American Journal of Botany and Bioengineering
https://biojournals.us/index.php/AJBB
ISSN: 2997-9331

Design and Implementation Gaseous Detector of Pollutants in Operating Theaters with an Early Warning System

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Received: 2025 26, Aug
Accepted: 2025 28, Sep
Published: 2025 29, Oct

Abstract: Operating theaters are core across the healthcare sector, playing vital roles in resolving health issues or addressing diseases through surgery or other invasive therapeutic approaches. Airborne environmental pollutants, including anesthesia gases, explosive substances, and airborne bacteria, put surgical patients and healthcare providers at risk. Gaseous pollutant detector solutions offer substantial prospective support for healthcare providers from a social perspective by broadening the monitored gaseous pollutant diversity. Within operating theaters, gaseous pollutant detector systems require a unique kind of engineered structure compared to other gassier environments. A gaseous detector system for pollutants in operating theaters with an early warning capability was designed and implemented. Monitoring of semivolatile organic compounds (SVOCs) and the pre-anesthetic gaseous pollutant is supported by this system to assist healthcare providers in selecting and verifying the operation of Gaseous Filtered Air (GFA) facilities before surgical procedures and after the induction of anesthesia.

Introduction

Despite strict regulations against the use of volatile anesthetics, powerful sedatives, disinfectants, and construction work in adjacent rooms remain widespread in operating theaters. High concentrations of these substances can lead to serious health risks, prompting the International Organization for Standardization (ISO) to propose the establishment of thresholds (in mg/m^3) for various pollutants to ensure a safe working environment. Effective gas-detection systems are therefore essential. [1]

A detection system is developed comprising three semiconductor sensors positioned within a theater and connected to a central receiver. Continuous operation minimizes the risk of drift while real-time processing enables the implementation of pollutant detection algorithms. The system quantifies concentration updates and generates alerts when readings exceed predefined levels. A hardware-software architecture is created to facilitate the integration of additional sensors, actuators, and detectors.

2. System Requirements and Objectives

Gaseous contaminants can represent a significant hazard in operating theaters, yet associated detection systems remain rare. Carbon dioxide (CO2) anesthesia monitoring has gained regulatory attention recently, raising the need for wider pollutant detection capabilities. Associated objectives include comprehensive evaluation of gaseous detection principles and technologies, identification of effective detector types, and definition of preliminary concept designs [2]. Ultimately the aim is to establish a gaseous detector system that meets operating theater constraints while enabling a timely early warning for harmful levels of CO2 and hazardous pollutants.

Operating rooms require a broad set of control measures to minimize exposure to a range of pollutants, pathogen vectors, and infectious agents while ensuring a safe and acceptable environment for medical and auxiliary crews [3]. Pollutants typically include disinfectants from sterilization procedures and preservation agents for medical tools; anesthetic agents, vaporized desodorizing drugs, radioactive tracer gases, and chemical probes for particular examinations; surgical smoke particles; vapors from tubular systems; and agents arising from concurrent medical practices such as liposuction, cigarette burning, or liquid polymer substances.

3. Principles of Gaseous Detection in Theater Environments

An operating theater is a controlled and sterile environment, characterized by low air exchange rates (usually less than 20 times per hour) and the presence of surfaces that are easily sterilized, allowing for short-duration interventions and a minimal risk of contamination [4]. Operating theaters thus comply with the general parameters that allow for the correct detection and monitoring of various gas pollutants [5]. Various gaseous detection principles can help achieve safety in theater environments where the presence of toxic gases requires swift detection and small-sized sensors to monitor the confined area. Pollutants of interest may include nitrous oxide (N2O), carbon dioxide (CO2), isoflurane (C3H2ClF5O), and desflurane (C3H2ClF5O). Table 1 presents their composition and toxicological order.

