Drone-based high-resolution air pollution monitoring: a comprehensive system and field evaluation

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ABSTRACT

This paper presents a novel air pollution monitoring system designed for drone deployment, featuring a specialized payload comprising sensor suites and processing components. The upper half of the payload accommodates MQ series sensors and an SDS011 particulate matter (PM) sensor, strategically positioned to provide comprehensive coverage of various air pollutants. Processing boards, including an Arduino and ESP8266 node micro controller unit (NodeMCU), facilitate data collection, transmission, and connectivity to a designated cloud platform for real-time monitoring and analysis. Additionally, the payload incorporates air pumps for pollution mitigation and relay modules for remote control. Field tests conducted in suburban and industrial areas evaluated the system's efficacy in capturing subtle air quality variations and responding to pollution spikes. Analysis of ground-level and airborne data provided insights into sensor performance and system adaptability across diverse environments. Overall, the proposed system demonstrates promising potential as a comprehensive solution for high-resolution air pollution monitoring, with implications for enhancing public health interventions and environmental management strategies.

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1. INTRODUCTION

Industrial operations such as manufacturing, power generation, mining, and oil refining are among the largest contributors to global air pollution, releasing harmful pollutants like particulate matter (PM), ground-level ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), and volatile organic compounds (VOCs) [1]. These pollutants have been strongly linked to severe health conditions, including respiratory illnesses, cardiovascular diseases, and cancer, as well as environmental problems like acid rain, haze, and climate change [2]-[5]. Studies further reveal that prolonged exposure to PM and O_3 significantly increases mortality rates [6]-[8]. CO, a highly toxic gas, also poses serious health risks, contributing to acute respiratory and cardiovascular conditions [9]-[11]. Despite the critical need for precise monitoring, existing air quality monitoring systems are often constrained by high costs, limited spatial coverage, and delayed responses [12].

Traditional air quality monitoring methods rely on stationary sampling stations with manual data collection, which lack the ability to capture spatial variations in pollutant concentrations across industrial sites.

Additionally, the time lag in manual data collection impairs the swift identification of pollution spikes, hindering timely interventions [13], [14]. Recent technological advancements have introduced unmanned aerial vehicles (UAVs) equipped with compact, low-cost sensors, offering a dynamic, cost-effective alternative for air quality monitoring [15]. UAVs enable flexible data collection, overcoming the limitations of stationary monitors by providing high-resolution spatiotemporal pollution data, essential for effective environmental management.

Research highlights UAV-based systems that integrate gas sensors and particle monitors for precise pollutant measurement. Modular designs, leveraging off-the-shelf components and open-source platforms, enhance affordability, adaptability, and programmability [16]. Solar-powered UAVs equipped with advanced controllers and data fusion modules provide continuous monitoring capabilities, marking significant progress in environmental monitoring technology [17]. Similarly, E-drones with specialized sensors ensure stable, accurate pollutant measurements while generating valuable air quality health index (AQHI) maps [18].

Internet of thing (IoT)-enabled monitoring systems further advance this field by integrating microsensors to measure CO_2, CO, PM_{10}, and NO_2, ensuring real-time, secure data transmission [19]. These systems facilitate localized air quality analysis, offering actionable insights for pollution control. Innovative UAV designs prioritize cost-effectiveness without compromising on accuracy, leveraging technologies like metal oxide semiconductor (MOS) sensors and optimized sensor placement [20], [21].

2. MATERIAL AND METHOD

2.1. Description of the system

In this paper, the proposed air pollution monitoring system comprises a specialized payload designed for attachment to a drone, consisting of two main parts: an upper half housing the sensor suite and an inlet/outlet hole, and a lower half containing processing boards, a battery holder, and air pumps with relay modules as shown in Figure 1. The upper half is equipped with six sections to accommodate MQ series sensors, renowned for their sensitivity to various gases, along with an SDS011 PM sensor. These sensors cover a wide range of air pollutants, including CO, carbon dioxide, ozone, methane, and SO_2, strategically positioned to provide comprehensive coverage across the monitored area. The SDS011 sensor specifically targets PM of varying sizes, including $PM_{2.5}$ and PM_{10} , essential for assessing air quality accurately.

