SCIENTIFIC CULTURE
www.sci-cult.com

SCIENTIFIC CULTURE, Vol. 11, No. 4, (2025), pp. 3522-3531
Open Access. Online & Print

DOI: 10.5281/zenodo.11425177

DEVELOPMENT OF A WIRELESS MULTISENSORY ELECTRONIC MODULE IMPLEMENTED IN AN INDUSTRIAL UAV FOR CARBON MONOXIDE DETECTION IN THE ATMOSPHERE

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Received: 03/06/2025
Accepted: 29/10/2025

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ABSTRACT

The acquisition of information is defined as a fundamental task in the development of projects related to the analysis and discrimination of volatile compounds. The system proposed in this research consists of a microcontroller integrated into an Arduino development board, selected for its robustness and processing speed. To facilitate connectivity, a printed circuit board (PCB) was designed with dimensions and characteristics that allow full coupling with the base board. The PCB integrates sockets for semiconductor oxide-based sensors, which exhibit resistance changes when exposed to specific gases. A signal conditioning circuit was designed for these sensors, delivering processed signals to the microcontroller. The sensors are interchangeable, allowing the system to be adapted to different perception tasks. The acquired data are stored in an SD module and simultaneously transmitted via point-to-point communication under the IEEE 802.15.4 standard. The described system was mounted on an industrial unmanned aerial vehicle (UAV) with appropriate characteristics for high-performance tasks. Additionally, a reception module with serial communication connected to a computer was developed. A graphical interface was designed based on a web page structure, stored locally, with the capability to visualize data, perform statistical analyses, and export it into different file formats. The objective of this research is to develop a portable and low-cost system for detecting volatile compounds in the environment, supporting data acquisition methodologies for the identification of pollutant particles in industrial and urban areas.

KEYWORDS: Communication and communication networks, Remote control via internet, Wireless technology and mobile devices, Monitoring and supervision, Signal analysis and processing.

1. INTRODUCTION

In recent years, there has been an increasing presence of pollutants and particulate matter in the air, progressively accumulating in the atmosphere with harmful effects on living beings that constantly interact with such environments. Most sources of air pollution are concentrated in urban areas, where contamination is mainly caused by productive activities (industries), hydrocarbon-based transportation, and widespread deforestation. This situation also extends the contaminating effect to surrounding areas with lower exposure to direct risk factors.

Monitoring atmospheric pollutants, in addition to the variables that characterize the sampling zone, is a major challenge that can be addressed through the implementation of new tools with the sensitivity to detect small variations—either increases or decreases—in the studied parameters. In such cases, the implementation of perception and analysis technologies capable of acquiring real-time air samples becomes highly important. These tools allow for the identification of airborne pollutants, establishing normal and critical thresholds of harmful agents, and thus enabling the adoption of corrective and preventive measures.

The reduction of air pollution plays a crucial role in supporting sustainable development. Air pollution, caused mainly by industrialization and energy consumption, is a pressing issue both globally and locally (Geng et al., 2019). It contributes continuously to global warming, becoming a major threat to climate stability, ecosystem services, human well-being, plant life, and economic development, among others (Sicard et al., 2016).

Human activities related to industry and energy consumption are key contributors to air pollutant emissions. However, energy generation and consumption through fossil fuels and biomass also contribute to atmospheric pollution (Wang et al., 2017). Air pollution has produced widespread negative effects, particularly on human health. According to the latest World Health Organization (WHO) report, the air we breathe has become increasingly polluted. Nine out of ten people are now inhaling contaminated air, leading to seven million deaths annually due to atmospheric pollution. One-third of stroke, lung cancer, and heart disease-related deaths are caused by air pollution (Cohen et al., 2017).