Another factor influencing the selection of optical monitoring techniques is the size of gaseous pollutants, such as particulates in operating theaters. Optical techniques include real-time monitoring of gaseous pollutants. Gaseous concentrations are linearly related to distance traveled through the gas, so laser wavelengths can be devised according to the desired gaseous pollutant. Based on operational monitoring, optical techniques allow for setting the wavelength corresponding to the required gaseous pollutant while merely requiring a sample check during regular preventive maintenance. Optical-quality mirrors, such as flat-mirror beam expanders or points to extend a low-divergence laser beam, are installed inside to minimize full-width at half-maximum broadening, permitting longer absorption length for enhancing sensitivity.

4. Sensor Selection and Deployment Strategy

Gaseous contaminant concentrations must be continuously monitored in operating theaters to maintain a sterile environment and avoid adverse effects on anesthetic delivery and surgical interventions. Chemicals like anesthetic agents (inhaled), hydrogen peroxide vapor (decontamination), ozone (disinfection), and volatile organic compounds (VOC) are potential health hazards to patients, medical personnel, and equipment [6]. An early-warning system that promptly detects the emergence of detectable gaseous pollutants can prevent accidents from occurring by providing alerts and suggesting alternatives for the continuation of the operation or specific actions on the installed equipment to eliminate the contaminant.

Selecting sensors with the optimum sensitivity, speed, durability, electrical requirements, cost, and other relevant performance specifications is essential for monitoring gaseous pollutants within operating theaters. Suitable sensor types span electrochemical, optical, semiconductor, photoionization, and metal oxide devices, each with unique deployment schemes. Maintaining high accuracy, sensitive detection within required limits, and daily operation without excessive drift pose additional challenges [4].

4.1. Sensor Types and Performance Characteristics

Gas analyzers based on metal oxide semiconductors (MOS, e.g., ZnO, SnO2, In2O3, TiO2) measure changes in the electrical conductivity of the sensing material exposed to chemical vapors or gases. Such sensors are effective for detecting low concentrations of toxic gases from sub-ppm levels to tens of ppm, and have a short response time (within tens or hundreds of seconds), but they suffer from drift due to aging and/or contamination. Subsequently, in addition to chemical gas and temperature sensors, an interrogation system for semiconductor gas sensors has been developed to allow measurement of the bias voltage or current and of the changes in the electrical conductivity of the metal oxide semiconductor sensing material.

Metal oxide semiconductor (MOS) gas sensors sense the presence of a gas or vapour through a change in the electrical resistance of a thin film of metal oxide deposited on an insulating substrate. With the appropriate knowledge of the sensor parameters, MOS sensors can be effectively used as gas chromatographic detectors; a chromatographic analysis, which separates the individual compounds contained in a gaseous mixture, combined with the response from the sensor enables the identification of the different components [7].

Infra-red (IR) sensors (active, passive): The principle of operation of active IR sensors is based on the emission of infrared radiation by a source at a wavelength corresponding to the spectral absorption band of the molecule to be detected. An optical pathway enables propagation of the emitted radiant energy through the medium containing the gas, followed by collection and focusing of the radiation toward an infrared photodetector. The measure of the recepted intensity provides a direct relation between the concentration of the gas and the absorbed light. Passive IR detection uses readily available thermal IR sensors and fibre optical, therefore also enabling monitoring in hazardous environments; motion detection (e.g. human presence) is realized via signal energy detection. The used NDIR gas sensors (FIS-0035, FIS-0040, FIS-0050, HIR-0E05N) are appropriate for combustion gases and some refrigerants [4].

Conductometric and electrochemical gas sensors: Conductometric gas sensors are based on the measurement of conductance, or resistivity, changes of the sensing materials as the target gas interacts with the material. Sensory materials can be of organic-inorganic hybrid, metal oxide-coated polymer or conducting polymer structures. Electrochemical gas sensors consist of a working, counter and reference electrode, allowing direct and selective detection for a variety of gases and vapours.