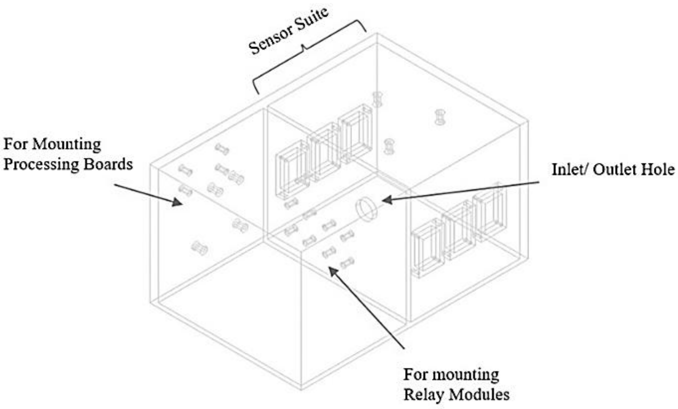

Figure 1. Design of payload

Within the lower half of the payload, the processing boards play a pivotal role in data collection and transmission. An Arduino board serves as the primary processing unit, responsible for gathering data from the sensors and transmitting it serially to the node micro controller unit (NodeMCU) ESP8266 board. Acting as a secondary processing unit, the NodeMCU ESP8266 facilitates connectivity to the cloud and transmits the collected data to a designated cloud platform for remote monitoring and analysis. The system prioritizes drone battery use for powering the processing boards whenever possible. However, for standalone operation, three lithium polymer (LiPo) batteries are housed within a dedicated holder positioned opposite the processing boards. This configuration guarantees uninterrupted power supply, ensuring continuous data collection and transmission even during detached operations.

Furthermore, the payload includes two air pumps positioned at the bottom of the box, each connected to relay modules controlled by the NodeMCU ESP8266 board. These air pumps serve as pollution countermeasures, capable of mitigating high pollution events by facilitating air circulation and dilution. The NodeMCU ESP8266 board can be programmed to regulate the activation of the relay modules at predefined intervals, controlling the operation of the air pumps autonomously. Alternatively, the relay modules can be remotely controlled via the cloud platform, providing flexibility in response strategies tailored to specific pollution scenarios.

2.2. Details of payload

In crafting our specialized payload, we've meticulously curated a comprehensive array of components essential for precise and reliable monitoring, including sophisticated sensors capable of detecting various air pollutants, data acquisition systems for real-time data collection, advanced data processing algorithms for analysis, and communication modules facilitating remote access and control. Figure 2 depicts the system's components and their interactions, highlighting how each element contributes to the overall functionality.

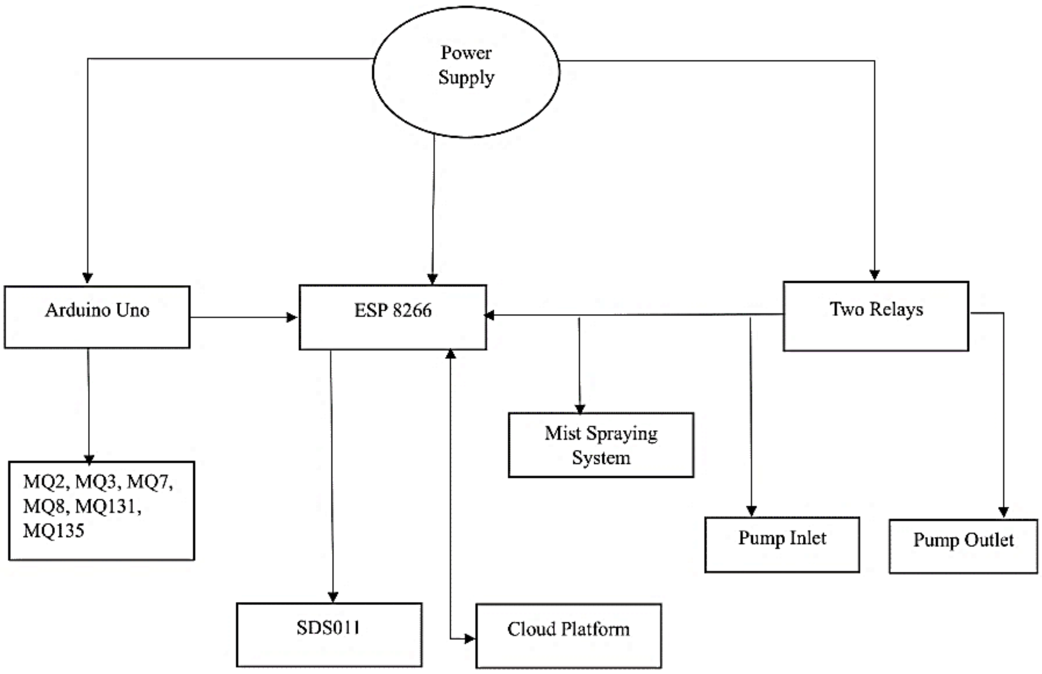

Figure 2. Block diagram

In this study, we utilized a combination of MQ series sensors and the SDS011 PM sensor to detect various gases and PM. The detailed specifications of these sensors, including their sensing parameters and detection ranges, are outlined in Table 1 [22], [23]. Table 1 serves as a comprehensive reference for understanding how each sensor contributes to the overall capability of the air pollution monitoring system, ensuring accurate detection of pollutants in different environmental conditions.

