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System design for hydrogen gas detection with intelligent embedded communication and Internet of Things integration

Shyam Kumar Menon[1], Adesh Kumar[1], Surajit Mondal[2]
[1]Department of Electrical and Electronics Engineering, School of Advanced Engineering, University of Petroleum and Energy Studies (UPES), Dehradun, India
[2]Energy Cluster, School of Advanced Engineering, University of Petroleum and Energy Studies (UPES), Dehradun, India

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ABSTRACT

The design and analysis of an embedded hydrogen gas detection system embody a complex engineering challenge that integrates sensor technology, embedded system design, and safety engineering. The fast advancement of microcontrollers, energy-efficient electronics, and sophisticated sensing algorithms is facilitating the creation of compact, efficient, and dependable hydrogen detection solutions. The research case article focuses on the hardware system design of Hydrogen gas detection. The hydrogen gas detection system includes an MQ8 sensor for gas sensing, a Raspberry Pi-4 as the main controller, Zigbee for wireless communication, a 16×2 liquid crystal display (LCD) for display, a light emitting diode (LED), and a buzzer for alerts, along with supporting circuitry for signal processing. The gas concentration is monitored and verified through the Thingspeak.com Internet of Things platform, which enables wireless data transmission. The designed system is verified based on environmental factors such as temperature and humidity for comprehensive analysis. The system response was analyzed and tested under different threshold conditions, including 300 ppm and 1000 ppm.

Corresponding Author:

Adesh Kumar
Department of Electrical and Electronics Engineering, School of Advanced Engineering, University of Petroleum and Energy Studies (UPES)
Dehradun, India
Email: adeshmanav@gmail.com; adeshkumar@ddn.upes.ac.in

1. INTRODUCTION

Hydrogen gas has emerged as one of the promising energy sources, as the global shift is experiencing towards sustainable and carbon-neutral energy systems. The major cause of its popularity is due to its high energy density, and it produces water as its only byproduct upon combustion, which makes it a clean and efficient alternative to conventional fossil fuels. The researchers are taking more interest in the growing field as it plays an important role in reducing greenhouse gas emissions, transportation, industries, and electricity generation [1]. Hydrogen gas should be adopted in various sectors such as transport, building construction, and power generation. Robust safety protocols are required for the extensive use of hydrogen technologies in energy storage, transportation, and industries. The primary challenge with hydrogen gas requires safe storage and handling infrastructure, as it has high flammability, low ignition energy, and a tendency to leak due to its small molecular size [2]. Continuous research support is required for the effective use of hydrogen for production, storage, transportation, and utilization. Therefore, it is required to have the early and accurate detection of hydrogen leaks in the system for critical usage and ensuring operational safety to process complete hydrogen-based systems. The conventional gas detection-based embedded systems, while operative in many situations, are generally restricted in terms of transportability, system response time, energy efficiency, and integration flexibility. The hardware-based solutions and embedded systems integration for real-time operations offer a solution to address the challenges by empowering the expansion of the design of low-cost, low-power, compact, and application-specific detection platforms. The hydrogen gas embedded detection system consists of a sensing module, a signal conditioning unit, a data processing module, and data communication components into an interconnected hardware-software system-level design that allows for real-time monitoring and detection [3]. The design approach is not applied only to enhance the detection accuracy but also provides the optimal response time and frequency that permits the simpler integration into present transportation and industrial plant operations and grid systems. It has been experienced that hydrogen is an odorless, colorless, and tasteless gas, making its leaks difficult to detect without dedicated instrumentation. Moreover, it forms volatile mixtures with air at concentrations as low as 4% by volume and can burn with minimal energy input (as minimum as 0.02 mJ) [4]. These characteristics underline the standing of real-time recognition and rapid response for detection systems. The pathways are achieved by embedding the system design to attain these points by strongly assembling the hydrogen sensor interface circuit with the digital control logic, comparator unit, decision-making modules, and related supporting algorithms. The exciting technologies are based on the metal oxide semiconductor (MOS) sensors, electrochemical sensors, palladium-based sensors, and micro-electro-mechanical systems (MEMS)-based sensing mechanisms have all been examined and verified in the plants for hydrogen detection [5]. These sensors have the issue of suffering from selectivity issues, drift velocity, and power consumption challenges.