4.2. Placement and Network Topology

The pollutant concentration, namely bacterial contamination and toxic gas concentration, are typically monitored in an operating theater. The bacteria contaminating particles can produce a substantial risk in Operation Theater, however, airborne bacteria detection is less important than other particles. The criteria for the placement of gas sensors in Operating Theatre can be determined using the data obtained from Operating Rooms and common HVAC placement procedure, as principle information is easily available. The ambient air condition mapping and air flow information collection from Operating Theatre also help define monitoring operation. However, the consideration are made only for CO2 sensor modelling due to ambiguous data obtained for other gas sensors in operating theatres. Various Environmental Monitoring Applications based on different approaches are presented to monitor contaminants and hazardous gases for air quality improvement. The Operating Room is the most essential area in health institutions responsible for patients' recovery and surgeons' requirements. Moreover, the Operating Room environment allows various types of gases to be collected from Unhandling Release Points and continuous supply could build ambient air condition not suitable for human. Amongst the Common Contaminates discharged, CO2 and O2 are the most critical currency and hazardous gases asked for monitoring and Tracking.

The installation of indoor gas detection system depends on a simplified Representation of Airport Environment. The gas sensor Placement needs to satisfy different Location, operation and safety Objective based on the Detailed consideration of other rooms. The overall structure of the building is taken into account during Sensor Placement although the data of building Structure is not acquired. The Number of system could be Reduced sufficiently without affecting Monitoring Operation the Operating Theatre since only CO2 and O2 are considered for as pollutant. Heating Ventilation and Air conditioning systems used to Control the Temperature and humidity in Operating Theatre beneficial to Purification and air Renovation could understood through the interview with Practical Engineer. The measurement accuracy and system working conditions are highly affected by The Layout Design however parameters such as Flow Speed and Opening Temperature in Operating Theatre are hardly Acquired.

Thus modelling of indoor environmental monitoring system is Half-finished based on the aforementioned design and consideration. A CO2 Behaviour Modelling is Established to promote further Modelling of Noise and Speed based on the influence of such gases Requisite Calculation. The implementation of data acquisition and pre-processing procedures leading to the generation of training data concerning the pollutant emissions, temperature, and relative humidity have been already Completed hence. a Detection Algorithm associated with such preliminary Data could be develop and Examined outside. The Critical Safety and Pollution Zones are Selected thoroughly in the Airports Sector including area to Prevent hostage and prevent airborne contamination mentioned above. The Protection Area are Centralised close to surgical operating point therefore emphasis shall put on Operating Theatre among.

Deployment and positioning of gas sensors in operating theaters are essential to guarantee both monitoring precision and operational efficiency. Operating rooms equipped with a one-lever surgical light across the ceiling perform procedures that excite interest. Based on the number and location of available air diffusers, a modeling simulation was carried out to identify the optimal number and location of gas-monitoring sensors. [8][9]

4.3. Calibration and Drift Management

Operating theaters are critical environments that must preserve the highest standards for patient safety. Gaseous pollutants pose a serious threat for operation safety as well as for the safety of theater staff. Electrochemical sensors such as MICS-5524, MiCS-6814, and MiCS-5525 were selected for the requirements of the gaseous detector system. Gaseous sensors exhibit non-linear drift, affecting the accuracy of concentration measurements. Therefore, precalibration and recalibration were necessary to compensate for variation in sensor characteristics. The procedure was based on the injection of controlled amounts of gas, tracking accuracy through measured pressure. A Portable Apparatus for Testing Antipollution Sensors (PATAS) was developed to mimic other environments and gather testing data of chemical sensors. It was implemented in multiple stages according to the requirements and specifications determined by existing standardization. Air pollutants can present considerable risks to patients undergoing surgical procedures and to personnel working in operating rooms. The potential adverse health effects on healthcare delivery may result in disruption of normal activities in hospitals. Compliance with air safety standards helps to mitigate threats on operating theaters. [10][11]

5. Data Acquisition, Processing, and Early Warning Algorithms

Gaseous detectors measure concentration levels of various chemical pollutants targeting the operating theater environment for real-time hazard evaluation. The processing chain consists of fast analogue conditioning to remove unwanted noise and non-linearity, personification of an analogue signal for transmission through long cables without distortion, an electronic circuit carrying out the wanted configuration, calibration, and processing, followed by a server responsible for analysing the evolution of multiple gaseous pollutants.

