Modeling an Internet of Things based Medical Gas Alarm System with Oxygen Purity Measurement Capability

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ABSTRACT

This article explores the significance of creating and deploying medical gas alert systems utilizing Internet of Things technology to gauge oxygen purity. In pursuit of delivering timely and high-quality healthcare services to patients, the medical equipment industry is embracing innovative approaches. The integration of medical gas alarm systems with the Internet of Things network holds promise for expediting error responses and executing necessary interventions. Monitoring oxygen purity in medical gas alarm systems is of paramount importance due to the potentially severe consequences of its inadequacy. Leveraging appropriate Internet of Things processors and tailored programming aligned with system requirements presents an effective avenue for enhancing the functionality of medical gas alarm systems. The article provides a comprehensive overview of management and control solutions and techniques aimed at enhancing the efficiency, dependability, and adaptability of medical gas alarm systems, underscoring the escalating demands in this realm amidst the modern challenges and intricacies of the healthcare industry.

Keywords: *Medical Equipment Industry, Internet of Things, Alarm Integration with IoT, Oxygen Purity Monitoring, Processor and Programming Optimization*

1. *INTRODUCTION*

1.1 The Importance of Designing an Internet of Things-Based Medical Gas Alarm System with Oxygen Purity Measurement Capability

The medical device sector is continually advancing and encountering fresh obstacles on a daily basis, necessitating the provision of appropriate solutions tailored for medical applications.
Ensuring prompt and high-quality healthcare services for patients stands out as a paramount requirement. Consequently, the development and refinement of medical equipment systems hold significant significance in this regard.[1]
The medical gas alarm system stands out as a crucial element within the medical gas infrastructure of all healthcare facilities. It is strategically positioned at various points along the medical gas piping network to continually monitor gas pressure levels. Should the pressure fall below predefined thresholds, the system triggers visual and auditory alarms to alert users. Integrating this system with Internet of Things connectivity capabilities enhances the efficiency of error notification, error type identification, and subsequent action-taking by operators, significantly expediting response times. [2]
When the medical gas alarm system identifies an error, it generates visual and auditory alerts based on the type of error detected (e.g., gas type), in accordance with the requirements outlined in IEC 60601-1-8:2020. These alerts aim to inform current users within the system's installation site of the error. [3]
Presently, the users within the installation environment of the medical gas alarm system primarily consist of medical personnel such as nurses, paramedics, and others working in hospital departments.
Subsequently, users must report these errors to medical gas operators and relevant authorities for appropriate action. However, based on ten years of experience in the medical gas industry, it is observed that this reporting process is often delayed due to hospital protocols. [3]

Although seemingly minor, these delays can have serious repercussions for patients in critical condition, particularly when the error pertains to medical oxygen. Medical oxygen is crucial for various clinical procedures, and even brief shortages can jeopardize the health of patients with cardiac and respiratory issues, premature infants, and others. [4]

By enhancing response times, this system contributes to patient safety by promptly addressing potential risks.

As mentioned earlier, these alarms are designed to detect errors based on decreases in medical gas pressure within hospital gas pipelines, which poses risks associated with medical oxygen gas.

In accordance with paragraph 5.6.5.1 of the ISO 7396-1:2016 standard, medical oxygen must adhere to specified parameters concerning factors that affect patient health.

Among these parameters, oxygen purity level stands out as the most crucial, followed by oxygen pressure. While common medical gas alarm systems monitor oxygen pressure, there is currently no monitoring of oxygen purity in oxygen gas transmission pipelines. [5]

Now, let's outline the risk scenario as follows: the oxygen purity meter sensor installed in the oxygen generating devices experiences a measurement error or becomes locked. Despite the actual oxygen purity level being below the permissible range, the oxygen purity device incorrectly identifies it as permissible. Consequently, oxygen with non-standard purity but adequate pressure is delivered into the consumption line. [6]

Given the system's nature, the medical gas alarm detects pressure within the acceptable range, thus failing to trigger an alarm, and non-standard oxygen reaches the patients.