The metal oxide semiconductor field-effect transistor (MOSFET) sensors are well-suited for embedding in system designs, as they offer high input impedance, fast switching, low power consumption, and high sensitivity at a low cost. The adaptive signaling processing and sensor calibration help design the appropriate embedded systems, which can moderate the system's limitations [6]. The hydrogen gas detection embedded system comprises several key components: the hydrogen gas sensor used to convert the chemical concentration into an electrical signal, a signal conditioning circuit used to amplify and filter the sensor output, an analog-to-digital converter (ADC) to digitize the signal, and a microcontroller unit (MCU) module that performs signal analysis, decision-making, and control tasks. The system is integrated with the communication interface used for remote monitoring, data logging, or alarm activation [7]. The efficiency of the system design depends on the correct selection of the assembly and selection of the components. The design considerations of such systems include sensor placement unit, power management module, fault tolerance, and environmental robustness. This can be shown with the help of an example of the variations in the temperature and humidity, which can affect the baseline response of sensors, requiring environmental compensation methods within the underlying algorithms. Furthermore, the low-power design techniques, such as the use of sleep modes and energy harvesting techniques, can considerably enhance the system performance for the remote or battery-operated operations [8]. The main challenges in such types of system design are to provide high selectivity and sensitivity while also maintaining low false positive rates. Hydrogen gas generally consists of multiple substances, like carbon monoxide, methane, or volatile organic compounds. Therefore, accurate detection is more challenging as they are often colorless, odorless, present at low concentrations, and require sensitive, selective sensors [9]. The latest embedded system design should be focused on enhancing detection capabilities, fast processing of data, and even integrating machine learning or neural network techniques. Intelligent controllers can distinguish and classify the different gases more efficiently. To ensure the reliability of such systems, they must work reliably in changing and sometimes harsh environments. This includes overcoming challenges such as gas levels, electrical noise, and gradual sensor wear. To improve robustness, embedded designs are increasingly incorporating self-check mechanisms and fault-tolerant features. One effective strategy is sensor fusion, combining data from multiple or redundant sensors to enhance system accuracy and resilience against failures [10]. Embedded hydrogen detection systems have a broad range of applications across various sectors, including fuel cell vehicles (FCVs), hydrogen refueling stations, industrial facilities, and home safety systems. In FCVs, continuous and real-time monitoring of hydrogen levels is crucial to prevent leaks that could lead to serious safety hazards. At refueling stations, these systems play a key role by being integrated into safety protocols, such as automatic shutdown mechanisms and safety interlocks, to mitigate risks during hydrogen transfer and storage. Their adaptability and reliability make them an essential component in ensuring safe hydrogen usage across different environments. Similarly, in industrial environments, continuous monitoring can aid in leak localization and risk assessment. The MCU plays an important role in the design of embedded systems, and real-time operating systems (RTOS) or lightweight scheduling frameworks are frequently active to process synchronized tasks such as sensor polling, data processing, and communication [11]. Moreover, internet of things (IoT)-based communication is enabled in communication protocols such as universal asynchronous receiver/transmitter (UART), serial peripheral interface (SPI), and inter-integrated circuit (I^2C), which can be easily integrated with wireless standards like Zigbee or long range (LoRa) to enable flexible sensor deployment in such types of environments. The critical analysis of the hydrogen detection systems depends on the different performance metrics such as sensitivity, response time, and accuracy. Moreover, other parameters are computational latency, power consumption, memory utilization, and cost estimation. The trade-off analysis is required, as optimizing one parameter may affect another parameter, and overall system performance will be affected. It can be understood with the example that an increment in the sampling frequency will enhance response time but will also consume more power and hardware processing resources [12]. The IoT-based embedded system was designed to emphasize the development and design of a low-cost air quality monitoring system (AQMS) built on Arduino microcontrollers and the Blynk cloud platform [13]. The MQ series sensors (MQ135 and MQ6) gather data on the dangerous and flammable gases present in the air. The digital humidity and temperature sensor model 11 (DHT11) and Sharp Optical Dust Sensor (GP2Y101) sensors gather the humidity, temperature level, and specific material present in the atmosphere, respectively. The suggested gadget can be used in a hydrogen station for gas leakage detection and prevention. IoT technology is increasingly being used for detecting hydrogen gas leaks, especially in environments like fuel stations, storage facilities, and industrial plants [14]. The embedding of smart sensors with wireless communication and IoT protocols in real-time will provide the exact monitoring of hydrogen gas concentrations. The detection of the gases is done continuously, and the sensors monitor the signal levels and notify the status in the control room. This type of warning system enables swift intervention, minimizing the chance of accidents and improving the overall safety of the system. This helps the control room to make decisions and take actions accordingly, such as system shutdowns or the activation of ventilation systems. IoT plays an important part in the current safety infrastructure since it makes operations more competent and lowers the risks of hydrogen's flammability. The hydrogen technology is growing continuously, and there has been a corresponding strengthening of safety and regulatory frameworks. International bodies such as the International Organization for Standardization (ISO), International Electrotechnical Commission (IEC*),* and Society of Automotive Engineers (SAE) are continuously working on refining standards that require safety, performance, and certification requirements of hydrogen detection systems. To be more suitable for the real-time simulation and analysis, the embedded system must be intended to meet safety and electromagnetic compatibility (EMC) norms and standards to ensure its commercial viability [15]. The organization of the manuscript is as follows. The introduction and related work are presented in sections 1 and 2, respectively. The proposed methodology and system design constraints are in section 3. The simulation and experimental results are in Section 4. Section 5 concludes the paper with future directions.

