Major Project Report

SentinelGuard: Advanced Safety Helmet for High-Risk Industries

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DECLARATION

We hereby declare that the project work entitled **“SentinelGuard: Advanced Safety Helmet for High-Risk Industries”** is an original and authentic record of the research carried out by us as part of our major project for the B.Tech program in **Electronics and Communication Engineering** at **Punjab Engineering College (Deemed to be University), Chandigarh**.

This project report has been submitted as a requirement for the completion of our degree under the guidance of **Dr. Divya Dhawan** and **Dr. Muzaffar Imam**, Department of Electronics and Communication Engineering.

We affirm that the information presented in this report is the result of our independent study, findings, and analysis, and it has not been submitted elsewhere for any degree or qualification. All sources of information and references used in this project have been duly acknowledged.

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Certified that the statements made by the students above are true and correct to the best of our knowledge and belief.

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ABSTRACT

The SentinelGuard is an advanced safety helmet designed to enhance worker safety in high-risk industries by integrating hardware and software technologies. The helmet is equipped with toxic gas sensors (MQ-135, MQ-7, MQ-6) that detect hazardous gases such as methane (CH_4), carbon monoxide (CO), and other pollutants, ensuring real-time environmental monitoring and ECG Monitoring System for real-time health monitoring. To provide wireless connectivity, the system incorporates Wi-Fi and GPS modules, enabling remote tracking of worker location and real-time data transmission to a centralized monitoring system for enhanced situational awareness.

The SentinelGuard also features instant audio and visual alarms to alert workers when dangerous conditions are detected, improving response time and reducing potential hazards. The ergonomic helmet design ensures compliance with industrial safety standards while maintaining a lightweight and comfortable structure for extended use.

A critical aspect of this project is testing and optimization. Individual components such as sensors, alarms, and GPS modules undergo rigorous functional validation before being integrated into the helmet. The system is tested in controlled environments simulating high-risk industrial conditions, ensuring accurate hazard detection and reliable communication. Post-deployment, regular maintenance and firmware updates are implemented to improve performance and safety over time.

The SentinelGuard project aims to revolutionize industrial safety by offering a scalable and intelligent safety solution for hazardous environments such as mining, oil and gas, chemical plants, and construction sites. By combining advanced sensors, wireless communication, and real-time monitoring, the helmet enhances workplace safety, reduces risks, and helps prevent industrial accidents. This innovative approach demonstrates the potential of smart protective gear in shaping the future of occupational safety and health management.

Table of Contents

List of Figures

List of Tables

CHAPTER 1

INTRODUCTION

1.1 Introduction

Workplace safety in high-risk industries such as construction, mining, oil and gas, and chemical processing is a critical concern due to the constant exposure to hazardous conditions. Industrial workers often face threats from toxic gas leaks, environmental pollutants, physical obstacles, and poor air quality, leading to serious health risks and fatal accidents [1][2]. Traditional safety measures rely on manual inspections and static monitoring systems, which often fail to provide real-time hazard detection and instant alerts [3].

To address these challenges, the SentinelGuard project introduces an innovative smart helmet equipped with advanced sensors, wireless communication, and real-time monitoring capabilities. By integrating gas detection sensors (MQ-135, MQ-7, MQ-6), ECG Monitoring, Obstacle Detection, GPS module, and an alert system, the helmet enhances worker protection, real-time hazard response, and situational awareness [1][4]. The system actively monitors air quality, temperature, humidity, and worker location, sending alerts to a central monitoring system in case of emergencies [2].

The SentinelGuard helmet aims to bridge the gap between traditional safety equipment and modern IoT-based smart solutions. By leveraging embedded systems, cloud communication, and real-time data processing, this project significantly improves the efficiency of industrial safety protocols [3]. Furthermore, its ergonomic design ensures worker comfort and compliance with industrial safety regulations [4].

This report outlines the design, development, implementation, and testing of the SentinelGuard helmet, highlighting its potential to transform workplace safety through technology-driven hazard detection and prevention. The project emphasizes scalability and adaptability, ensuring that the solution can be deployed across various high-risk industries for enhanced worker safety and operational efficiency [1][3][4].

1.2 Motivation

In high-risk industrial environments such as mining, oil and gas, chemical manufacturing, and construction, worker safety remains a critical concern. Despite the implementation of conventional safety protocols and protective equipment, incidents involving toxic gas exposure, environmental hazards, and undetected health anomalies continue to pose significant threats to human life and operational continuity. The limitations of traditional safety gear—typically passive and non-interactive—highlight the need for a more intelligent and proactive approach to personal protective equipment (PPE).