Table 1. Main specifications of sensors

Sensors types	Sensing parameter	Measuring range
MQ-7	CO	20–2,000 ppm
MQ-135	Carbon dioxide	10-1,000 ppm
MQ-131	Ozone	10-1,000 ppm
MQ-2	Methane	300-10,000 ppm
MQ-3	NO_2	10-1,000 ppm
MQ-8	Hydrogen	100-10,000 ppm
PM sensor SDS011	$PM_{2.5}$	0.0-999.9 µg/m^3
	PM_{10}	0.0-999.9 µg/m^3

The Arduino and ESP8266 NodeMCU boards serve as the core processing units within the payload, offering markedly reduced hardware costs in comparison to proprietary alternatives. Arduino is renowned for producing one of the most widely recognized microcontroller development boards suitable for a multitude of embedded applications. Additionally, the ESP8266 chip is notable for its integrated TCP/IP protocol setup, facilitating the transmission of microcontroller data signals to Wi-Fi networks [24], [25]. The programming for both processing boards was carried out using the Arduino IDE. To regulate the inlet and outlet air pumps, two relay modules are utilized. These relay modules function as electronic components, enabling the remote control of electrical loads via low-power electrical signals.

2.3. Unmanned aerial vehicle features and capabilities

The UAV used for this research is a quadcopter, featuring a 680×680 mm carbon fiber chassis that weighs 675 g. This lightweight yet highly durable construction is optimized for carrying a payload of 1,200 g while maintaining structural integrity and flight efficiency. The drone is powered by a 22.2 V, 6,400 mAh LiPo battery, offering a flight time of approximately 17 minutes. This energy capacity allows it to sustain data acquisition operations at altitudes ranging from 150 to 300 meters, making it suitable for diverse aerial monitoring tasks. After incorporating all necessary sensors, modules, and payload, the total system weight reaches 2.9 kg, which is meticulously calibrated to ensure that both flight performance and payload handling are optimized for extended missions. The drone's capability to achieve a maximum speed of 16 m/s allows it to cover substantial areas quickly, while still maintaining precise control and stability for scientific or industrial applications.

The quadcopter is equipped with brushless motors, high-efficiency propellers, and advanced electronic speed controllers (ESCs) to ensure reliable performance. The propellers are carefully sized to generate sufficient lift for the drone’s total weight of 2.9 kg, facilitating stable flight even under varying environmental conditions. The ESCs regulate motor speeds in real-time, ensuring smooth, controlled movements, and providing dynamic adjustments based on the drone's flight conditions. This combination of components ensures that the quadcopter maintains a high level of operational stability, enabling it to perform data-gathering missions with precision and efficiency, especially in scenarios requiring high maneuverability and reliability.

2.4. Optimal payload arrangement

To ensure optimal weight distribution within the payload, the components are precisely positioned for both functionality and stability. The Arduino board and the NodeMCU ESP8266 board, which serve as the primary and secondary processing units, are mounted on the left and right walls of the lower half of the payload. This lateral arrangement is carefully considered to maintain a balanced center of gravity. These processing units are affixed to a custom-designed shock-absorbing platform to mitigate the impact of in-flight vibrations, ensuring the reliable operation of the onboard electronics. At the base of the payload, two air pumps and a centrally positioned battery holder containing the LiPo batteries are symmetrically arranged. This balanced configuration minimizes any risk of lateral tilt or destabilization during flight. Additionally, all wiring between the processing units and power supply is neatly routed, reducing potential for tangling and mechanical stress, which is critical for maintaining the overall integrity and functionality of the system during operations.

The relay modules responsible for controlling the air pumps are mounted at the top of the lower half of the payload, strategically connected to the NodeMCU ESP8266 board. This vertical placement provides efficient access and control while preserving symmetrical alignment of all critical components. For further stabilization, the payload box is mounted directly beneath the drone's central axis, ensuring alignment with the centre of gravity. A robust attachment mechanism, utilizing vibration-dampening straps or brackets, mitigates oscillations and potential imbalances, thereby enhancing flight stability. This configuration not only ensures balanced weight distribution but also promotes reliable operation of the system's sensors, processing boards, and air pumps, making it suitable for precise data collection and mission-critical applications in dynamic environments.