2. RELATED WORK

An embedded IoT framework has been designed to automate hydrogen generator systems [16]. The system was controlled using an Arduino-compatible microcontroller in which multiple sensors were embedded, including a flow sensor. The research establishes a framework for automation and system design. However, it does not provide a detailed implementation of safety-critical hydrogen gas leakage detection. The hardware design is modular and utilizes commonly available components; however, fault-tolerant mechanisms are deficient, and gas-specific calibration strategies, which are critical in volatile hydrogen environments. The system was integrated with a microgrid in which the hydrogen generator was powered by an array of photovoltaic panels. The developed system was detailed in terms of hardware complexity, software, and communications, along with successful experimental results. In [17], the hydrogen compressed natural gas (HCNG) plants were proposed to resolve long-distance communication challenges prevalent in extensive industrial settings. The principal innovation involves the utilization of LoRa modules integrated with microcontrollers for the instantaneous transmission of safety data. Although providing a comprehensive communication solution, the system is deficient in the thorough integration of sophisticated gas sensors or machine learning algorithms for anomaly identification. Their hardware configuration comprises LoRa transceivers, unidentified gas detectors, and simple microcontrollers; however, the lack of hardware-level redundancy and power optimization constitutes a significant deficiency. The use of hydrogen-powered proton exchange membrane (PEM) fuel cells as a sustainable power source for IoT systems was explored [18]. This study transitions from gas detection to the powering of sensor networks, tackling power limitations in off-grid or hazardous environments. The proposed system demonstrates the capability of hydrogen energy to sustain low-power IoT devices, enhancing their deployment feasibility. Nonetheless, the study does not address gas leak detection or safety mechanisms, which are essential for a closed-loop hydrogen infrastructure. The hardware setup features a PEM fuel cell, power converters, and microcontrollers; however, it does not include integrated gas sensing components, highlighting a disconnect between energy sustainability and real-time environmental monitoring. A separate embedded system has been designed as a general-purpose gas leak detector, incorporating IoT capabilities to track various hazardous gases, including hydrogen. This system utilizes an ESP8266 microcontroller with built-in Wi-Fi, connected to a series of MQ sensors capable of detecting gases such as methane (CH_4), carbon monoxide (CO), and hydrogen (H_2). While the research effectively demonstrates multi-gas detection with cloud-based data logging, it falls short in addressing key aspects like sensor selectivity, response time, and resistance to environmental interference factors that are vital for safe operation in hydrogen-sensitive environments [19]. Although the hardware design is cost-effective and suitable for prototyping, it lacks the durability and real-time control features necessary for use in industrial or safety-critical applications. An intelligent air quality monitoring system was designed and employed with the combination of gas sensors MQ-2, MQ-7, MQ-8, and MQ-135 integrated via a NodeMCU ESP32 board for IoT-based environmental monitoring [20]. The study highlighted the versatility of low-cost sensor arrays in detecting a range of gases, including hydrogen, carbon monoxide, and other atmospheric pollutants. The system stands out for its ability to monitor multiple gases simultaneously and transmit data wirelessly, making it suitable for basic environmental monitoring applications. However, its effectiveness is limited by challenges in sensor selectivity and calibration accuracy factors that are especially critical when dealing with highly flammable gases like hydrogen, where precise detection is essential for safety. Furthermore, employing general-purpose MQ sensors devoid of temperature or humidity adjustment engenders measurement errors. The hardware design is effective for prototyping and small-scale monitoring; nevertheless, it is deficient in industrial-grade safety protocols and real-time response mechanisms necessary for critical hydrogen detection settings and the needs for deployment in safety-critical areas. Table 1 presents the findings and gaps from the survey for the design of a hydrogen gas detection embedded system and IoT communication with different hardware designs and testing environments. The problem statement of the work is to design an embedded system that supports the hydrogen gas leakage effectively and communicates the information wirelessly for active communication in the control room as a warning system in the case that the gas detection is beyond the threshold limits.

Table 1. Findings and gaps from the survey

Ref.	Outcome	Hardware platform	Gaps
[21]	Developed an integrated microsystem for hydrogen gas detection using a Pd-doped ZnO thin film sensor.	Integrated microsystem likely includes MEMS sensors, application specific integrated circuit (ASIC)	Lacked detailed real-time wireless communication, and scalability was not addressed.
[22]	Used a field programmable gate array (FPGA) for fast hydrogen leakage identification; emphasized real-time response and switching.	Virtex-5 FPGA	Power consumption and miniaturization are not detailed; limited environmental testing.
[23]	Designed a microcantilever-based sensor for high-sensitivity hydrogen detection.	Focused on MEMS structure, microcantilever sensor	Integration with real-time systems and microcontrollers has not been explored.
[24]	Developed a hydrogen detection prototype using wireless sensor networks.	Microcontroller with wireless interface	Limited energy optimization; lacked long-term deployment data.
[25]	Created a self-powered wireless hydrogen sensor node system.	Self-powered sensor with embedded controller	Power management is impressive, but sensitivity under varying environmental conditions is unaddressed.
[26]	Wireless gas detection system using microcontrollers, programmable logic controller (PLC), and Supervisory Control and Data Acquisition (SCADA).	Microcontroller, PLC, SCADA system	Limited real-time wireless integration; higher latency in data fusion.
[27]	Developed a system combining multi-sensor data fusion with AI for gas identification.	Microcontroller with multi-Sensor fusion	AI was basic rule-based; no machine learning integration or FPGA acceleration.
[28]	Integrated MEMS gas sensor with IC in a microsystem for hydrogen detection.	Custom IC with integrated logic, MEMS gas sensor, and integrated circuit	Integration with commercial platforms like Arduino/STM32 has not been explored; difficult to scale.
[29]	Developed a hydrogen gas detection system emphasizing low-cost design.	Arduino, hydrogen gas sensor system (like MQ sensors, unspecified MCU	Lacked high-speed processing and AI integration; mainly for lab-scale or educational use.
[30]	Designed a multi-channel gas sensor system using STM32 and LabVIEW for visualization.	STM-32 microcontroller, LabVIEW interface	Not optimized for portable applications; no AI or predictive analytics included.
[31]	Monitored hydrogen production from PV-SPE using IoT integration.	ESP32 (likely), or similar IoT module, IoT system (sensors + MCU for PV-SPE system)	Did not explore long-term reliability or harsh environmental deployment.
[32]	Designed IoT-based monitoring of hydrogen flow and volume from electrolyzers.	ESP8266 or Arduino, a compatible IoT board, IoT Devices (Sensors, likely microcontroller-based)	Precision and calibration issues are not discussed. It lacks an AI/data analytics layer.
[33]	Used MQ sensors and microcontrollers for methane.	Arduino microcontroller, MQ sensors,	Limited data processing capability; no real-time predictive modelling.
[34]	Improved ADC-based resistive measurement from MQ sensors with microcontrollers.	Generic microcontroller with ADC (Arduino, STM32)	Focused only on signal quality; lacked system-level deployment discussion.
[35]	Developed a toxic gas detection Android app using Arduino Nano 33 IoT.	Arduino Nano 33 IoT	Limited to mobile interface; not scalable for industrial-grade sensing.
[36]	Implemented a gas sensor array and neural network for indoor hydrogen gas detection.	Gas sensor array, neural network system, likely Arduino or STM32	Neural network basics; lacked hardware acceleration or FPGA utilization.
[37]	Developed an FPGA-based trigger system for automating metallic tokamak processes.	FPGA	Not specific to gas sensing; gap in applying similar FPGA automation to hydrogen detection
[38]	Designed an industrial hydrogen gas leakage detector using IoT.	IoT modules (microcontrollers and gas sensors), ESP8266/ESP32	Security and real-time fail-safe mechanisms are not elaborated.
[39]	Introduced physical unclonable function (PFU) for secure microcontroller/FPGA use.	Microcontrollers & FPGAs	Does not integrate gas sensing; potential for secure authentication in sensor networks.
[40]	Digital memristor neural network used for gas recognition in e-nose systems.	Memristor+digital Neuromorphic circuits	Lacks comparison with conventional MCU or FPGA setups; still emerging tech.