This non-standard oxygen can lead to decreased blood oxygen levels, severe hypoxemia, and potentially even brain damage in premature infants. Hence, the significance of monitoring oxygen purity levels in medical gas alarm systems cannot be overstated. [7]

1.2 Utilizing Suitable Internet of Things Processors and Programming

A With the rapid progress of technology and the widespread integration of Internet of Things (IoT) and artificial intelligence (AI) applications into various aspects of daily life, facilitating human-machine interactions has become increasingly crucial. Consequently, the significance of linking medical systems to the IoT has never been more apparent.

One effective approach to connect the medical gas alarm system to the IoT and utilize it efficiently involves employing appropriate processors tailored for IoT-based system design. Processors, such as those from the ESP family developed by Espressif, are ideal for seamlessly connecting to the Internet. Additionally, programming these processors according to the specific needs of the system is essential.

A significant advantage of incorporating programming into the design of the medical gas alarm system is the ability to simulate and assess its performance before actual implementation. Simulation software enables the system's behavior to be simulated under various conditions, facilitating the prediction of its performance and effects across different scenarios.

Moreover, programming allows the integration of artificial intelligence tools and algorithms to enhance the efficiency of the medical gas alarm system. These algorithms can be intelligently designed to interact with other relevant equipment.

For coding purposes, development environments like Arduino and MicroPython can be utilized. Furthermore, simulators like Proteus offer the capability to simulate and test written algorithms under more realistic conditions, aiding in the verification of the code's functionality.

2. *System Modeling*

To establish the system model, the initial step involves crafting a control algorithm tailored to meet the requirements of medical facilities and industry standards. Each component is meticulously designed considering its physical, electrical, and mechanical attributes to accurately replicate real-world behavior.
Various methods such as physical modeling, mathematical modeling, and simulation are employed for precise system modeling. Physical modeling delves into the detailed physical and mechanical characteristics of the system, utilizing physical principles to articulate its behavior and performance. While this method typically yields high accuracy, it may be time-intensive due to the intricacy of processes and equipment involved.
Mathematical modeling entails describing system inputs and outputs through mathematical equations and models. This approach is typically suitable for systems with predictable behavior, allowing for the modeling of dynamic effects.
Post-system modeling, simulation enables the exploration of system performance under diverse conditions, facilitating necessary optimizations. This enables a thorough review and evaluation of system performance prior to implementation, enabling the identification of any shortcomings and the implementation of suitable enhancements.
For instance, the system model is developed using the simulation section of Proteus software, incorporating blocks to simulate requisite sensors and the circuit behavior, alongside the algorithm designed to address sensor errors.

3. *System Simulation and Its Corresponding Results*

In this segment, we tailor the model to suit the system's specifications and requirements, ensuring an accurate emulation of real operational conditions. The modeling and simulations are designed to effectively adapt to variations in oxygen pressure and purity, both of which are monitored by sensors.
The medical gas alarm system comes in various configurations, depending on the number of gases it can monitor, ranging from single-gas models to those capable of monitoring up to six gases. For our modeling purposes, we focus on a three-gas medical gas alarm system, equipped to measure the pressure of compressed air, vacuum, and oxygen gases, along with assessing the purity of medical-grade oxygen.
Key parameters for measurement in this setup encompass positive pressure for oxygen and compressed air, negative pressure for the vacuum gas, and the detection of oxygen purity via sensors. These sensors are available in two variants: 4-20mA current and 0-5V voltage, necessitating connectivity to the analog-to-digital converter (ADC) section of the processor.
Considering that processors and microcontrollers lack native support for interpreting current sensor values, a preliminary step involves converting these values to a 0-5V voltage range before linking them to the processor's ADC. This ensures the processor can accurately interpret and process the received values.
The operational sequence of the circuit is as follows: upon activation, the system initializes by linking embedded sensors to the relevant medical gas conduits, initiating measurement and data processing. Simultaneously, it scans the WIFI network to establish a connection.