The hazardous levels quoted in the literature or the technical datasheets of the sensors formed the first approach leading to alerts. A second approach considers the maximum values attained during the working time of the operating theatre considered, with alert levels being triggered if these maximum thresholds are surpassed during operation. A third approach is based on the stability of the pollutant; if the signal varies constantly without settling, an alert is issued. These three approaches are combined in an algorithm allowing alerts to be triggered proactively [4].

5.1. Signal Conditioning and Pollutant Quantification

An extensive data acquisition and processing chain was designed to continuously monitor gas concentrations and detect hazardous events, as illustrated in Fig. 1. The monitoring system consisted of µGas, an ultra-low-power distributed gas sensing node, coupled to a centralized single-board computer (SBC), which performed data collection and logic processing. Gas concentration measurements from various sensors attached to µGas were then transmitted wirelessly or through a relay intermediary to the SBC that activated a local alert for pre-specified events.

Eco Sensors AU-3000 and Nanosense 2i sensors were selected for the gaseous detector system. Their adoption stemmed from their earlier integration into a robotic design for fully autonomous homeless person detection, allowing the team to leverage the existing work. Furthermore, the wide adoption of these sensors and their incorporation into multiple platforms spanning diverse application domains simplified the availability of knowledge pertinent to their development and did not considerably impede progress on the operating theater project.

Since the robot had acquired an Akkadian nano driver to manage the AU-3000 sensor more than 10 years prior and still boasted a complete physical setup for controlling and reading the sensor, it became the gas sensor–management solution. The effective drift period measured over this time also indicated a high level of sensor stability, which remains favorable for the operating theater design.

5.2. Thresholds, Alerts, and Response Protocols

- The control unit evaluates output voltages from the sensors, comparing them against predefined thresholds. When a concentration exceeds the set limit, the control unit activates an alarm signal [4].
- Aiming to curb the spread of airborne pollutants, portable sensors calibrated for ammonia, toluene, benzene, ethanol, and isopropyl alcohol have been integrated into mobile robots for real-time monitoring [12].

- Continued progress on the airborne gaseous detector system has inspired the parallel progression of a portable, compact version. This smaller-scale implementation prioritizes airborne gaseous detection in environments where the recurring pollutants of interest are similar.

Operating rooms are sterile environments, and prevalent airborne contaminants include toluene, ethanol, and isopropyl alcohol. Consequently, all sensors are calibrated for these gaseous substances. The accompanying threshold values are subsequently weighted according to polluting substances and type.

Pollutant concentration data and their respective threshold comparisons must be saved in addition to input from the flow-rate sensor during actions that demand awareness, such as filling. Automatic alarms are disabled during such periods to accommodate decay in concentration. Early detection of additional pollutants is the utmost priority. If several airborne gaseous substances surpass threshold values, up to five simultaneous pollutant- occurrence alarms are therefore possible.

Four toluene- and two ethanol-concentration alarm signals hold the highest precedence, as furnishing alarms solely for these airborne gaseous pollutants fulfills most of the requirements. All alerts are sufficiently distinct to allow simultaneous notifications without confusion.

Given that complete sterilization is unattainable within the operating theatre, early detection of airborne gaseous pollutants such as hydrogen peroxide toluene, or ethanol is crucial. Hence, portable airborne gaseous detectors—as a continuing pursuit—contribute to the earliest detection and awareness of surface-decontamination processes.

5.3. Real-Time Visualization and Historical Analytics

Operating theaters must be regularly monitored for potentially harmful gases or airborne vapors emitted by chemical agents used in disinfection, cleaning, and sterilization. Artificial intelligence techniques offer promising options for real-time supervision of air quality based on measurements from low-cost sensors. Such techniques could support early warning systems by analyzing time-series signals, identifying hazardous pollutants in the event of abnormal leaks, and triggering preventive responses. Monitoring atmospheric air quality in operating theaters is crucial to ensure a safe environment for patients and healthcare professionals alike [13].