3. METHOD

The hydrogen gas detection system consists of two modules, in which the first section is for the transmitter, and the second section is for the receiver. The hydrogen gas detection depends on the change in concentration of hydrogen and comparing the values of the check to determine if it exceeds a certain threshold [41], [42]. Figure 1 presents the transmitter and receiver block for the hydrogen gas detection embedded system. The major components of the embedded system design are MQ8 Gas Sensor, Load Resistor (R_L), Capacitor (for filtering), Raspberry Pi 4 controller, MCP3008 (ADC), MCP3008 (ADC), Potentiometer for LCD, LEDs red and green, alarm, Zigbee Module, DHT11 sensor, and barometric pressure sensor (BMP) 180 pressure sensor. The specifications of the components are given here with featured values. The transmitter side is responsible for detecting hydrogen gas and sending the data wirelessly to the receiver [43]. In this setup, an MQ8 hydrogen gas sensor is used to sense the presence of hydrogen in the environment. This sensor is connected to a Raspberry Pi-4, which serves as the main controller. The Raspberry Pi continuously reads the sensor's output to monitor hydrogen gas levels. If the gas concentration exceeds a predefined threshold, the Raspberry Pi processes the data and transmits it using a Zigbee module (such as XBee). Zigbee is chosen for its low power consumption and reliable short-range communication. The data packet, which includes the gas concentration and possibly a timestamp, is sent wirelessly to the receiver block for further action or logging. On the receiver side, another Zigbee module is used to receive the transmitted data. This module is connected to another Raspberry Pi or a computer that collects the information. The receiver decodes the incoming data and uploads it to the ThingSpeak IoT platform using the internet connection [44]. ThingSpeak allows real-time monitoring by displaying the hydrogen gas levels in a graphical format. Alerts or notifications can also be configured if the gas levels cross the safety limit. This setup ensures that any gas leakage is detected promptly and can be monitored remotely for safety management. A 16×2 LCD is used in the system to present real-time information directly from the Raspberry Pi. It displays the current hydrogen gas concentration in ppm, the system status, such as 'SAFE' or 'ALERT', and warning messages if the gas levels exceed the safety threshold. This provides immediate, human-readable feedback without the need for a computer or internet connection. In addition to the LCD, visual and audio indicators are included for effective local alerts. A green LED lights up when conditions are normal and safe, while a red LED is activated when a potential gas leak is detected. Alongside this, a buzzer or alarm is triggered by the Raspberry Pi whenever the hydrogen concentration crosses a critical level, ensuring that nearby personnel are promptly alerted to take necessary action [45]. These components work together to enhance the safety and usability of the system. The systems are helpful for industrial monitoring and controlling gases in hazardous environments. Table 2 lists the components required for system design. The originality of the work lies in the design and implementation of the gas detection and alarming system, which can be deployed in any hazardous environment, and the monitoring can be done in the control room wirelessly. The management and the operator can take the decisions based on the alarm message and control signal received in the sensing environment. The system not only provides safety but also provides a platform for the safety engineer to find a way of connecting the electronics hardware in the harsh environment, especially high-hydrogen gas generation plants.

