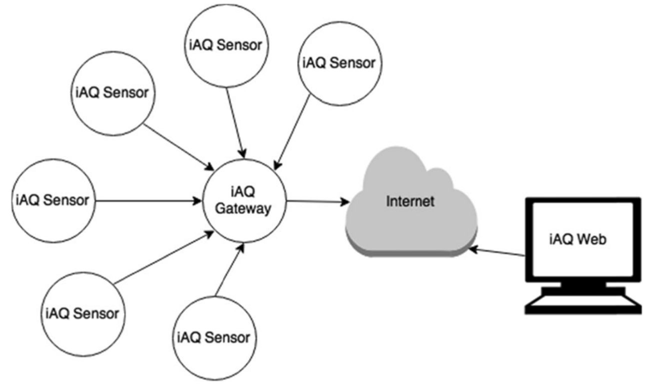


Fig. 1 iAQ WSN Architecture

Recently, several new systems have been developed for monitoring environmental parameters, always with the aim of improving the indoor air quality efficiency [12]. Actually, the availability of cheap, low power, and miniature embedded processors, radios, sensors, and actuators, often integrated on a single chip, is leading to the use of wireless communications and computing for interacting with the physical world in applications such as air quality control [13]. A wireless indoor air quality monitoring in order to provide real time information for assisted living is proposed by [11]. The proposed system has carbon dioxide, carbon monoxide, propane and methane sensors. Another study involving wireless sensor networks for indoor air quality monitoring was proposed by [14], which also incorporates ZigBee technology for wireless communication, and monitors the humidity, temperature and carbon dioxide parameters.

Fig. 2 iAQ Web Alerts system

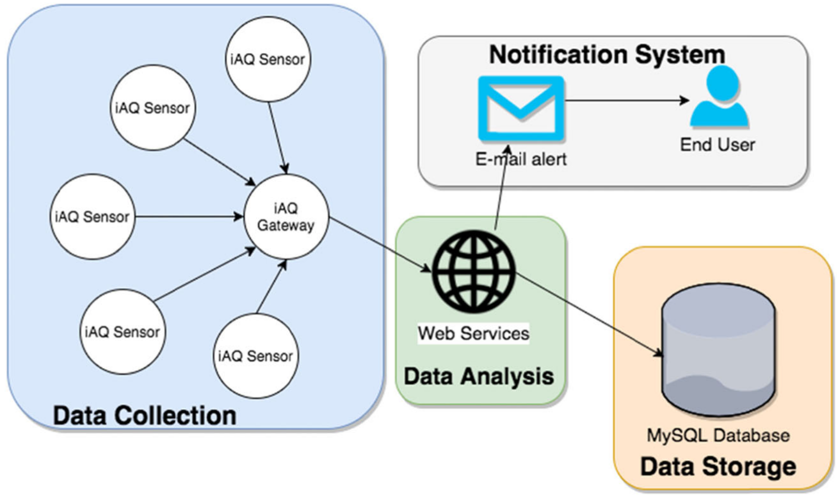


Fig. 3 iAQ Web alerts architecture

This study describes the iAQ system, developed by the authors, which aims to ensure, autonomously, accurately and simultaneously, the indoor air quality monitoring of different building rooms. The system consists of a low cost indoor air quality monitoring wireless sensor network system, developed using Arduino, XBee modules and micro sensors, for storage and availability of monitoring data on a web portal in real time. This system collects five environmental parameters (air temperature, humidity, carbon monoxide, carbon dioxide and luminosity) from different places simultaneously. Other sensors can be added for monitoring specific pollutants. Currently, in the preliminary laboratory tests, only two remote modules were used.