The SentinelGuard project was motivated by the pressing need to bridge the gap between conventional safety practices and emerging digital technologies. By integrating real-time environmental sensing, physiological monitoring, wireless communication, and cloud-based data management into a single wearable device, this project seeks to redefine industrial safety through innovation. The goal is to provide timely alerts, improve situational awareness, and enable data-driven interventions before minor incidents escalate into life-threatening emergencies.

Furthermore, the motivation extends to supporting broader industrial transformation initiatives such as Industry 4.0 and smart factory ecosystems, where interconnected systems and real-time decision-making are foundational. SentinelGuard aspires to be a forward-looking solution that not only safeguards individual workers but also contributes to organizational safety intelligence, predictive maintenance, and regulatory compliance.

By addressing these challenges through a scalable, customizable, and intelligent safety helmet, the project aims to significantly enhance workplace safety, reduce human risk, and demonstrate the transformative potential of integrating embedded systems and IoT technologies into industrial PPE.

1.3 Problem Formulation

Workplace accidents in high-risk industries like construction, mining, and chemical processing remain a major concern due to hazardous gases, physical risks, and the lack of real-time monitoring. Conventional safety measures rely on manual supervision, which is inefficient and prone to human error. Workers often face exposure to toxic gas leaks, extreme temperatures, and undetected obstacles, leading to severe health risks.

Despite the availability of PPE, the absence of integrated smart solutions limits real-time hazard detection, worker tracking, and automated alerts. Most safety gear lacks instant communication with monitoring teams, causing delayed emergency responses.

The **SentinelGuard Safety Helmet** addresses these challenges by integrating gas detection sensors, ECG monitoring, GPS tracking, and an emergency alert system into a lightweight, ergonomic device. The system transmits real-time data to a monitoring dashboard, enabling proactive safety management.

1.4 Objectives

- To detect toxic gases like methane (CH_4), carbon monoxide (CO), and other hazards using advanced sensors.
- To implement wireless communication for remote monitoring via Wi-Fi technology and location tracking through GPS module.
- To integrate ECG monitoring for real-time heart activity tracking, ensuring early detection of worker health anomalies.
- To integrate audio-visual alert systems within an ergonomically designed, lightweight helmet compliant with industrial safety standards.

1.5 Chapter Organization

Chapter 1: Introduction- Introduces the need for enhanced safety in high-risk industries and presents the SentinelGuard helmet as a smart, sensor-integrated solution.Defines the project's motivation, objectives, and the specific problems it aims to solve.

Chapter 2: Literature Review- Summarizes existing research and technologies related to smart helmets in industrial safety applications.Identifies gaps in current solutions and justifies the need for an integrated system like SentinelGuard.

Chapter 3: Tools and Techniques- Describes the hardware (sensors, microcontrollers) and software (Arduino IDE, Firebase) used in development.Explains testing methods and the rationale behind choosing specific components and tools.

Chapter 4: Setup and Design of Sentinel Guard- Details the system architecture, including sensor integration, circuit diagrams, and firmware design.Covers hardware implementation, power management, and the development of a real-time monitoring dashboard.

Chapter 5: Results and Analysis- Presents sensor performance data and dashboard outputs from real and simulated environments.Analyzes the system's response to hazardous conditions, verifying accuracy and alert effectiveness.

Chapter 6: Conclusion and Future Scope- Concludes with the effectiveness of SentinelGuard in industrial safety enhancement.Proposes future upgrades including AI integration, advanced health monitoring, and edge computing.

CHAPTER 2

LITERATURE REVIEW

The evolution of smart helmet systems has become a focal point in occupational safety research, particularly in hazardous environments such as mining and construction. These intelligent systems leverage advancements in embedded technologies, sensor networks, and wireless communication to monitor real-time physiological and environmental parameters. The primary objective of this literature review is to explore the current landscape of smart helmet technologies, highlight their functionalities, and identify areas where further innovation is required. By examining a wide range of research studies, this review aims to establish a foundation for understanding the strengths and limitations of existing solutions and to justify the need for a more integrated and user-centric approach.