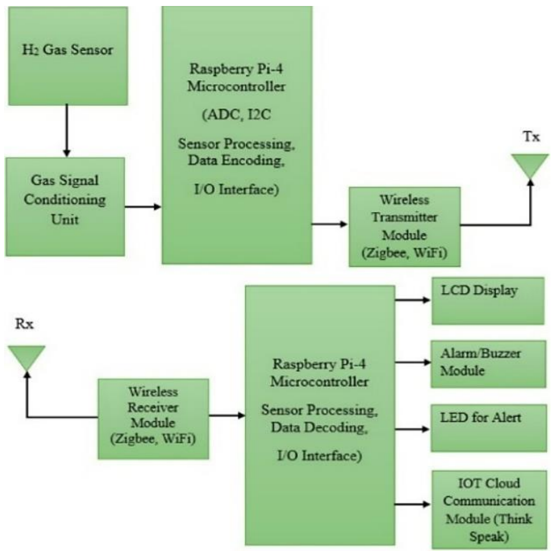

Figure 1. Hydrogen gas detection embedded system transmitter and receiver

Table 2. Component specifications for system design

Component	Specification	Value	Purpose/notes
MQ8 gas sensor	Detects H_2 gas (100-10,000 ppm), analog output	-	For the connection via ADC (e.g., MCP3008) to the controller
Load resistor (R_L)	Used with the MQ8 sensor to form a voltage divider	10 kΩ	For connecting the sensor output to a ground
Capacitor (for filtering)	Filters sensor noise and smooths the power line	0.1 µF (ceramic)	Required between V_{CC} and GND (near sensor)
Raspberry Pi 4	Main controller, 3.3V logic, needs ADC for analog input.	-	For controlling the transmitted and received blocks
MCP3008 (ADC)	10-bit ADC, SPI interface	-	It converts an analog sensor signal to digital.
16×2 lcd display	2 lines × 16 chars, 5V operation	-	Applied for 4-bit mode for fewer general-purpose input/output (GPIO) pins
Potentiometer for LCD	Adjusts LCD contrast	10 kΩ	Required for the V_{EE} pin of the LCD
Red LED	Alert indication	220 Ω resistor	For a current-limiting resistor in series with the LED
Green LED	Safe indication	220 Ω resistor	Current limiting resistor in series with the LED
Buzzer/alarm	5V buzzer	100 Ω	An optional base resistor for the transistor switch
NPN Transistor	Drives buzzer or LED from GPIO	BC547 or 2N2222	Use for switching high-current devices
Base Resistor (Transistor)	Controls current into the transistor base	1 kΩ	Between the GPIO and the transistor base
Zigbee Module (XBee)	UART-based wireless communication	-	Used with a level shifter if simulating with a 5V MCU
Capacitor (Decoupling)	Filters power noise near ICs	0.1 µF (ceramic)	It is close to the power pins of ICs (ADC, controller)
Pull-down Resistors	For stable logic inputs	10 kΩ	Used on unused input pins if needed
DHT11 sensor	Measures temperature and humidity	Temp range: 0–50°C (±2°C), Humidity range: 20 90% RH (±5%)	Digital output via single-wire interface
BMP180 pressure sensor	For the BMP pressure	1.8V to 3.6V	I^2C digital interface

4. RESULTS AND DISCUSSION

The hydrogen gas leakage detection system comprises several key components, each with specific features suited for its role. The MQ8 hydrogen gas sensor is used to detect the presence of hydrogen in the environment. The sensor detects in the range between 100 and 10,000 ppm and provides an analog output signal corresponding to gas concentration at 5V. The main microcontroller is the Raspberry Pi-4, which is configured with a quad-core 64-bit ARM processor and available in 8GB RAM variants. The hardware interfacing is done using GPIO pins, and it does not include the ADC, which is essential for reading the analog signal values. Therefore, an external ADC module, MCP3008, is applied that has 8 channels and provides 10bit resolution and communicates through the SPI interface. Zigbee hardware is a wireless communication module that works on the IEEE 802.15.4 standard, operates at a 2.4 GHz frequency, and communicates data at a rate of 250 kbps via UART. The system status is continuously monitored based on sensors and displayed on a 16×2 LCD. The LCD works on 5V and operates in 8-bit mode for flexibility in GPIO usage.

The buzzer is used as an alarming device to provide immediate alerts, typically working at 5V or 12V, which is controlled via GPIO or through a switching transistor. The red LED and green LED are also used as simple visual indications, working on 2V forward voltage and providing 10–20mA current. The embedded system is powered by a regulated 5V power supply module that provides a stable power supply to all critical components, including the Raspberry Pi controller, sensor, and display modules. The integration of these components on the printed circuit board (PCB) ensures reliable communication, detection, and warning in the case of hydrogen gas leakage. The accuracy of the gas detection depends on the surrounding temperature and humidity, which is monitored using a DHT11 sensor. The BMP180 sensor measures air barometric pressure and temperature. It supports the tracking of environmental changes as it measures complete atmospheric pressure using a piezoresistive element, and the temperature sensor boosts the system's overall performance by compensating for temperature. Figure 2 depicts the internal schematic designed in the Proteus simulation environment that includes the humidity sensor DHT11 and the BMP180 pressure sensor.

The hydrogen gas detection systems are employed in gas industries under different threshold levels based on the applications to ensure safety. In industrial safety surroundings, a typical alarm is activated at a threshold value of 1000 ppm (0.1%), which is adequate to signify the presence of hydrogen before it reaches hazardous concentrations. This threshold is reduced for home or indoor environments in the range from 100 to 300 ppm to enable the early warning systems and prevent hazardous accumulation in the bounded spaces. The threshold value is changed for the automotive applications, such as hydrogen fuel cells, in which hydrogen reacts with oxygen inside the cell. The threshold largely lies in the range of 200 to 500 ppm**,** which varies depending on safety regulations and system design requirements. In automotive applications, the lower explosive limit (LEL) for hydrogen is around 40,000 ppm (which is 4% by volume in air)**,** which signifies 100%

LEL and signals an instantaneous explosive risk if ignited. The thresholds help in the calibration of the sensors, and the real-time processing of the data for the alarming circuit to ensure safety. The designed system records the sensor output, which may be analog or digital, based on the type of sensor used. The recorded raw data is then converted into ppm using the definite calibration parameters provided by the sensor manufacturer's data sheet, confirming an accurate representation of gas concentration. The system has an in-built comparator module that compares the threshold values. If the measured value goes beyond the predefined safety threshold of 1000 ppm, then the system initiates immediate response actions. These responses are repeatedly triggered, and an audible buzzer is included as a visual alarm to alert nearby personnel. Simultaneously, these alerts are transmitted remotely via Global System for Mobile Communications (GSM) or IoT protocols, which enable the off-site monitoring and system response. In the critical situations where hydrogen exists poses a severe risk, such as fuel storage or sensitive manufacturing operations, the system may also be configured to automatically shut down processes to avoid accidents, reflecting a layered approach to safety and control. The designed embedded hardware comprises the transmitter section and receiver section. The IoT communicated data is verified on the ThingSpeak IoT platform to gather, store, process, and display hydrogen sensor data in real time. By delivering sensor readings, e.g., ppm levels, to the cloud, it allows remote monitoring, alerts, and data logging for hydrogen gas detection, hence enabling users to monitor trends and guarantee prompt safety responses. The verified data is listed in Table 3 against each quantity noticed from the embedded hardware for the sensor threshold value of 300 ppm. Table 4 shows measured hydrogen gas values from the ThingSpeak IoT platform, including a threshold value of 1000 ppm.