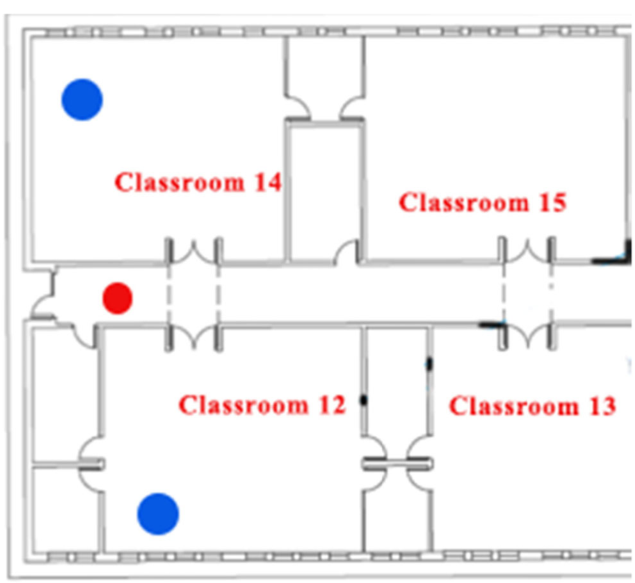


Fig. 4 Schematic of the test system installation (●iAQ Sensor; ●iAQ Gateway)

Technical solution

Implementation

The iAQ system is an automatic indoor air quality monitoring system that allows the user, such as the building manager, to know, in real time, a variety of environmental parameters as air temperature, relative humidity, carbon monoxide (CO), carbon dioxide (CO2) and luminosity. Other sensors for specific pollutants can be added.

The parameters are monitored using the iAQ Sensor system that collects data and sends it to the iAQ Gateway system that records the data in a MySQL database using web services developed in PHP (Fig. 1).

The end user can access the data from the web portal iAQ Web built in PHP. After login, the end user can access the iAQ Web and can get all the information

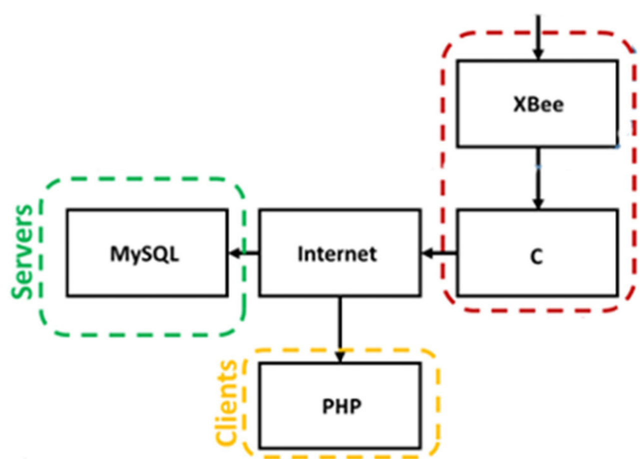


Fig. 5 iAQ GATEWAY architecture

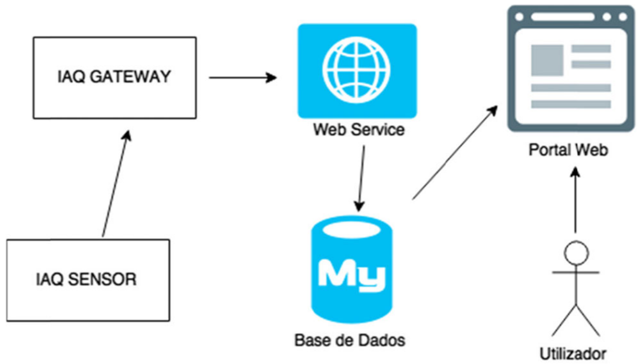


Fig. 6 iAQ System architecture

Table 1 Component prices of the iAQ System

	iAQ Sensor	iAQ Gateway	Cost
Arduino Mega	X	X	10.59USD
XBee	X	X	22.39USD
Ethernet Shield	–	X	4.98USD
SHT10	X	–	3.46USD
MQ7	X	–	1.31USD
T6615	X	–	115.20USD
LDR	X	–	0.10USD
PCB	X	–	3.65USD
Cables and Box	X	X	9.59USD
Total	166.29USD	47,55USD	

about environmental parameters. The monitoring data are shown as numeric values or in a chart form. This portal also allows the user to keep the parameters history. Providing a history of changes, the system helps the user to analyze precisely and detailed the air quality behaviour. This is very important to decide on possible interventions to improve the air quality in the building. The iAQ Web is also equipped with a powerful alerts manager that advises the user when a specific parameter exceeds the maximum value as shown in Fig. 2.