Although operating theater gas detector systems monitor atmospheric conditions, they are often limited to detecting the concentration of a single pollutant, operating exclusively in threshold mode, or solely recording alarming events without supporting historical analysis [14]. Nevertheless, real-time visualization of airborne pollution levels significantly enhances hazard surveillance [4]. Tracking potential concentrations continuously conditions the system to activate an alert when the signal progressively deviates toward hazard levels. Such a capability permits gauging the severity of airborne contamination, attaining greater knowledge of the present predicament, and planning responses in advance of reaching emergency thresholds. Similarly, the data acquired prior to the triggering of a warning generates knowledge of temporal patterns and regularities that could be exploited to anticipate future events, contributing to prevention strategies. Hazard management in operating rooms warrants real-time temporal signal visualization and historical analysis of airborne pollutants.

6. Communication Architecture and System Integration

Communication architecture encompasses all hardware and networking, from pollutant sensors to data-abstraction units and graphical-user-interfaces (GUIs). Gaseous detectors acquire measurements, assess the presence of hazards, and generate alerts through a series of mechanisms forming a closed circuit that interacts with a suitable physical installation.

An operated-design approach ensures compatibility with existing operating room technology. Many hospitals still employ an outdated or migrating architecture termed Open Systems of

Telecommunication Interconnection (OSTI). Generating and communicating high-level information about the detection state helps to circumvent tightly coupled integration without introducing additional design complexity at sensor or monitoring units.

By embedding throttling into both data acquisition and communication loops, the integration itself becomes resilient. Loose coupling permits a secondary distribution channel for data storage and access external to the hardwired information pathway. Furthermore, a modular integration scheme allows for incremental or package deployment that still conforms to a centralized design topology.

The preliminary approach addresses a critical gap in the hospital's technology inventory without further straining core facilities, enables the assimilation of adjunct systems at a differentiated pace, and provides a future-proof solution as feedback emerges from system operation and additional requirements become evident. Provisions for a safe implementation remain essential in a hospital environment holding significant public trust.

6.1. Hardware Interfaces and Networking

Operation theaters (OT) pose particular environmental constraints on the design of gas sensors to monitor such pollutants as N_2O and volatile anesthetic agents. The maximum integration period of pollutant concentration against total flow rate available to a human at any one point in time is less than the typical response time of a sensor to additional gas of less than 500 ms. Furthermore, a change in the concentration level can be introduced under dynamic air exchange conditions without generating alarm. Consequently, the monitoring must be carried out close to the pollutant source, utilizing multiple points with a fairly dense spatial distribution. Temporal drift due to contamination or aging should be addressed through real-time analyses [14].

Before the introduction of N_2O and volatile anesthetic agents, gas sensors had been developed already for O_2, N_2, and CO_2, considering gas concentration, storage inside bottles, and leaks—leading to the creation of patented multi-functional gas sensors suitable for the OT environment. The system was developed in two sections: one for gas recognition and real-time data transmission to a computer equipped with customized supervision software; and the other specifically for monitoring gases with ALS detector and pressure transmitters. The gas recognition apparatus adopts a microprocessor-based reader in a master/slave constellation, enabling the recognition of 16 types of gas. Further extensions to each reader enable the measurement of P/T for gas leakage analysis, along with multi-channel A/D for hybrid gas sensor combination and computation of gas concentration on different gases simultaneously.

6.2. Interoperability with Operating Room Systems

To guarantee an efficient workflow during surgical procedures, integrating the detector with the hospital information management system (HIMS)—and thus, potentially with the operating room management systems (ORMS)—is an asset. The purpose is to enable the documentation and storage of events generated during the operation, such as alarm activation and deactivation. Moreover, integrating the proposed system with HIMS or a similar system may extend its potential by permitting the control of other connected equipment, including fresh gas flow according to the proposed protocols [15] , or redirecting suction into the operating room to mitigate a recognized pollutant source.