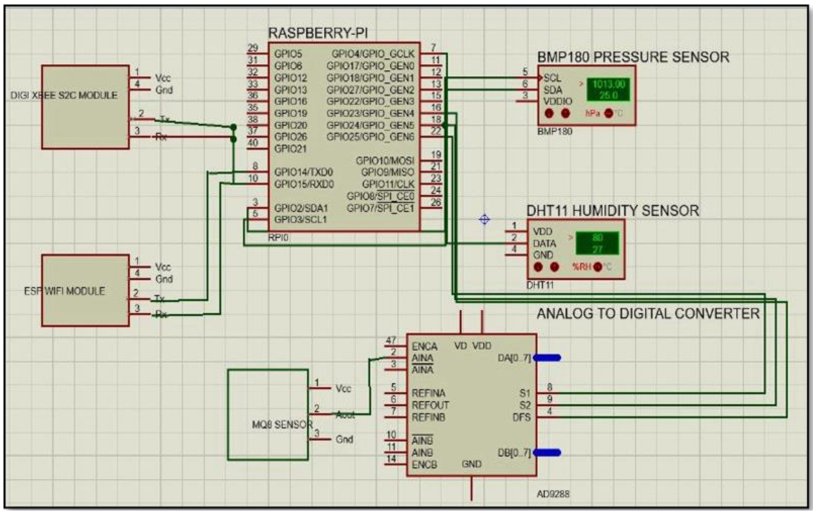

Figure 2. Internal schematic using the proteus simulation environment

Table 3. Measured values from the ThingSpeak IoT platform with H_2 gas threshold value 300 ppm

Timestamp	H_2 sensor value (ppm)	Threshold (ppm)	Status	Voltage (V)	ADC Value	Temp (°C)	Humidity (%)
2025-05-15 09:00:00	333	300	Alert	1.07	33	26.2	48.0
2025-05-15 09:00:15	296	300	Safe	0.95	29	25.6	44.4
2025-05-15 09:00:30	398	300	Alert	1.28	39	26.0	43.2
2025-05-15 09:00:45	340	300	Alert	1.10	34	26.0	42.8
2025-05-15 09:01:00	339	300	Alert	1.09	33	25.5	40.0
2025-05-15 09:01:15	303	300	Alert	0.98	30	25.6	47.2
2025-05-15 09:01:30	281	300	Safe	0.91	28	27.9	49.4
2025-05-15 09:01:45	337	300	Alert	1.09	33	25.2	44.5
2025-05-15 09:02:00	259	300	Safe	0.84	25	27.3	43.0
2025-05-15 09:02:15	283	300	Safe	0.91	28	25.1	44.6
2025-05-15 09:02:30	335	300	Alert	1.08	33	27.4	45.0
2025-05-15 09:02:45	288	300	Safe	0.93	28	26.4	42.5
2025-05-15 09:03:00	286	300	Safe	0.92	28	26.0	49.2
2025-05-15 09:03:15	269	300	Safe	0.87	26	25.4	49.1
2025-05-15 09:03:30	359	300	Alert	1.16	35	26.2	47.8
2025-05-15 09:03:45	358	300	Alert	1.15	35	26.2	41.8
2025-05-15 09:04:00	300	300	Safe	0.97	30	27.6	48.3
2025-05-15 09:04:15	398	300	Alert	1.28	39	25.6	46.0
2025-05-15 09:04:30	349	300	Alert	1.13	34	26.0	42.8
2025-05-15 09:04:45	377	300	Alert	1.22	37	26.7	44.2
2025-05-15 09:05:00	250	300	Safe	1.05	27	27.00	54.0

Table 4. Measured values from the ThingSpeak IoT platform with H_2 gas threshold value 1000 ppm

Timestamp	H_2 Sensor value (ppm)	Threshold (ppm)	Status	Voltage (V)	ADC value	Temp (°C)	Humidity (%)
2025-05-15, 08:00:00	917	1000	Safe	2.95	91.00	26.00	48.1
2025-05-15, 08:00:15	1097	1000	Alert	3.54	109	26.2	44.3
2025-05-15, 08:00:30	902	1000	Safe	2.91	90	27.5	43.2
2025-05-15, 08:00:45	1012	1000	Alert	3.26	101	26.9	41.1
2025-05-15, 08:01:00	981	1000	Safe	3.16	98	27.2	47.6
2025-05-15, 08:01:15	1120	1000	Alert	3.61	112	27.2	41.1
2025-05-15, 08:01:30	975	1000	Safe	3.15	97	26.7	40.0
2025-05-15, 08:01:45	1083	1000	Alert	3.49	108	26.4	48.8
2025-05-15, 08:02:00	1056	1000	Alert	3.41	105	25.2	47.7
2025-05-15, 08:02:15	1108	1000	Alert	3.57	110	25.1	44.4
2025-05-15, 08:02:30	1053	1000	Alert	3.40	105	27.8	44.7
2025-05-15, 08:02:45	1121	1000	Alert	3.62	112	26.5	42.7
2025-05-15, 08:03:00	783	1000	Safe	3.17	98	26.8	48.4
2025-05-15, 08:03:15	1050	1000	Alert	3.39	105	27.3	44.0
2025-05-15, 08:03:30	1140	1000	Alert	3.68	114	25.0	44.3
2025-05-15, 08:03:45	815	1000	Safe	2.95	91	27.8	45.7
2025-05-15, 08:04:00	746	1000	Safe	3.05	94	25.3	42.6
2025-05-15, 08:04:15	1053	1000	Alert	3.40	105	25.6	48.0
2025-05-15, 08:04:30	651	1000	Safe	3.07	95	27.8	45.7
2025-05-15, 08:04:45	1005	1000	Alert	3.24	100	26.1	42.7
2025-05-15, 08:05:00	560	1000	Safe	2.25	89	22.3	42.5