The maximum and minimum health quality values are predefined by the system, but the user can also change this values to specific proposes. When a value exceeds the defined threshold the used will be notified by e-mail in real time. This functionality enables the user to act in real time ensuring good ventilation the indoor environment. The data collected by the iAQ Sensor's is analyzed before being inserted into the database, if the data exceeds the parameterized limits the user receives an email automatically as shown in the Fig. 3.

Wireless sensor network architecture

The wireless communication is implemented using the XBee module what implements the IEEE 802.15.4 radio and ZigBee networking protocol [15]. The IEEE 802.15.4 standard specifies the physical and medium access control layers for low data-rate wireless personal area networks. ZigBee is a low-cost, low-power, wireless mesh networking standard built upon 802.15.4 [16, 17].

Communication signals are transmitted from the iAQ Sensor to the base station iAQ Gateway use XBee. The modules operate within the 2.4 GHz frequency band and outdoor RF line-of-sight range up to 4000 ft. (1200 m) and RF data rate 250,000 bps. These modules use the IEEE 802.15.4 networking protocol for fast point-to-multipoint or peer-to-peer networking. They are designed for high-throughput applications requiring low latency and predictable communication timing. XBee modules are ideal for low-power, low-cost applications. XBee-PRO modules are power-amplified versions of XBee modules for extended-range applications [18].

An important advantage of the use of ZigBee communication is that we can have many iAQ Sensors (represented as blue circles in Fig. 2) collecting indoor air quality data and only one iAQ Gateway must be connected to the Internet (represented as red circle in Fig. 2) as Zigbee have an indoor RF line-of-sight range up to 50 m. This is extremely necessary in some scenarios, in this way is no longer being required network coverage wi-fi throughout the all area of housing and is only required internet connection at the location of IAQ Gateway. Figure 3 represents a schematic case of the implementation of iAQ system in a house.

Figure 3 represents the experiment of the implementation of iAQ system. For testing purposes two distinct classrooms

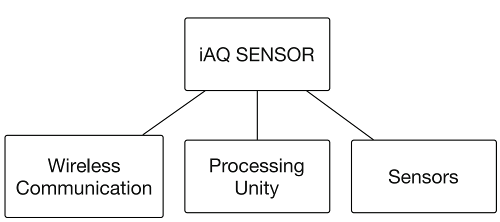


Fig. 7 iAQ Sensor architecture

Table 2 Current consumption values (mA)

State	iAQ Sensor	iAQ Gateway
Sleeping	138	171
Awake (Transmitting)	294	333
Awake (Receiving)	159	281

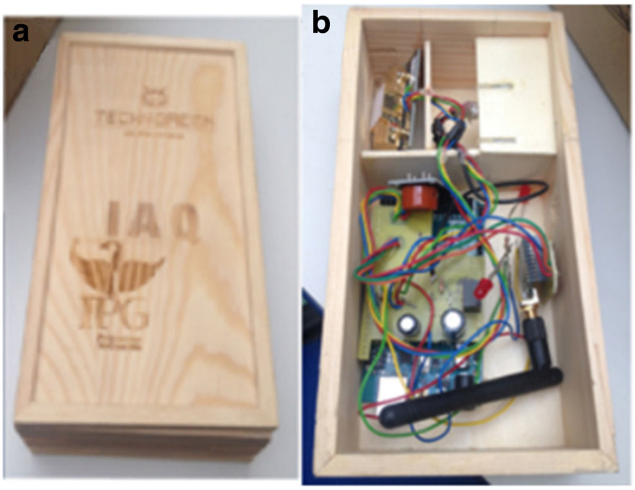


Fig. 8 Photograph of the iAQ sensor hardware (**a** – Inside view, **b** – Outside view)

of the School of Technology and Management of Polytechnic Institute of Guarda were monitored. Two iAQ Sensor modules were used and one iAQ Gateway module was placed in the hallway as shown in Fig. 3. All modules are powered by the power grid using 230 V-5 V AC-DC 2A power supply. Indoor air quality data were collected for 3 months which showed that under certain conditions air quality values are significantly lower than those considered healthy for occupants.