If the gas pressure falls below the predefined threshold as per the software, aligned with regulatory standards, the corresponding error indicator light illuminates, accompanied by an audible alarm activation.
In instances where oxygen pressure remains within permissible limits but the purity sensor detects a deviation from the specified range, the purity error indicator light illuminates, triggering the audible alarm.
A manual button allows for temporary silencing of the audible alarm during the error notification and resolution process. Upon activation, the alarm remains muted for a 5-minute interval. If the error persists after this duration, the audible alarm reactivates automatically.
Moreover, all measured values are transmitted online via the HTTP protocol to a server, enabling real-time monitoring of values and error statuses on a web interface.

For modeling purposes, four potentiometers, as illustrated in figure 1, function as pressure sensors and purity gauges. This setup enables the simulation of various error scenarios by providing input variations to the processor.

These sensors consist of:

1- Sensor for monitoring medical compressed air pressure
2- Sensor for monitoring medical oxygen pressure
3- Sensor for assessing oxygen purity
4- Sensor for monitoring vacuum pressure

These sensors are linked to the ADC (Analog-to-Digital Converter) channels of the processor. ADC channels are responsible for accepting analog signals and converting them into digital signals that the processor can interpret. Through programming, we can formulate control instructions utilizing these converted digital values.

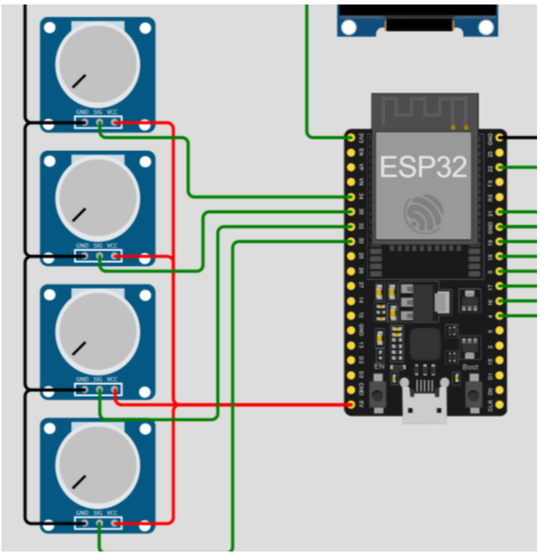

Fig.1. Pressure and purity sensors

As depicted in Figure 2, an OLED display has been implemented to showcase the measured parameters on-site, enabling users to easily access information regarding the pressure of medical gases and the purity of oxygen directly from the device.

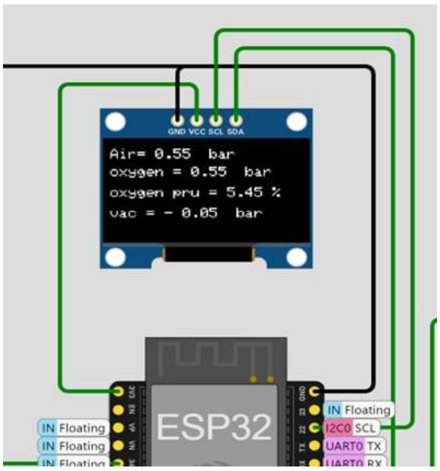

Fig. 2. System Display

As previously stated, this system requires both a visual indicator for gas faults and an audible alarm. To fulfill this requirement, as depicted in Figure 3, four LEDs serve as visual indicators, accompanied by a buzzer for generating audible alerts.