Figure 3 presents the H_2 gas concentration testing over the IoT Platform with a threshold value of 300 ppm for a 5-minute duration in real-time. Figure 4 presents the H_2 gas concentration testing over the IoT Platform with a threshold value of 1000 ppm for a 5-minute duration in real-time. The measured values are obtained from the ThinkSpeck.com IoT platform on May 15, 2025, to determine the system's real-time monitoring fitness for environmental conditions, specifically alarming hydrogen gas, using a definite threshold value of gas concentration of 300 ppm. The observation was carried out for five-minute duration, and the platform logged variations in voltage levels, sensor readings, and ambient environmental parameters such as temperature and humidity. It is observed that the sensor values are exceeded beyond the threshold at multiple intervals, particularly at 09:00:00, 09:00:30, 09:00:45, and 09:01:00, triggering an "Alert" status, demonstrating potentially hazardous air quality levels. The higher values of the sensor readings were associated with increased voltage outputs, reaching up to approximately 1.28 V, and corresponding ADC values as high as 39. In contrast, the gas concentration is observed the defined threshold during periods, such as at 09:00:15, 09:01:30, 09:02:00, and 09:02:15. The system status was marked as "Safe," representing improved air quality. The voltage levels declined to around 0.84 V during the mentioned times, and the ADC values decreased accordingly. Temperature measurements persisted reasonably constant, usually ranging between 25 °C and 27 °C, while humidity values have proven more variable, fluctuating between 40.0% and 54.0%. This dataset demonstrated the sensor platform's responsiveness to even intelligent shifts in gas concentration and its sensitivity to environmental changes. The rapid changes in the alarming situation between 'Safe' and 'Alert' settings over small intervals also present the dynamic behavior of indoor air quality. Continuous monitoring of unsafe gas leakage helps in quick action to prevent explosions and health accidents.

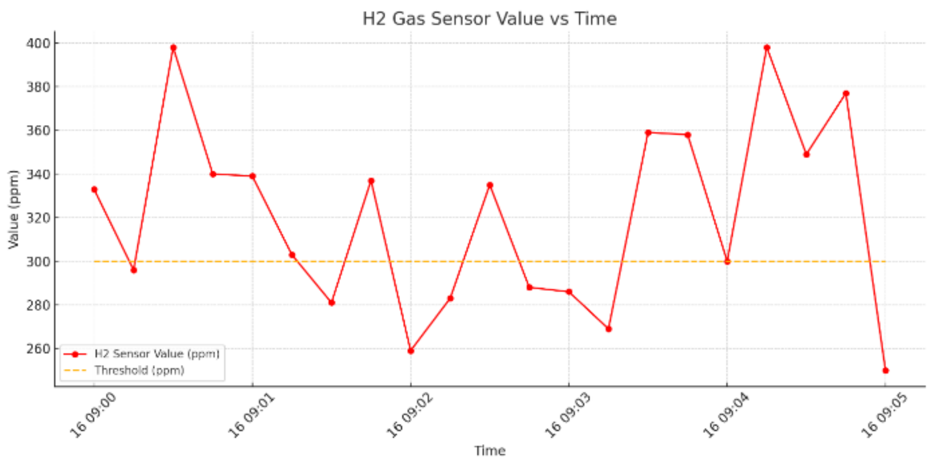

Figure 3. H_2 gas concentration testing over the IoT platform with a threshold value of 300 ppm

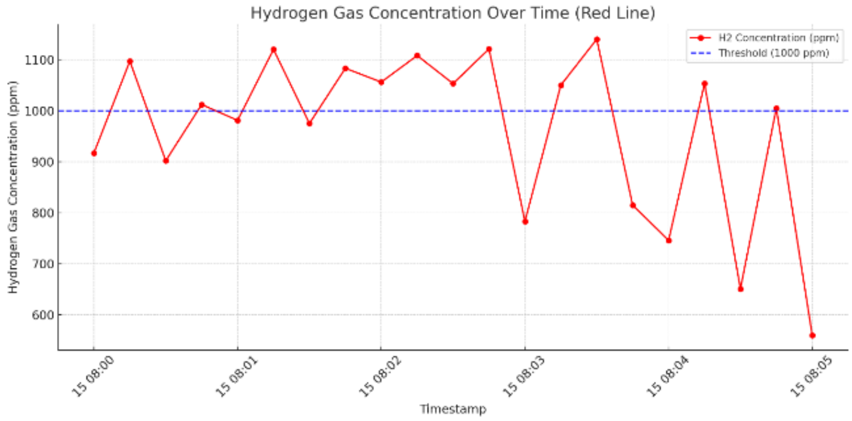

Figure 4. H_2 gas concentration testing over the IoT Platform with a threshold value of 1000 ppm

The MQ-8 H_2 gas sensor works based on the principle of the change of resistance of the sensing element when exposed to H_2. The sensor is calibrated to ensure accurate gas concentration readings. The sensor is connected to V_{CC}, the ground pin, and the analog output of the Arduino board. The sensor is turned on for 24 hours for preheating and utilized for 5 minutes to stabilize its internal resistance R_0. Then the sensor is placed in an H_2-free, clean environment, and readings of the sensor are observed. The values of R_0 are calculated with multiple readings and matched with the datasheet values. The gas concentration is observed based on sensor resistance (R_s) in an H_2 environment and resistance (R_0) in a clean environment. The sensor is exposed to 1000 ppm H_2 gas, and the sensor analog out is recorded. The plot of gas reading against values of (R_s/R_0) is matched and scaled with Arduino code to match the gas (ppm) value. The value of has been verified using the equation. $H_{2\,(ppm)} = \alpha(R_s/R_0)^{\beta}$, in which the values of α and β are estimated for the sensor curve, and analog values are followed till the actual value of gas concentration is not achieved.