Hardware and system architecture

The iAQ system is composed of one or several iAQ Sensor's. They are used to collect and transfer environmental factors from the different rooms where they are installed. The iAQ Sensor's send the data to the iAQ Gateway (Fig. 4), which is connected to the Internet with an Arduino Ethernet Shield, for recording data in the database.

Therefore, it is made possible to construct a modular system that can monitor one or more spaces simultaneously. Figure 5 schematically illustrates the system architecture used in the iAQ.

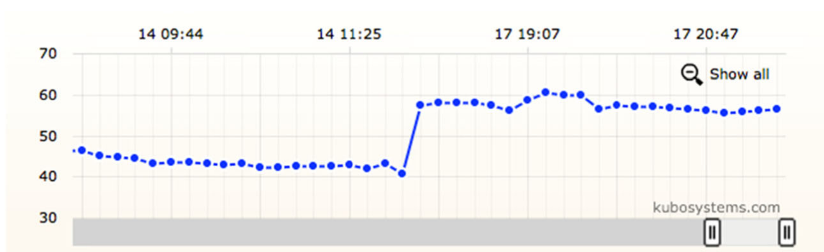
The iAQ Sensor is built using the embedded Arduino Mega system, an open source platform that incorporates an Atmel AVR microcontroller [19, 20]. In order to allow communication between the iAQ Sensor's and iAQ Gateway, the ZigBee technology was applied with the use of Xbee modules.

The iAQ Sensor is equipped with multiple sensors, a processing unit (Arduino MEGA), and a wireless communication and mesh networking module as schematically shown in Fig. 6 (see also [21]). Currently, the iAQ Sensor is equipped with five sensors (Fig. 7): air temperature, relative humidity (RH), carbon monoxide (CO), carbon dioxide (CO2) and luminosity.

A brief description of the used sensors is presented below. Table 1 describes the cost of the components incorporated in the iAQ system.

- Sensor SHT10 – it is a low power, stable and fully calibrated Relative humidity and Temperature sensor [22]; Measurement range: 0–100% (humidity), −40 °C ~ 120 °C (temperature); Accuracy: ±4,5% (humidity), ± 0.5 °C (temperature); Response time < 30 seg.
- MQ7 Sensor – it is a high sensitivity CO (carbon monoxide) sensor with several many features [23]: high sensitivity, fast response, wide detection range (20 to 2000 ppm), stable performance and long life, simple drive circuit; Requires manual calibration.
- T6615 CO2 Sensor – it is a low power, good performance CO2 (carbon dioxide) sensor (designed for HVAC purposes), with the following main specifications [24] - Measurement range: 0-5,000 ppm; Accuracy: ±50 ppm ± 3% of Reading; Response time: 2 min; Automatic calibration (every 24 h).
- LDR 5 mm Sensor – it is a sensor that allow to detect light; it is basically a resistor that changes its resistive value (in ohms) depending on how much light is shining onto the squiggly face [25]; Since it is low cost but inaccurate, they shouldn't be used to try to determine precise light levels in lux; instead, we can expect to only be able to determine basic light changes. Resistance range: 200 K ohm (dark) to 10 K ohm (10 lx brightness); Sensitivity range: CdS cells

Fig. 9 Data visualization: relative humidity (%)