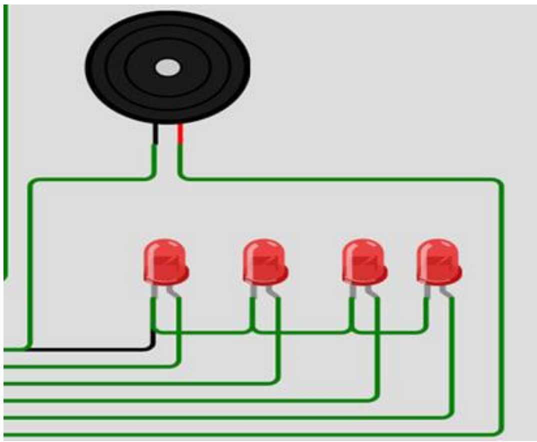

Fig. 3. Visual and auditory alarms in the system

It's essential to note that visual and auditory alarms serve more than just illuminating an LED or activating a buzzer; they must adhere to the guidelines outlined in the IEC 60601-1-8:2020 standard. According to this standard, medical gas alarm systems fall under the category of high-priority alarms, and their activation follows specific criteria. Alarm signal generation should comply with Tables 1,2, and 3 of the standard, where Clause 6.3 outlines requirements such as alarm sound, pulse distance, and indicator frequency for high-priority alarms, which must be documented in the tables.

Alarm category	Indicator colour	Flashing frequency	Duty cycle
HIGH PRIORITY	Red	1,4 Hz to 2,8 Hz	20 % to 60 % on
MEDIUM PRIORITY	Yellow	0,4 Hz to 0,8 Hz	20 % to 60 % on
LOW PRIORITY	Cyan or yellow	Constant (on)	100 % on

Table. 1. Characteristics of alarm indicator lights

Characteristic	HIGH PRIORITY ALARM SIGNAL	MEDIUM PRIORITY ALARM SIGNAL	LOW PRIORITY ALARM SIGNAL[d]
Number of PULSES in BURST [a, e]	10	3	1 or 2
PULSE spacing (t_s) (see Figure 1)			
between 1st and 2nd PULSE	x	y	y
between 2nd and 3rd PULSE	x	y	Not applicable
between 3rd and 4th PULSE	$2x + t_d$	Not applicable	Not applicable
between 4th and 5th PULSE	x	Not applicable	Not applicable
between 5th and 6th PULSE	0,35 s to 1,30 s	Not applicable	Not applicable
between 6th and 7th PULSE	x	Not applicable	Not applicable
between 7th and 8th PULSE	x	Not applicable	Not applicable
between 8th and 9th PULSE	$2x + t_d$	Not applicable	Not applicable
between 9th and 10th PULSE	x	Not applicable	Not applicable
INTERBURST INTERVAL [b, c] (t_b)	2,5 s to 15,0 s	2,5 s to 30,0 s	>15 s or no repeat
Difference in amplitude between any two PULSES	Maximum 10 dB	Maximum 10 dB	Maximum 10 dB

Where: x shall be a value between 50 ms and 125 ms,

y shall be a value between 125 ms and 250 ms,

the variation of t_d, x and y within a BURST shall ~~be~~ not exceed ± ~~5~~ 20 %, and

MEDIUM PRIORITY $t_d + y$ shall be greater than or equal to HIGH PRIORITY $t_d + x$.

The INTERBURST INTERVAL (t_b) for HIGH PRIORITY auditory ALARM SIGNALS shall not be greater than the INTERBURST INTERVAL for MEDIUM PRIORITY auditory ALARM SIGNALS which shall not be greater than the INTERBURST INTERVAL for LOW PRIORITY auditory ALARM SIGNALS.

[a] See also Table 4 for characteristics of the PULSE.

[b] Unless otherwise specified in a particular standard for a particular ME EQUIPMENT.

[c] MANUFACTURERS are encouraged to use the longest INTERBURST INTERVAL consistent with the RISK ANALYSIS. Writers of particular standards are encouraged to consider the longest appropriate INTERBURST INTERVAL of the auditory ALARM SIGNAL for the particular ALARM SYSTEM application. Long INTERBURST INTERVALS can under certain conditions negatively affect the ability to correctly discern, in a timely manner, the ~~source~~ origin of the ALARM CONDITION.

[d] The generation of the auditory component of a LOW PRIORITY ALARM CONDITION is optional.

[e] Unless inactivated by the OPERATOR, MEDIUM PRIORITY and LOW PRIORITY auditory ALARM SIGNALS shall complete at least one BURST, and HIGH PRIORITY auditory ALARM SIGNALS shall complete at least half of one BURST.