Gas sensors play an important role in numerous applications such as environmental monitoring, industrial production, safety, and medical diagnostics (Vargas-Pérez et al., 2020). Consequently, much attention has been devoted to identifying new sensing materials and developing gas sensors for specific purposes. Semiconductor oxide-based gas sensors are devices that exhibit variations in internal resistance when exposed to gases for which they were configured to react, mainly volatile organic compounds (VOCs) (Parvez et al., 2020). The internal resistance of these sensors is heated to release solid compounds carrying oxygen and other gases, converting the reaction into a variable signal (Xu et al., 2010). Currently, this methodology of information acquisition is frequently applied in different remote monitoring applications for critical pollutant particles in the environment [S]. It is also widely used in agricultural quality control—such as monitoring the exposure of crops to chemicals used in biosanitary management—and in detecting respiratory diseases in humans by analyzing exhaled air to identify particles directly associated with specific pathologies (Neethirajan et al., 2009).

Early research focused on leveraging metal oxide semiconductor sensors arranged in arrays, capable of mimicking a biological olfactory system (Zhu et al., 2018), This initiated the development of the first electronic nose prototypes and fostered the exploration of other types of sensors, mainly based on conductive polymers. As a result, electronic noses were used in the characterization and identification of chemical products transported through different media (Kaneyasu et al., 2000).

In recent years, electronic noses have been applied in a wide range of fields. Notable examples include the development of perception systems to detect food adulteration that may pose risks to public health (Apetrei & Bounegru, 2021), Another example is the automation of bovine ovulation detection based on the exhaled breath of animals, achieving satisfactory classification rates above 80% and providing promising data for future studies (Hut et al., 2021). In environmental monitoring, multisensor systems have been employed in wastewater treatment plants to perform quantitative and qualitative analysis of gas mixtures. Using statistical methods, these systems can discriminate and predict the concentration of possible pollutants (Blanco-Rodríguez et al., 2018).

The main limitations of common multisensor monitoring systems are related to accessibility to the target environments. Depending on the variables to be measured, these tasks become more complex when identifying airborne pollutants in open environments. In this regard, unmanned aerial vehicles (UAVs) are increasingly being adopted in public and civil industries, especially for hazardous tasks that are often inconvenient for humans (Zaigham Abbas Naqvi et al., 2021). UAVs offer advantages such as flexible deployment, wide operational coverage, and the ability to take off or hover at any time (Singh & Silva, 2018). While UAVs were initially developed mainly for military applications, they are rapidly expanding into other sectors including commerce, science, entertainment, and agriculture. Current examples include surveillance, payload delivery, aerial photography, and remote sensing (Chen et al., 2019).

UAV operations are generally divided into four phases: take-off, when the aircraft is launched; route, in which the UAV flies to the target area and mission planning and navigation play critical roles; action, the key phase where the UAV performs its main task such as aerial imaging, remote sensing, or surveillance; and redeployment, when the UAV returns to its initial launch point. Additionally, UAV maneuvers are commonly classified into five patterns. For instance, a quadrotor UAV can perform the following: vertical take-off and landing, hovering in a fixed position for a set time, straight-line flight from point A to point B with or without a flight angle, arc flight with a given radius R, and combined maneuvers such as zigzagging (Ordoukhanian & Madni, 2019).

Air quality control has long been a priority for governments, universities, and environmental authorities due to the harmful effects of atmospheric pollutants. Traditionally, balloons, airplanes, or ground stations have been used. Nowadays, UAVs are gaining importance in air quality control (Vinković et al., 2022) By installing measurement instruments on drones, it is possible to identify airborne elements required for different types of observations (Chang et al., 2020).

Considering the large number of successful results obtained with electronic noses in the identification and quantification of gases in controlled and uncontrolled environments, the present study introduces an innovative approach. It implements an electronic module on an industrial UAV to acquire information by exposing sensors to environments with high pollutant concentrations, while also enabling the use of such mobile platforms in underexplored areas of research such as air quality monitoring.