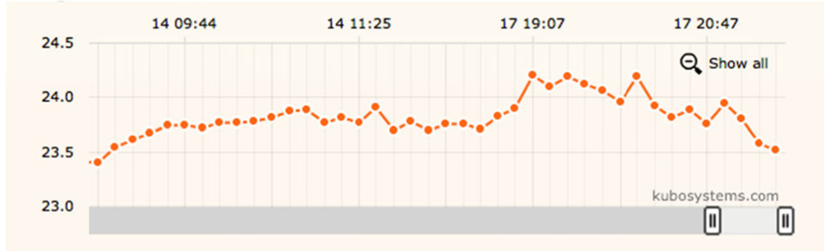


Fig. 10 Data visualization: temperature (°C)

respond to light between 400 nm (violet) and 600 nm (orange) wavelengths, peaking at about 520 nm (green).

Instead of most sensors on the market that cost around 500 USD and don't provide real time monitoring data, iAQ system is a suitable low-cost and real-time solution for enhanced living environments.

The current consumption of the iAQ Sensor and iAQ Gateway were measured and the results are presented in Table 2. Considering 15% of iAQ Sensor time in transmission state, 10% in receiving state, and 75% in sleeping state, the medium consumption values are 126 mA. Considering 10% of iAQ Gateway time is in transmitting transmission state, 10% in receiving state and 80% in sleeping state, the medium consumption values are 198 mA.

Taking into account that the system is intended to be used in indoor environments where there is available electricity there was no great concern with the choice of ultra low-power sensors. The focus of the research was the real-time data collection and the notification functionality. The selection of the sensors was based on the cost of the system. To decrease energy consumption electromechanical sensors will be incorporated in the system.

Software

The firmware of the iAQ Sensor and iAQ Gateway was implemented using the Arduino platform language in the IDE ARDUINO. It belongs to the C-family programming languages.

The iAQ Web was developed in PHP and MySQL database. Web services that allow data collection are also built in PHP [26].

Results and discussion

The iAQ Sensor hardware used to collect environmental data presented in this section is represent in Fig. 8. The iAQ Web allows viewing the data as numeric values or in a chart form. A sample of experiment data for a selected room is shown in Figs. 9, 10, 11, 12 and 13. Some illustrative graphs of relative humidity (Fig. 9), air temperature (Fig. 10), CO2 (Fig. 11), carbon monoxide (CO) (Fig. 12) and luminosity (Fig. 13) are shown below.

The graphic display of the environmental factors allows a greater perception of the behaviour of the monitored parameter than the numerical display format. On the other hand, the Internet portal also allows the user to access the historical data, which enables a more precise analysis of the detailed temporal evolution of environmental parameters [27]. Thus, the system is a powerful tool for the detection of problems and decision making on possible interventions to improve air quality in the building.

The iAQ system is in the testing phase. At this stage the main goal is to make technical improvements, including their calibration. Among other advantages of the iAQ system, it stands out for its modularity, small size, low cost of construction and ease installation. Improvements to the system hardware and software are planned to make it much more appropriate for specific purposes such as hospitals, commercial buildings or factories.

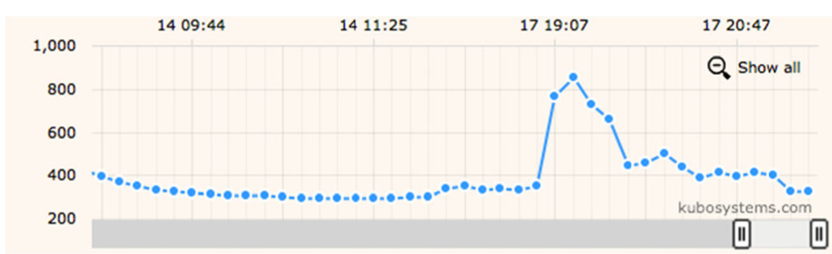


Fig. 11 Data visualization: carbon dioxide (CO2) concentration (ppm)