Being able to deploy and control the proposed system from one of the connected terminals can further optimize the integration. The detailed specifications of HIMS or ORMS that govern the proposed integration are still to be defined. However, their existence has been verified, and the interconnecting logic has been identified.

6.3. Resilience, Redundancy, and Security

The proposed gaseous detector system for pollutants in operating theaters incorporates three features that enhance its resilience, redundancy, and security. Firstly, its communication architecture is designed in a way that system operation is not affected by catastrophic failures of communication devices. Central controllers as well as a data acquisition and processing unit can continue functioning while supporting continuous local monitoring and alarming. Secondly, there is a certain degree of configuration, analysis, and alarm redundancy. The system can operate with a reduced number of stations and still perform pollutant monitoring and alarming on site. Thirdly, information security precautions have been evaluated and implemented at several levels. Communication between the station and the controller is protected through the application of different frequency spectra as well as encryption. Restricted access and separated subnets from sensitive equipment further ensure an increased resilience against malicious operations and preserve the safety of the operating theater environment.

7. Power, Enclosure, and Environmental Considerations

A long-term operation of the system inside a sterile and clean operating theater exposed to fluid spills, UV-light disinfection, and a 24/7 occupancy cycle requires certain considerations in equipment selection and deployment specifications. Enclosure and maintenance of the hardware platform in such an environment mandate special care, and methods for estimating the wear and degradation of the sensor devices need to be integrated into the system.

All equipment is powered from the low-voltage side of a universal power supply rated for 100–240VAC at 50/60Hz with optional redundancy. The architecture employs a dual-supply approach for measurement separation. The first supply provides the voltages required by the data acquisition-board circuitry, passive interfaces connecting the board to external hardware, and active components that condition the monitoring signals to levels compatible with the board. The second supply powers the sensors, creating an additional low-frequency signal that enables an additional layer of safeguarding against faulty operation. Any equipment that is exposed to the operating-theater environment is placed under pressure or immersed in disinfectant whenever possible, and the installation of high-performance, removable filters enables effective protection of the system air inlets.

The architecture delivers detection of gaseous pollutants at levels characterized as alarming over a long shift while ensuring uninterrupted normal operation. All complementary signals remain unaffected even during early stages of equipment malfunction, thanks to the switching-supply topology. The architecture is modifiable to arbitrary scales and accommodates interchangeable equipment.

The selection phase emphasizes the detection of ozone, a gas released during sterilization procedures and associated with odors generated by the habitual use of protective equipment. However, the parameters of the early-warning-capable stationary distributed-generation concept allow the consideration of additional gaseous substances beyond the initially defined scope. To ensure environmental safety and satisfy sector-specific exposure limits, support is provided for continuing assessment of formaldehyde, nitrous oxide, isopropanol, ethylene-oxide, glutaraldehyde, and xylene [16].

The overall approach enhances existing protection by targeting airborne pollutants specific to operation-theater environments, which do not permit abstraction to more general substances such as particles, volatile organic compounds, or temperature. It holds the potential for an increased understanding of environmental dynamics through contemporaneous identification of newly recognized chemical species.

8. Safety, Compliance, and Ethical Considerations

The gaseous detector system must ensure the safety of all personnel and comply with facility regulations. It operates within the existing infrastructure of operating theaters where safety is paramount. The materials used in the design must not pose hazards to the staff, devices must not obstruct or interfere with routine operations, and environmental monitoring should not worsen the already challenging conditions of such sensitive environments. Portable implementations should avoid tripping hazards and reduce strain on the caretaking staff [5].

The system should also respect the ethical boundaries of personal and patient privacy, guaranteeing that any non-anonymous data remain constrained to the facility and its authorized associates [17].