2. METHODOLOGY

An initial research study was carried out in which the agents present in environments with high concentrations of harmful volatiles, or whose quantification is categorized as air pollution, were characterized. This process began with the identification of the gaseous components present in polluted air. Then, the number of ppm that could be detected was determined, along with the ranges considered representative. In this way, it was possible to identify which of these contaminating components appeared consistently, regardless of atmospheric changes. Likewise, an analysis and selection of the electronic sensors with the best characteristics for detecting the identified pollutants was performed, taking into account parameters such as cost, availability in the region, commercial accessibility, sensitivity to small variations (resolution), all to ensure accurate and reliable direct or indirect measurement of pollutants.

Once the sensors were selected, the next step was to design circuits for conditioning the voltage and current signals of the sensors, so that the captured information could be properly modulated and transferred. These circuits were implemented on a printed circuit board (PCB), previously designed to fit a development board, ensuring perfect coupling. It was essential to evaluate the characteristics of different development boards available on the market in order to determine the best options according to processing capacity, speed, as well as physical properties such as size and weight, and how these relate to their functional performance.

The unmanned aerial vehicle (UAV) selected was the DJI Matrice 100. This UAV has important features that make it versatile, thanks to a chassis capable of adapting external components while supporting a variable payload, allowing the aircraft to perform normal flight activities. A critical step in this research was determining the appropriate mounting location for the electronic system on the UAV, ensuring that the multisensor module could collect data effectively. The study of these characteristics also helped define design constraints for the protective structure of the electronic module, which was manufactured using rapid prototyping tools.

Finally, once the entire remote monitoring system was assembled, a web-based interface was developed. This interface allows real-time observation and analysis of the collected data, as well as storage for later access from anywhere in the world. The interface runs on a public server configured to restrict access to registered users on the platform. With the system connected to the interface, validation tests were performed to confirm the correct operation of the developed prototype.

2.1. Analysis of Variables

Among the main sources of polluting gas emissions are road traffic and industry in urban environments. The World Health Organization (WHO) provides thresholds and maximum limits in parts per million (ppm) for pollutants present in the atmosphere, which are key to reducing risks to public health (RINCÓN et al., 2016). These guidelines apply mainly to carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3), which were estimated to have caused more than 4.2 million premature deaths worldwide in 2016 (Martí Valls, 2017).

2.1.1. Carbon Monoxide

Carbon monoxide is a colorless, odorless, and toxic gas produced by the incomplete combustion of fossil fuels (Vanotti et al., 2021) Its main pathophysiological effect is tissue hypoxia, a condition in which blood is not adequately oxygenated, preventing cells from performing their biological processes. This results in severe harmful effects on human health (K. K. Lee et al., 2020). It is also one of the main causes of severe neurological damage, cerebrovascular injuries, and consequently psychiatric disorders (Mazo et al., 2020).

2.1.2. Carbon Dioxide

Carbon dioxide, on the other hand, is a greenhouse gas present in the Earth's atmosphere. Unlike CO, CO_2 is formed through complete oxidation (Parvez et al., 2020)(Xu et al., 2010) in reactions such as the combustion of carbon-containing substances and biological respiration (Ertugrul et al., 2016) It is a gas of great importance for various industrial applications (Neethirajan et al., 2009), uman health control (Chunwu et al., 2022) and environmental monitoring mechanisms (Kaneyasu et al., 2000). For human safety, it is recommended that CO_2 concentrations in the atmosphere do not exceed 20% (Liu et al., 2010).

2.1.3. Nitrogen Dioxide

The main source of nitrogen dioxide (NO_2) comes from motor vehicle emissions, making it directly related to traffic (Stranger et al., 2008). This harmful gas is strongly associated with respiratory problems such as airflow obstruction, exacerbations in asthmatic individuals (Linaker et al., 2000) and increased severity of viral respiratory infections (Becker & Soukup, 1999). The WHO established maximum permissible values of 10 $\mu g/m^3$ as an annual mean and 25 $\mu g/m^3$ as a daily mean (Organization, n.d.).