2.1 Smart Helmet for Coal Mine Workers :Punam Patil, Manisha K. Bhole, Dilip N. Pawar, Swati Nadgaundi, Rohit Pawar, and Aniket Mhatre

This research paper [1] presents a smart helmet designed for miners, addressing critical safety challenges in underground mining operations. The study highlights the frequent hazardous incidents in the mining industry, which often result in severe injuries or fatalities. The proposed smart helmet integrates multiple sensors to detect toxic gases (CO, CH_4, NH_3), temperature, humidity, and pulse rate monitoring to ensure miner safety. An infrared sensor is incorporated to ensure compliance with safety protocols by detecting whether the miner is wearing the helmet. When any sensor exceeds its predefined threshold, an alert system activates a buzzer, notifying miners and supervisors of potential dangers. The system enhances safety by transmitting real-time data using Wi-Fi and ThingSpeak, enabling centralized monitoring of underground conditions. This facilitates quick decision-making and rapid emergency response. Additionally, the system operates on low power, making it suitable for prolonged use in remote mining environments.

The study underscores the application of IoT-based smart helmets for miner safety, emphasizing real-time hazard detection, wireless communication, and worker health monitoring to minimize mining-related accidents.

2.2 The Smart Helmet System: Towards Providing Safer Construction Work Sites -Janani Priyanka Perumpally Rajakumar and Jae-ho Choi

This research paper[2] explores the development of a smart helmet aimed at enhancing worker safety in construction sites through the integration of wearable sensor technology and wireless communication systems. The study highlights the increasing risks and fatal accidents in the construction industry and the necessity for advanced protective equipment. The proposed smart helmet incorporates real-time monitoring features, allowing site administrators to track worker location, environmental conditions (UV index, temperature), helmet battery charge, and emergency alerts. By utilizing wireless transmission technology, the helmet continuously transmits critical data to a central control unit, ensuring quick responses in emergencies.

The research further discusses the growing use of wearable sensors across industries, including mining, healthcare, transportation, and manufacturing, where these technologies assist in detecting physical exertion, exhaustion, stress, and hazardous conditions. The integration of such sensors enhances situational awareness and prevents accidents, particularly in cases of sunstroke or high-temperature exposure. The study emphasizes the need to transform traditional helmets into smart, IoT-enabled devices that actively monitor workers' conditions rather than serving as passive protective gear. The proposed system aims to provide automated hazard detection, emergency response mechanisms, and improved communication channels between workers and supervisors. The research contributes to the advancement of intelligent safety systems in the construction industry, demonstrating how sensor-driven smart helmets can reduce workplace hazards, enhance worker protection, and improve industrial safety standards.

2.3 Smart Helmet and Health Monitoring Kit for Mining Workers: S. Kurundkar, A. Andhale, R. Chaudhari, S. Datir, N. Harak, and K. Hiwrale

This study[3] introduces a Smart Helmet and Health Monitoring System designed to enhance mine workers’ safety by integrating IoT-enabled sensors for environmental and physiological monitoring. The system includes a DHT sensor for temperature and humidity detection, an MQ-07 gas sensor for hazardous gas identification, an ultrasonic sensor for obstacle detection, and an oximeter for monitoring oxygen levels and heart rate. These sensors continuously track both external conditions and worker health, ensuring early detection of risks. The collected data is transmitted to ThingSpeak, a cloud-based data visualization platform, allowing real-time monitoring by supervisors.

Additionally, machine learning algorithms analyze the data for predictive maintenance, early health issue detection, and automated alert generation, improving worker safety and minimizing accident risks. The study highlights high fatality rates in mining, reporting an average of 38 worker deaths per year in India, emphasizing the necessity for real-time health tracking and immediate communication systems. The helmet is equipped with IoT-based call and message transfer mechanisms, enabling seamless communication between workers and supervisors for quick emergency responses.

2.4 Smart Helmet And Monitoring For Miners With Enhanced Protection: Arnob Banik, Divakar Mishra, and N. Manikandan

This research paper[4] investigates the application of IoT technology in the mining industry, focusing on real-time hazard detection and worker safety enhancement. The proposed smart helmet is equipped with sensors and communication modules that continuously monitor environmental conditions, including temperature, humidity, and air quality. The system incorporates a helmet buzzer to alert miners in case of potential hazards, ensuring immediate action.

A notable feature of the proposed model is the application interface, which enables real-time data visualization through a mobile application and a web platform. This allows both miners and administrators to remotely track environmental changes, providing crucial insights through continuously updated graphs and alerts. By integrating modern sensors and tracking technologies, the smart helmet provides a comprehensive safety solution tailored to the unique challenges of mining environments. The system facilitates continuous monitoring and early hazard detection, allowing for swift emergency responses and preventive actions.