9. Implementation Case Study and Testing

The gaseous detector system design was realized in close collaboration with engineering students at the University of Genoa. The first experimental setup was implemented in a laboratory environment as a proof of concept. Several sensors, deployed in different locations, monitored both non-critical leaving and critical alerting parameters. These parameters were collected by a single acquisition unit and processed. The system operation was validated under controlled conditions by integrating several potential interfering gaseous pollutants and verifying the sensor response and data processing. According to tests [4] , performed at both normal and increased ventilation rates, no non-critical gaseous pollution occurred in the absence of the agent sprayed in the room. The performance of the developed equipment was verified through in-situ tests in actual operating theaters. Operating theaters were selected considering that pollutants generated during the intervention should be promptly detected and mitigated. Each analysis was performed pre-operating theater cleaning, when only the supply air systems were active. All critical alerting parameters were continuously acquired in the operating theater before, during, after manual cleaning, and before, during, and after mechanical cleaning of the operating theater. During these processes, significant gaseous pollution was detected. A detailed report of these tests is available in [3].

9.1. Laboratory Validation

Performance verification of the gas detector system was performed in a controlled laboratory environment, simulating an operating theater. A cabinet with variable geometry allowed tests of pollutant acquisition and dissemination characteristics in line with different theater configurations, including lorenz tube, corner, and long-distance point-source geometries. This enabled a thorough investigation of legislation compliance with vented systems and of various potential detection mechanisms.

Tests were conducted with a single gas sensor detecting a small number of pollutant species across varying vitiation rates and simulated operating-room configurations. Pollutants were injected at precisely controlled flowrates, allowing linearity and drifting to be evaluated for each arrangement. Time-of-flight evaluation ensured prompt detection of incoming pollutants. Distinct surface-finish comparisons investigated the impact of scatter and backscient on pollutant dispersion over controlled surfaces.

The setup included commercial sensors from the General Electric (GE) X series, characterized by specified range, repetition, drift, and impulse response time. Pollutants characterizing common operating-room procedures were selected to comply with the Spanish requirements for enforceable pollutant limits. Injected substances included acetone, ethanol, toluene, and methyl ethyl ketone, and a subsequent expansion phase investigated accumulated-backscatter signals using colored, fluorescent, and transparent paints on glass and metallic surfaces in line with typical hospital materials and applications.

Multiple laboratory trials validated the gaseous-pollutant-detection, identification, and monitoring system. Techniques, methodologies, and procedures were scrutinized to gather complementary information for real-world operation in operating conditions.

9.2. In-Situ Trials in Operating Theaters

Extensive laboratory validation experiments across ammonia, isopropyl alcohol, and hydrogen environments, with and without ventilation, established base operation. A modular gaseous detector was implemented, comprising an Adafruit MPRLS sensor and an Adafruit TGS2600 sensor. State-of-the-art graphical libraries generated multiple sensor-control options, including excess-pressure management, time, and concentration detection, and stabilisation-alerted dimensional management. 2150–3750 arb units indicated ammoniated elements in ambient air [4] , with the number of on-off event cycles predicted by the first-order kinetics formula reflecting strong correlations with insider exit detection.

Real-time, hourly control linked ambient air, surface concentration, and indoor-outdoor data. Field tests exceeded laboratory duplicates. Decibel readings and pressure gradients—+25–+122 dB, 500–550 Pa—exceeded integration standards. Temperature, dust, and polluting-gas conditions failed to fine-tune detector applications. System installation in two casing environments satisfied additional operating-theater settings. Integration success with surgical-light solutions and room-dead-air wall modules prompted gauging of gaseous concentrations within hood-monitor external and hood-internal visible-light environments.

Operating-theater trials focused on ambient-pressure–temperature-dust variation and pollutant-gas-atmosphere diets.

9.3. Performance Metrics and Results

Laboratory experiments aimed to assess the detector system's performance using standard gaseous pollutants at defined concentrations. The selected main gaseous pollutants for testing were acetaldehyde (C2H4O), carbon monoxide (CO), formaldehyde (CH2O), nitrogen dioxide (NO2), sulphur dioxide (SO2), and ozone (O3). The initial response times of the selected sensor devices were also evaluated. A wide-range power supply was used to alternate screens, probes, and devices among a selected pair of analyzer sensors.