2.1.4. Sulfur Dioxide

Sulfur dioxide (SO_2) is released into the atmosphere from both human activities (Malik & Kumar, 2021) and natural sources such as volcanic eruptions (Heaviside et al., 2021). It is closely linked to acute respiratory diseases, coughing, chronic bronchitis, hospitalizations, and mortality among people exposed to high concentrations of this harmful gas (Atkinson et al., 2014). The WHO, in its Air Quality Guidelines (AQG), sets a maximum exposure limit of 500 $\mu g/m^3$ over 10 minutes for individuals with respiratory symptoms (Joseph et al., 2015).

2.1.5. Ozone

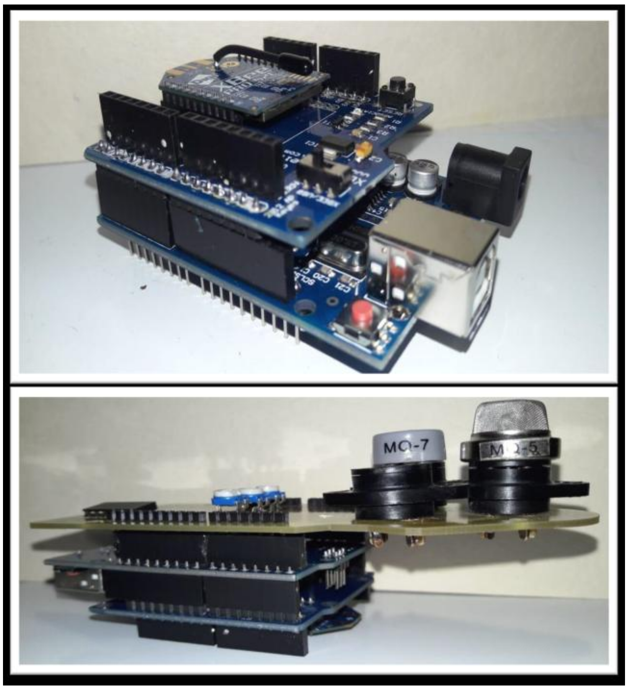
Ozone is a secondary pollutant, meaning it is not emitted directly. This gas forms through complex chemical reactions between volatile organic compounds and sunlight (Cohan et al., 2005). Therefore, its presence in the environment fluctuates throughout the year. Its impact on health includes not only respiratory complications but also ocular problems (H. Lee et al., 2013). In addition, short-term exposure can aggravate conditions in patients with asthma, pneumonia, or chronic obstructive pulmonary disease (COPD) (Tian et al., 2020).

2.2. Architecture of the Multisensor Electronic Module

The multisensor system for acquiring information on volatile pollutants present in the atmosphere includes two important stages: the electronic module with the integrated sensor array, and the storage and transmission module for connection with the web-based database application.

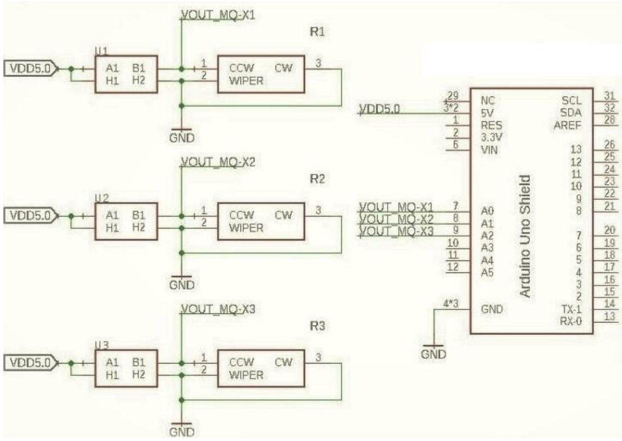
Following the study of different development boards currently available that could perform the tasks described, it was concluded that the Arduino platform was the most suitable. Arduino offers many features within a single brand, with the added advantage of providing a wide variety of complementary modules that can be adapted in an organized manner. Moreover, it allows the design and integration of custom circuits, thus not restricting the applicability of the technology. Based on this, the sensor array circuit was adapted into a custom PCB designed and built by the research group.