2.5. Working steps

Initiated by the Arduino board, data collection from the sensors begins. To facilitate data collection, the payload employs two pumps to ensure a consistent airflow within the sensor chamber. This ensures that the sensors receive a consistent and representative air sample for monitoring purposes. Once this initial sample is acquired, the intake pump is turned off, which creates a temporary period of stillness within the chamber, allowing the air sample to stabilize and homogenize. During this stabilization phase, the sensors continue to collect data, and the moving average windowing technique is applied to smooth out any fluctuations in the readings. This technique involves averaging the sensor readings over a specified window size, effectively filtering out noise and providing more accurate and representative measurements of the air quality. Once the stabilization period is complete, the outlet pump is activated, and the cycle repeats, ensuring continuous and accurate monitoring of air pollutants.

With the collected information stored in memory of Arduino board before transmission to the ESP8266 NodeMCU board. Once interconnected, the ESP8266 NodeMCU board initiates a connection with the cloud platform, enabling the transfer of gathered data for real-time monitoring and analysis by users. Utilizing the cloud platform, users gain access to observe air quality metrics and can configure personalized alerts to notify them when pollution levels exceed preset thresholds.

3. SYSTEM TEST

To comprehensively evaluate the real-world functionality of our proposed air pollution monitoring system, field tests were conducted in two geographically distinct locations with contrasting air quality profiles. Figure 3 illustrates the locations where system testing was conducted. The two test sites are marked on the map, highlighting their geographical context. This approach allowed us to assess the system's effectiveness across a wider spectrum of pollutant concentrations and flight states (ground level and airborne). The results of these tests, including detailed pollutant readings, are presented in Table 2 for ground-level measurements and in Table 3 for airborne measurements, allowing for direct comparison between the two operational states.

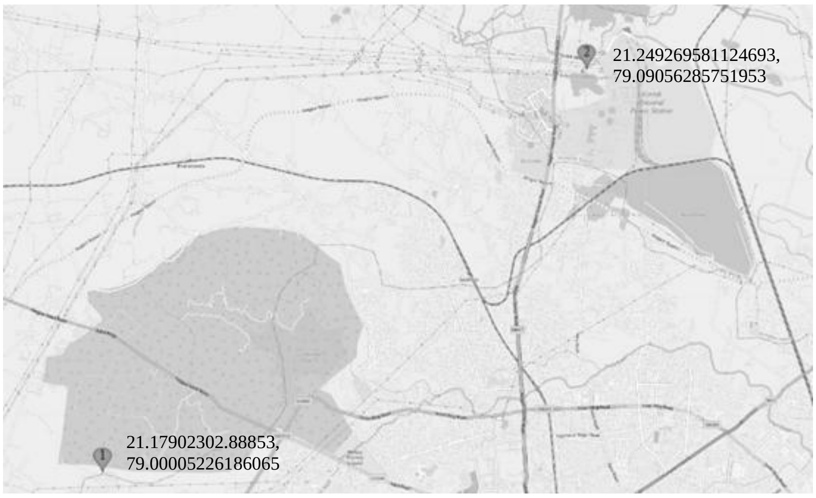

Figure 3. Geotag of location 1 and location 2

Table 2. Data from device on ground

Parameters	Location 1 (ppm)	Location 2 (ppm)
Methane	0	2
NO_x	17	19
CO	1	3
H_2	585	600
Ozone	47	55
$PM_{2.5}$	60	68
PM_{10}	125	170

Table 3. Data from device in air

Parameters	Location 1 (ppm)	Location 2 (ppm)
Methane	0.5	2.5
NO_x	17.28	19.8
CO	1.6	4
H_2	590	615
Ozone	47.4	59
$PM_{2.5}$	61	70
PM_{10}	127	180

The first test site was a suburban area known for relatively clean air. This environment served as a baseline for sensor sensitivity and data accuracy. Here, we focused on the system's ability to detect subtle variations in air quality common in less polluted areas. Collected data, summarized in Table 2, was compared against established air quality standards to determine how well the system could capture even minor fluctuations in pollutant levels, both on the ground and during flight (data shown in Table 3).

The second test location was an industrial zone known for significantly higher levels of air pollution. This rigorous environment challenged the system's ability to handle substantial pollutant concentrations. The system's response to pollution spikes and its capacity to capture dynamic changes in air quality within this heavily industrialized area are detailed in Tables 2 and 3 for ground-level and airborne readings, respectively. By monitoring the system's performance under these conditions, we aimed to assess its suitability for real-world deployment in areas with potentially hazardous levels of air pollution.