Table. 2. Characteristics of the burst of auditory alarm singnals

Characteristic	Value
Frequency component in the range of 150 Hz to 1 000 Hz	At least one that is among the four frequency components with the largest sound pressure level
Number of peaks in the frequency range of 150 Hz to 4 000Hz	At least four peaks in the frequency domain
Effective PULSE duration (t_d) (see Figure 1) HIGH PRIORITY MEDIUM and LOW PRIORITY	 75 ms to 200 ms 125 ms to 250 ms
RISE TIME (t_r) (see Figure 1)	[a]
FALL TIME (t_f) (see Figure 1)	[b]

Within the frequency range of 150 Hz to 4 000 Hz, the relative sound pressure levels of the four frequency components with the largest sound pressure levels should be within 15 dB of each other.

NOTE Care is needed to ensure that the MEDIUM PRIORITY ALARM SIGNAL cannot be confused with the audible emergency evacuation signal specified in ISO 8201:2017 [30].

[a] The RISE TIME should not be so short as to create mechanical speaker noise.

[b] The FALL TIME should be short enough to ensure that the PULSES do not overlap.

Table. 3. Characteristics of the pulse of auditory alarm singnals

As per the guidelines outlined in the IEC60601-1-8:2020 standard, the medical gas alarm device must activate high-priority visual and audible alarms. The visual alarm should consist of a red flashing light with a frequency ranging from 1.4 to 2.8 Hz and a duty cycle of 20 to 60% ON for activation. Additionally, the audible alarm should operate according to the specifications provided in Table 1, following a one-second cycle. Based on these specifications, the required operational rhythm to activate the audible alarm is as follows.

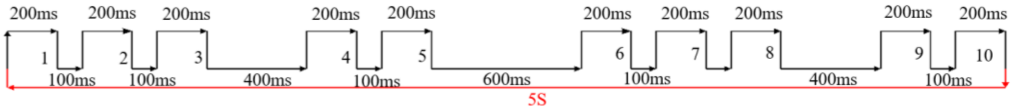

Fig. 4. Related Frequencies

Please be aware that the sound frequency must align with the specified values in the tables, and the generated sound should exceed the ambient white noise level at the installation site by at least 10 decibels. For detailed guidelines, please consult the IEC 60601-1-1:2020 standard.
Additionally, we introduce a mute function using a key, as depicted in Figure 5, to enable a silent mode for the audible alarm. Pressing this button deactivates the audible alarm for a period of 5 minutes. After this duration, it automatically reactivates in case of an error.

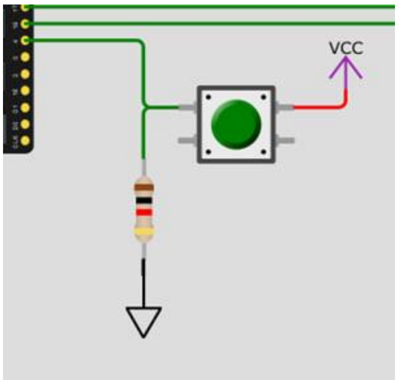

Fig. 5. Audible Alarm Button

Now, it's time to assess the operational scenario of the medical gas alarm system.
1- All readings fall within the permissible range.
In this scenario, as depicted in Figure 6, the screen displays the measured values, with no visual or audible alarms activated, indicating that the system is functioning normally.