The electronic design was developed to ensure optimal adaptation of input and output signals with the Arduino Uno board, while maintaining compatibility with two official Arduino shields: the data storage shield (microSD card) and the shield for wireless transmission (XBee module).



The figure shows the assembled electronic system with all its components, including the Arduino Uno, the semiconductor oxide sensors with their conditioning circuit, the data storage module, and the wireless transmission module via radio frequency. The three sockets allow for interchangeable sensors, depending on the gases to be identified in the sampled environment. This research focused on the detection of carbon monoxide in the atmosphere, since high concentrations—both in the short and long term—cause respiratory alterations and significant public health problems.

The system architecture includes connectors that facilitate the adaptation of different gas sensor models. For this reason, it was necessary to implement a simple circuit capable of converting resistance changes into voltage variations that can be read by an analog input of a microcontroller, as illustrated in the figure. The printed circuit boards (PCBs) used in the system were manufactured with the aid of a professional routing machine, ensuring that conduction paths reduce parasitic currents, noise interference, or other potential issues. These sensors vary their resistance when exposed to volatile compounds.



For the prototype developed in this study, three different gas sensor models were considered. These MQ-series sensors are low-cost but exhibit very good characteristics. They are excellent for gas leak detection and safety systems, offering high sensitivity, fast response, and the ability to detect a wide range of volatile compounds in parts per million (ppm). The circuit includes variable resistors that allow the sensitivity of the sensor to be adjusted according to calibration data provided in the datasheet. Taking into account the preliminary study of the most common pollutants present in contaminated areas, as well as the identification of recurring volatile compounds regardless of atmospheric variations in the analyzed or sampled environment, it was possible to select the most relevant sensors with the greatest impact for environmental monitoring.

The following table presents a description of the sensor references used in this research, listing the sensor model together with the gases it responds to, its sensitivity range, and the power required for its operation.

Tabla 1: Gas sensor references with technical characteristics.

Sensor	Gases Detected	Detection Rango	Power Consumption
MQ5	LPG, butane, propane, carbon monoxide, hydrogen, and alcohol.	200-10000 ppm	<800mW
MQ7	Hydrogen, LPG, methane, alcohol, and carbon monoxide	20-2000 ppm	<300mW
MQ135	Ammonia, alcohol, benzene, NOx, smoke, and carbon dioxide	10-1000 ppm	<800mW

The output signals from the sensors are received by the Arduino Uno board and stored on an SD card through an SD slot module or adapter. This module enables the application thanks to its easy integration with Arduino boards, as it is compatible with any model of this brand. The SD shield was implemented with the purpose of generating a backup of the information transmitted by the sensor module. Considering the priority of the stored information, the data can be successfully read from any computer or text editor (.txt).

In addition to storing data on the SD card, the system also incorporates wireless data transmission using a ZigBee Series 2 communication module operating at 2.4 GHz, with a data transfer rate of 250 Kbps. This module complies with the IEEE 802.15.4 ZigBee standard, providing a communication range of up to 90 meters indoors and up to 1,600 meters outdoors with line of sight. The Series 2 module enhances output power and improves the data transfer protocol. These modules enable the creation of complex mesh networks based on the XBee ZB ZigBee mesh firmware.

Through this module, a reliable communication link is established between the data acquisition system and the control center for data collection, since the receiver is connected to the serial port of a computer. The following figure shows the architecture of the wireless communication system.

2.3. *Adaptation to the electronic module*

An important part of this study was selecting the appropriate location for the installation of the developed module on the DJI MATRICE 100 platform, with the aim of ensuring optimal sampling while maintaining UAV maneuverability. It was essential to guarantee that the sensors were not affected by turbulence generated by natural airflow through the propellers. For this reason, it was determined that the best data collection occurred when the electronic module was placed at the bottom of the vehicle, with the sensors oriented perpendicularly to the flight path once the UAV reached its cruising altitude. Dimensional limits such as the size and weight of the module were also established to ensure that the UAV's take-off, flight, and landing were not compromised. During the construction process, tests were carried out with dead weight attached to the UAV, confirming that the appropriate flight time for monitoring operations was 15 minutes under normal weather conditions.