By comparing ground-level readings with those taken during flight, we aimed to determine any potential differences in sensor response due to altitude or air movement patterns. This analysis provided valuable insights into the system's ability to capture accurate air quality data across various flight states, ultimately informing best practices for data collection during future deployments. By comparing and analyzing the data collected from both locations and flight states, as presented in the Tables 2 and 3, we aimed to demonstrate the system's versatility and adaptability in diverse air quality settings, ultimately validating its effectiveness as a comprehensive air pollution monitoring solution.

4. CRITICAL DISCUSSION

This research offers a significant leap forward in air quality monitoring with the development of a novel drone-based system. The system prioritizes cost-effectiveness by utilizing readily available and affordable MQ-series sensors, making it a more accessible solution for wider deployment compared to traditional methods. This, coupled with its adaptability to various flight states (ground-level and airborne), broadens its potential applications. Imagine targeted data collection in specific areas of concern or comprehensive air quality mapping across a wider geographical range – all facilitated by this innovative system.

However, there's always room for improvement. While the MQ-series sensors offer a cost advantage, they can be susceptible to interference from other pollutants and may experience sensor drift over time. Future iterations could explore incorporating more selective sensors or implementing calibration routines to mitigate these limitations. Additionally, analyzing air quality data, especially with dynamic pollution patterns, can be challenging. Distinguishing localized sources from broader trends requires further exploration. Advanced data filtering and analysis techniques could be investigated to enhance the clarity and interpretability of the information collected, particularly when comparing ground-level and flight data.

By addressing these limitations, we can refine the system's effectiveness even further. Future research could explore more robust sensor types, advanced data analysis methods, and strategies for handling real-world complexities like weather conditions and varying flight patterns. Ultimately, this critical discussion paves the way for further development and optimization of drone-based air pollution monitoring, promoting its potential as a truly comprehensive environmental monitoring solution.

5. CONCLUSION

This paper presented a novel air pollution monitoring system designed for drone deployment. The system utilizes a specialized payload equipped with a suite of sensors for detecting various air pollutants, including gaseous pollutants (MQ-series sensors) and PM (SDS011 sensor). Data processing and transmission are handled by an Arduino and NodeMCU ESP8266 board combination, with the option for both drone battery and standalone LiPo battery power. Furthermore, the payload incorporates air pumps for optimized airflow within the sensor chamber, ensuring accurate and representative air sample collection. Field tests conducted in contrasting air quality environments (suburban and industrial) demonstrated the system's effectiveness in capturing diverse pollution levels and its adaptability to various flight states (ground-level and airborne). The ability to analyze collected data remotely via a cloud platform empowers users with real-time air quality insights and facilitates informed decision-making.

6. FUTURE SCOPE

Future research on this air pollution monitoring system should focus on several key areas to enhance its effectiveness and applicability. Advancing sensor technology is a primary avenue, including the integration of higher sensitivity and more accurate sensors to detect a wider range of pollutants and lower detection thresholds. Additionally, improvements in data analysis techniques, such as incorporating machine learning and artificial intelligence, could enable more sophisticated real-time data interpretation and anomaly detection, leading to more accurate pollution assessments and predictions.

Another critical area for future research is the design and optimization of the pollution abatement system integrated into the payload. This includes use of the mist sprayers used for particulate pollutant reduction, ensuring they effectively disperse fine droplets to capture and neutralize PM in the air. Future research should also identify which chemicals the mist sprayers will use, such as water, calcium carbonate, or sodium bicarbonate, to effectively reduce specific pollutants. Addressing practical implementation challenges, such as integrating these mist sprayers with various drone models and optimizing their performance across different environmental conditions, is essential. Expanding field tests to diverse geographic and climatic conditions will provide valuable insights into the system's adaptability and robustness. By focusing on these aspects, the technology can be further refined to become a versatile and reliable tool for comprehensive environmental monitoring and effective pollution mitigation, ultimately contributing to better air quality management and public health outcomes.

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AUTHOR CONTRIBUTIONS STATEMENT

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Shreerang Vyawahare	✓	✓	✓		✓	✓		✓	✓	✓	✓			
Latika Pinjarkar			✓	✓	✓		✓			✓	✓		✓	
Tanishq Kohli	✓	✓	✓			✓			✓					
Parimal Sah		✓			✓		✓		✓	✓		✓	✓	
Meena Panchore					✓					✓			✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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