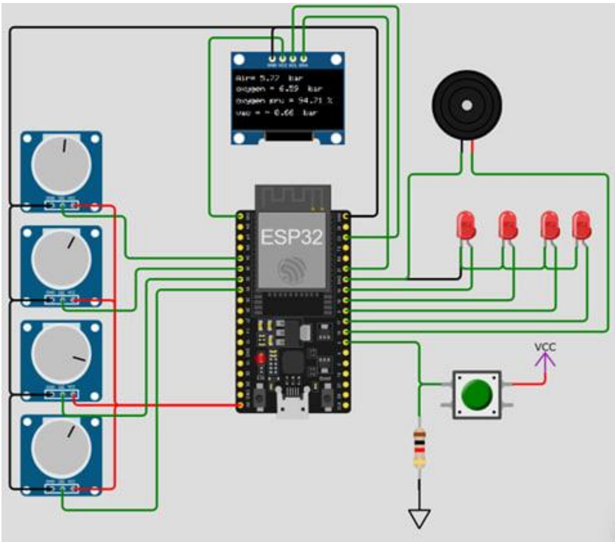

Fig. 6. System Overview When Values Are Within the Allowable Range

2- The pressure readings of the gases available, namely medical compressed air, medical oxygen, and vacuum, drop below the permissible range. In this scenario, as depicted in figure number 7, the corresponding visual alarms for each faulty gas are triggered, accompanied by an audible alarm from the device.

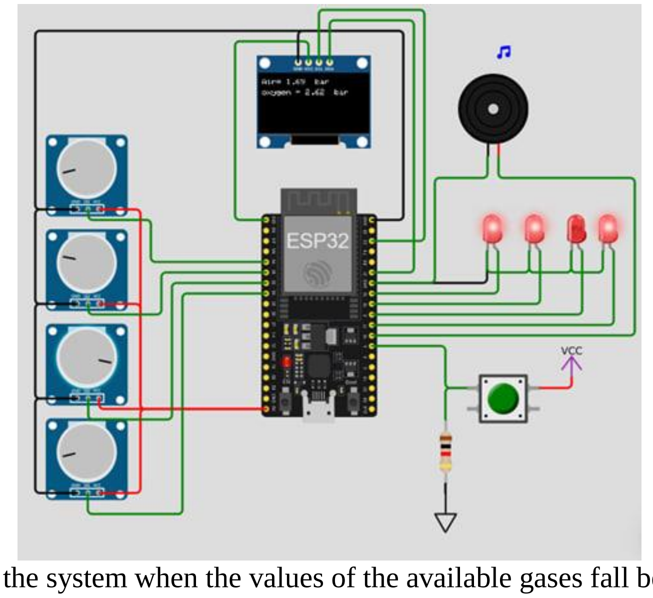

Fig. 7. Overview of the system when the values of the available gases fall below the permissible range

3- While the pressure values of medical gases remain within acceptable limits, the system detects a decline in the purity of medical oxygen. In this scenario, as depicted in scenario number 2 and illustrated in picture number 8, the visual alarm corresponding to the detected error in oxygen purity, along with the audible alarm, is triggered.