The computerized design was performed using SOLIDWORKS v2020, which, due to its capabilities, allowed the simulation not only of each individual component but also of the assembled system as a whole. This software provided a general analysis of the physical properties of each piece and included a comprehensive materials database considering not only mechanical and physical properties but also realistic aesthetics. This made it possible to visually assess the system and verify its structural resistance to house the electronic module. To determine the real dimensions of each component for manufacturing purposes, a 3D model was developed to generate measurements and technical drawings. These were then used for the complete assembly of the parts, providing a clear idea of the layout of each piece and the necessary steps for the assembly process.

Once all component designs were completed, rapid prototyping was carried out by printing the pieces using an ANET-A8 3D printer. This facilitated the molding process, particularly for the interior and structural elements. With all pieces and the required materials available, assembly began with the support of the technical drawings and the 3D model. After the fabrication stage was completed, the overall structural performance was evaluated to proceed with the installation of the electronic components, resulting in a functional product.

Finally, the electronic module was integrated into the DJI MATRICE 100 for subsequent validation tests in controlled environments, followed by field trials in selected areas with different levels of atmospheric pollution. Programmed flight routes were executed, and the collected data were analyzed to determine the concentration of pollutants in the study area, as well as to identify the gaseous components present in greater or lesser amounts. The following figure shows the system fully integrated with the UAV.

2.4. System Functionality validation

The validation of the constructed electronic module was carried out through tests conducted in controlled environments. These tests demonstrated the effectiveness of the developed system during the air sampling process, considering the aerodynamics of the fluid, its transition and expulsion to the exterior, the analysis of the samples by the selected sensors to identify pollutants, the processing and storage of data in the chosen development board, and the export of the acquired data.

The selected transmission module enables data transfer rates of up to 250 Kbps using point-to-point communication under the IEEE 802.15.4 standard. This type of connection makes it possible to establish communication between multiple XBee modules, providing highly reliable links in a relatively simple manner. The transmission range between transmitter and receiver can reach up to 1,600 meters in line-of-sight conditions without obstacles. Configuration of the XBee module was performed using the X-CTU software.

The information collected by the electronic nose is transmitted to the receiving XBee module, which is connected through the computer's serial port, and then forwarded to a local domain server. Through a web application, the acquired data can be visualized in parts per million (ppm). The application includes user registration and login features to securely store the information collected by each prototype user, ensuring data protection. The transmission of measurements can be observed in real time while the UAV performs its flight and the sensors gather information from the sampled area. Each user also has the option to access the historical data log by date and time, filter the information by sensor, and export it in .txt format for later processing in any compatible software.

3. CONCLUSIONS

The prototype of the developed multisensor electronic module presents specific characteristics for the selected application. This required adjustments to the different signals from the sensors, which were previously characterized. The XBee-Pro® S2B radiofrequency modules were configured, demonstrating the design phase of the wireless link using point-to-point communication in transparent mode. This configuration enabled communication between multiple sensors through the XBee shield connected to the Arduino Uno microcontroller board, allowing the measurement of various volatile compounds. In turn, the serial port coordinator made it possible to visualize the data in real time through the web application within the local area network.

The multisensor system allows for the detection of volatile compounds, achieving long-distance transmissions of up to 1.6 km in open spaces. The electronic module was integrated into a DJI Matrice 100 UAV as an application of new technologies. The fully assembled system enabled information acquisition during flights of up to 13 minutes. Additionally, the SD module allows storing data relating RO/RS vs. ppm, along with voltage values, in file formats that can be imported into other software for pattern detection and future research applications.

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