5. CONCLUSION

An embedded hardware system was successfully designed for hydrogen gas detection using a Raspberry Pi controller and validated through IoT communication on the ThingSpeak platform. The design was tested under different threshold levels set at 300 ppm and 1000 ppm. The results have demonstrated that the system constantly detects hydrogen concentrations up to 1000 ppm, which makes it more suitable for manufacturing industries and power plant safety monitoring. The ThingSpeak platform collects data and shows the system's accuracy and sensitivity in tracking hydrogen gas levels. The sensor readings were changing between 'Safe' and 'Alert' status in the five-minute monitoring period beginning at 08:00:00, which shows that the gas concentration is changing. The testing is done for both scenarios. For example, the sensor detected a 917 ppm H_2 gas concentration value at 08:00:00 that lies below the alert threshold, indicating a 'Safe' condition. Moreover, the readings were changed to 1097 ppm after 15 seconds, triggering an 'Alert' warning of potential danger. In the entire nontroubling duration, similar types of fluctuations were recorded throughout the session, with the prominent threshold crossings at 08:00:45, 08:01:15, 08:02:00, and 08:03:15. These functions are based on the adequate and unstable behaviour of hydrogen gas concentrations in the monitoring environment. The voltage readings closely correspond to the gas levels in the range of 2.25 V at 560 ppm (08:05:00) and a high of 3.68 V at 1140 ppm (08:03:30). The ADC follows the same pattern, and the value lies in the range from 89 to 114. The temperature persisted fairly steady between 22.3°C and 27.8°C, while humidity changed more noticeably between 40.0% and 48.8%, implying some environmental effect on sensor performance. Overall, the data underscores the IoT-based system's competence for continuous gas level monitoring and rapid hazard detection, making it a valuable asset in settings where hydrogen leaks pose safety risks. Future improvements could comprise integrating the global positioning system (GPS) modules for location-specific updates, incorporating field- programmable gate array (FPGA) hardware for enhanced processing, and applying machine learning techniques to predict leakage movements and energetically regulate exposure thresholds based on environmental factors. The future work will be focused on including advanced methodologies for sensor calibration strategies, considering incorporating temperature and humidity effects. The hardware design and system-level integration can be focused on fault-tolerant analysis, including testing in real-world environments with safety-critical scenarios. The testing environment can be directly in the industrial environment. The system reliability can be increased by embedding the safety protocols and testing the hardware in real-time applicability and trustworthiness.

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Shyam Kumar Menon	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓			
Adesh Kumar	✓						✓		✓	✓	✓		✓	
Surajit Mondal	✓								✓	✓		✓		

C : **C**onceptualization
M : **M**ethodology
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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
The authors state no conflict of interest

DATA AVAILABILITY
The authors confirm that the data supporting the findings of this study are available within the article.

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BIOGRAPHIES OF AUTHORS

Shyam Kumar Menon is currently working as a principal electrical engineer at wood engineering, Doha, Qatar. He has 21 years of experience in the field of design of electrical facilities for the oil & gas and power sectors. He completed his B.Tech. from Mangalore University, Karnataka and pursued M.Tech from Manipal Academy of Higher Education (MAHE), Udupi, Karnataka. He is currently pursuing a Ph.D. from the University of Petroleum & Energy Studies (UPES), Dehradun, Uttarakhand. He is also a chartered engineer registered with the engineering council, UK. He is also an approved electrical engineer by engineers Australia, Petroleum Development Oman, Qatar Energy and Shell. He has published one paper in the clean energy journal and presented 2 papers at international conferences. His area of interest includes renewable energy integration with the grid, electromagnetic transient studies, subsynchronous resonance and distributed grids. He can be contacted at shyam_k_menon@yahoo.com.

Adesh Kumar is working as a professor in the Department of Electrical & Electronics, Engineering, School of Advanced Engineering, The University of Petroleum and Energy Studies (UPES), Dehradun, India since 2010. He has B. Tech in electronics & communication engineering from UPTU, Lucknow, India, in 2006. M.Tech (Hons) in embedded systems technology from SRM University, Chennai in 2008. Ph.D. (electronics engineering) from UPES, Dehradun, India, in 2014. He has also worked as a senior engineer in Tata Elxsi Limited, Bangalore, and as a faculty member in ICFAI University, Dehradun. His areas of interest are VLSI design, embedded systems design, telecommunications, and signal processing. He has supervised 12 Ph.D. scholar, and 5 candidates are doing research under his supervision. He has worked on more than 10 editorial assignments for edited books, conference proceedings, and journals, having citations of more than 4000, h-index >30. He has 18 years of experience in teaching, research, and industry, and published more than 150+ research papers in international peer-reviewed journals (SCI/Scopus) and conferences. He can be contacted at adeshmanav@gmail.com; adeshkumar@ddn.upes.ac.in.

Surajit Mondal is serving as an associate professor in the Energy Cluster Department at UPES, Dehradun. He holds a B.Tech. in electrical engineering, an M.Tech. in energy, and a PhD in electrical engineering (specialization in renewable energy). He is a certified ISO 50001:2018 lead auditor for energy management systems by CQI and IRCA. With over a decade of experience, he has contributed substantially to teaching, research, project management, and event organization. During this time, He has efficiently organized 30+ international and national conferences and seminars as a secretary, event manager, and organizer. His accomplishments include 50+ research articles, 30 in Scopus/SCI journals, work on 8 edited/textbooks, and 88 patents (26 granted). He has overseen a 42 lakh INR DST-funded project and is currently leading another project of 33.7 lakh INR under the young scientist scheme, Government of India. He has secured INR 1.2 crore from DST, Govt. of India, for battery testing unit lab development and effectively managed UPES's IPR cell and the centre for alternate energy research (CAER). His commitment to university accreditation through NAAC, NBA, and IQAC cells reflects his commitment. He has also actively supported faculty in external and internal R&D projects. He can be contacted at surajitmondalee@gmail.com.