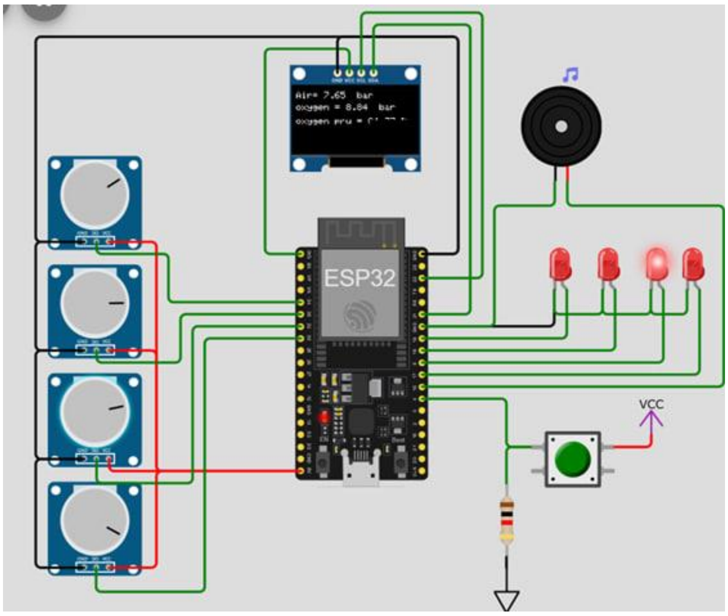

Fig. 8. System Overview in Normal State with Decreased Medical Oxygen Purity

The simulated system operates in accordance with the standards and algorithms specified in the program. Now, we will proceed to connect the system to the internet and view the data and errors on a web page. Initially, to enable the ESP32 processor to connect to the internet and transmit data, the program settings need to be configured to allow the processor to connect to a designated Wi-Fi network. Once the processor is connected to the internet, adjustments must be made to convert the processor's measured values into strings to enable data transmission under the HTTP protocol. Subsequently, the server address must be entered into the settings. It is then essential to determine and configure the appropriate method for data transmission and reception by the server. These methods typically include the POST and GET methods. In this simulation, we utilize the POST method to transmit values to the server.

Next, we need to capture the data transmitted to the server and archive it in the database tables. Subsequently, we can retrieve this data from the database, populate it, and exhibit it on web pages. To acquire data on the server, we need to input the requisite commands in PHP language on the designated page. These commands validate the data received by the server, ensuring it conforms to the specified method and title, and provided that the data received through SQL methods is non-zero, it is stored in the designated table within the database. Following this, we must retrieve the stored data from the database using appropriate commands and methods and exhibit it on the web page utilizing HTML codes. CSS commands can be employed to style HTML codes.

Conclusion

In this modeling and simulation endeavor, we successfully developed and simulated a medical gas alarm system based on the Internet of Things, tailored to measure oxygen purity, in accordance with the stipulated requirements and conditions. Through meticulous consideration of the system's attributes and needs, our modeling accurately emulated real operational conditions, allowing for continuous system monitoring via adept programming techniques.The implementation of a medical gas alarm system grounded in the Internet of Things offers expedited notification to medical gas operators within healthcare facilities, facilitating swift responses and necessary interventions. Furthermore, administrative personnel, including medical equipment supervisors and senior managers, gain the ability to monitor error occurrences and oversee timely resolutions effectively.

Moreover, the incorporation of an oxygen purity sensor into the medical gas alarm system enhances the assurance of medical oxygen presence within hospital supply lines at permissible purity levels. Consequently, *this enhances patient safety and healthcare quality, particularly for individuals reliant on medical oxygen, while mitigating risks associated with non-standard oxygen consumption among critically ill patients.*

REFERENCES

[1] T. O. Edoh, "Advanced Systems for Improved Public Healthcare and Disease Prevention: Emerging Research and Opportunities: Emerging Research and Opportunities," 2018.

[2] S. Oniani, G. Marques, S. Barnovi, I. M. Pires, and A. K. Bhoi, "Artificial intelligence for internet of things and enhanced medical systems," *Bio-inspired neurocomputing,* pp. 43-59, 2021.

[3] R. Akalanka, P. Bandara, K. Jayasanka, and S. DA, "Design and Implementation of IoT Based Real-Time Toxic Gas Detector," *University of Vocational Technology*.

[4] U. S. Q. I. C. T. Force, *Doing what Counts for Patient Safety: Federal Actions to Reduce Medical Errors and Their Impact, Report of the Quality Interagency Coordination Task Force (QuIC) to the President*. Quality Interagency Coordination Task Force, 2000.

[5] X. Meng, S. Kim, P. Puligundla, and S. Ko, "Carbon dioxide and oxygen gas sensors-possible application for monitoring quality, freshness, and safety of agricultural and food products with emphasis on importance of analytical signals and their transformation," *Journal of the Korean Society for Applied Biological Chemistry,* vol. 57, pp. 723-733, 2014.

[6] H. J. Pasman, *Risk analysis and control for industrial processes-gas, oil and chemicals: a system perspective for assessing and avoiding low-probability, high-consequence events*. Butterworth-Heinemann, 2015.

[7] F. F. Ahsan, A. Fatima, N. Rasheed, and A. S. Mohammad, "Conceptual Importance of Medicinal gases for its Significance in Pharmaceuticals," *Asian Journal of Research in Pharmaceutical Science,* vol. 7, no. 1, pp. 8-12, 2017.