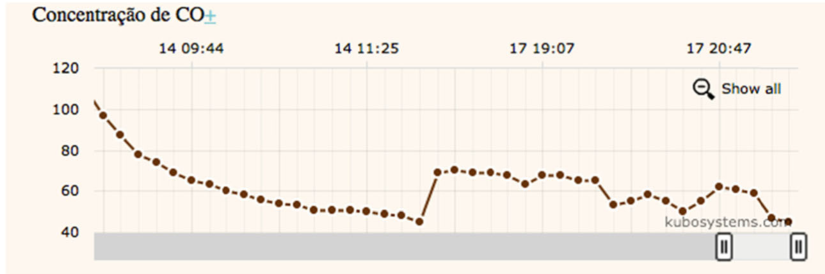


Fig. 12 Data visualization: carbon monoxide (CO) concentration (x10E-1 ppm)

Conclusion

This work aimed to present an effective indoor air quality monitoring system to prevent exposure risk. The system is developed using low-cost micro gas sensors and an open source microcontroller development platform Arduino. Five micro sensors of environmental parameters were used in each module, but other sensors can be added as needed. The system was tested by monitoring two classrooms. The results obtained are very promising, representing a significant contribution to indoor environmental studies. Nevertheless, the system needs further experimental validation in real environments, in particular with the assembly of more than two remote modules as used in laboratory tests, in order to verify and calibrate the system more accurately. In addition to this validation study, physical system and web portal improvements have been planned with a view to adapt the system to specific cases or problems, such as schools, kindergartens or shops.

Compared to existing systems, it has great importance due to the use of low cost and open-source technologies. Note that the system has advantages both in ease of installation and configuration due to the use of wireless technology for communication between the IAQ sensor and IAQ Gateway, but also due to its small size, about 20×10 cm2, compared to other systems. However, we intend to miniaturize even more the modules through the use of smaller components and more effective methods of heat dissipation. As we spend about 90% of our lives in indoor environments it is necessary to monitor these environments in order to plan changes of habits and even interventions in the ventilation of these spaces. This system makes a significant contribution compared to existing air quality monitoring systems due to its low cost of construction, installation, modularity, scalability and easy access to monitoring data in real time through the web application. Another great advantage of this system is the notification system that allows users to act in real time in order to significantly improve indoor air quality through the ventilation or deactivation of pollutant equipments. Compared to other systems the scalability of the system provides flexibility and expandability as the user can start with a few stations, and then keep adding as the needs and complexity of the indoor environment.

This system is extremely useful in monitoring air quality conditions inside buildings to better understand the current status of air quality as well as to study the behavior of environmental parameters. Thus, the system can be used to help the building manager for proper operation and maintenance to provide not only a safe and healthy workplace, but also a comfortable and productive one. All in all, a system like the explained in this work would be of benefit in Public Health by stopping and preventing the burden of symptoms and diseases that have been linked with indoor air pollutants. In industrialized countries, this is a problem of increasing importance taking into account that people, throughout all ages, spend most of their times indoors.

This paper is a revised and expanded version of a paper entitled 'Monitoring Indoor Air Quality to Improve Occupational Health' presented in New Advances in Information Systems and Technologies (pp. 13–21). Springer International Publishing [28].

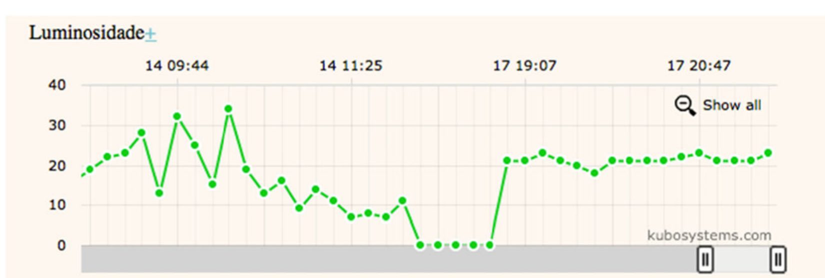


Fig. 13 Data visualization: luminosity (x10 lx)

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