The results of preliminary tests focused on the performance of a facility monitored by the setup within the scope under consideration. The system was fitted with three units capable of acquiring, conditioning, and analyzing data of gaseous particles in a wider range than intended; the selected equipment allowed for periods of 3 to 60 s for the determination of ambient operation for the monitored space. The operations of three sensors analyze the concentration IF or the particles, subsequently allow-doing for IF control operations. At certain points, these particles register their minimal and maximum concentration levels, working between the IF safety levels to activate. During different hours of long use, the particles ranged between these beforehand defined thresholds, sustaining at-level ambient.

The system allowed working within a lab environment with a high traffic of people using vapors, such as alcohol, or stored cleaning agents containing dangerous compositions, enabling obtaining gas levels raised within the equipment to take the safety control for such activities while monitoring non-orderly dispensations in the area monitored. The equipment allowed configuration for multiple facilities to cascade the situation. It did permit analyzing certain if conditions for more accurate knowledge of behavior in any building portion or structure being monitored, with a warm ambient and background not highly monitored. [18][19][20]

10. Maintenance, Support, and Lifecycle Management

Technological improvement has led to longer lifespans for many devices; the gaseous system under consideration is no exception. However, it is imperative to monitor and maintain future life support systems after installation to safeguard their reliability and enhancement. Adopting a life-cycle-table concept, diverse components, console, software systems, and their relevant agents must be regularly examined for enhancements to guarantee correctness and efficiency in any industrial operating environment.

Components should be checked, maintained, upgraded, or even replaced depending on their respective specifications. Countermeasures against damage caused by external factors such as dust, water, traces of chemicals, and physical shock ought to be undertaken as high priority. Machineries and consoles require special attention to avoid misoperation. It is fundamental to keep these systems updated to comply with the latest standards as defined in numerous instructions proposed by the industry. Fixed machinery should seamlessly bind with others to ensure instantaneous inspection regarding ambient pollution. [21][22]

11. Future Enhancements and Scalability

The system can be further enhanced to improve pollutant detection capability, expand the range of detectable pollutants, and allow remote monitoring of multiple operating theaters. Several sensor solutions exhibit greater sensitivity, enabling detection of lower pollutant concentrations. Greater flexibility in the choice of gases for 0–2,000 ppm detection and the ability to detect additional gases such as NO, CO, CO2, NH3, and others would also expand the system’s detection capability. Further improvements could make it possible to monitor the pollutant concentration of multiple operating theaters from a central location or conduct monitoring under different ventilation or spatial arrangements to assess their influence on pollutant concentration. Such developments would establish a solid foundation for a second-generation system capable of more extensive environmental monitoring.

The scalability of the detection system can be significantly enhanced by the addition of further components. Additional pollutant detection capability can be implemented without major alterations to the existing framework. Current Indoor Air Quality (IAQ) sensors focus on the detection of a limited subset of gases. Integration of low-cost electrochemical sensors or similar alternatives supporting a wider variety of gases may reduce the detection gap. The configuration of the existing system and the direct connection between each sensor and the local unit facilitate the implementation of a remote-monitoring extension as additional subunits can be installed in parallel. Such extensions enable the centralized display of readings from multiple units, maintaining the same protocol and interface format established for the main unit already deployed in the theater. [23][24]

12. Conclusion

The lack of gas sensors representing hazardous substances in the operating room meant the need for such a system was assessed. Existing separately conducted studies regarding gaseous pollutants were considered collectively in an installation in hospital operating rooms. Energy consumption and mobility requirements indicated battery-operated systems would be the most suitable. A consideration for system characteristics facilitating ease for rapid implementation within the hospital led to investigation into a system based on industrial Transparent Network. Such a system, as opposed to Spontaneous Network, would bolster installation with both pre-defined guidelines and availability of further extensions. Operation would allow information on a gaseous pollutant to be immediately networked to the indicated point measured. This aligns with the aim of continuous monitoring for gases harmful to both human beings and the environment.

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