2.5 Smart Helmet Using Zigbee: Sanjay B. S., Dilip K. A., Balasaheb T. A., KinnuKumar S., and Saware N.

This research paper [5] shows that a Zigbee-based smart helmet can provide continuous, real-time monitoring of hazardous underground conditions. The helmet is equipped with sensors to detect methane gas, temperature, and humidity levels—critical environmental parameters that often precede mining accidents. These sensors feed data to a microcontroller, which processes and transmits it wirelessly via Zigbee to a central monitoring station.

Zigbee was chosen for its low power consumption, reliable short-range communication, and suitability for closed environments such as mines. Its ability to establish mesh networks enhances communication even in areas with obstructed paths, ensuring that real-time alerts can be sent even from deep within mining tunnels. The system generates warnings if parameters exceed safe limits, thereby enabling timely intervention.

The design emphasizes affordability, practicality, and ease of deployment. Through a successful prototype demonstration in simulated conditions, the study validates the application of this technology in real mining environments. It proposes a shift from manual monitoring to automated safety systems, ensuring better protection and reduced risk for mine workers.

2.6 IoT-Based Coal Mining Safety for Workers Using Arduino: Prabhu D., Nikhil V. N., and Kumar J. S.

This research paper [6] shows that IoT-enabled systems utilizing Arduino microcontrollers can enhance mining safety through real-time monitoring and communication. The helmet features gas sensors, a temperature sensor, and humidity sensors, all connected to an Arduino Uno board. These components continuously track environmental conditions and activate alerts when unsafe levels are detected.

The system transmits sensor data to a control room using either Wi-Fi or GSM modules. This allows for centralized monitoring and quicker responses to dangerous situations. The inclusion of a panic button adds a layer of human interaction, allowing miners to signal emergencies manually, which improves both worker confidence and safety responsiveness.

This study underscores the importance of using low-cost, open-source platforms like Arduino to make safety systems scalable and accessible. Its modular architecture makes it suitable for retrofitting in existing operations, ensuring broader adoption in resource-constrained mining industries. The proposed system bridges the gap between manual inspections and automated risk prevention.

2.7 A Smart and Secured Helmet for Coal Mining Workers: Charde A., Dehankar B., Ghaturle S., Bende B., and Kitey S.

This research paper [7] shows that integrating environmental and security sensors into a helmet can significantly improve the safety of coal mining workers. The helmet includes sensors for gas detection, temperature monitoring, and ambient light measurement. It also features fall detection using accelerometers, which helps in identifying physical trauma in real time.

The system is connected to a microcontroller that interprets sensor data and sends it to a remote control center. If any readings indicate a dangerous situation, the system immediately issues alerts. This proactive approach allows mining supervisors to initiate safety protocols quickly, reducing the likelihood of injury or fatality.

What sets this study apart is its focus on security and positional tracking. With GPS integration, the system monitors the location of each worker. Additionally, the design incorporates anti-tamper mechanisms, ensuring the helmet remains secure and functional throughout its usage. These features make the helmet a comprehensive safety and security solution.

2.8 Design and Implementation of a Smart Helmet System for Underground Miner's Safety: S. M. Minhajul Alam, Arnob Barua, Ahamed Raihan, M. Alam, R. Chakma, S. Mahtab, and C. Biswas

This research paper [8] shows that combining environmental and physical monitoring sensors in a smart helmet is effective in protecting underground miners. The helmet includes methane, carbon monoxide, temperature, humidity, and motion sensors to provide a complete assessment of both the surroundings and the wearer's physical status.

Data is collected and transmitted via Wi-Fi or GSM modules to a control station, where it is monitored in real time. Alerts are automatically triggered if gas concentrations rise above safety thresholds, if the miner is exposed to excessive heat or humidity, or if a fall is detected. The system can also communicate the miner's location, which is essential in coordinating rescue operations during emergencies.

The study demonstrates the feasibility of real-time data acquisition and alert generation, emphasizing the use of low-cost microcontrollers and sensors. It shows how modern communication protocols and embedded systems can be deployed to ensure operational safety and efficiency in mining environments. The solution is scalable and can be tailored to other high-risk industries as well.

2.9 Virtual Reality for Mine Safety Training in South Africa: A. P. Squelch

This research paper [9] shows that virtual reality (VR) technology can revolutionize mine safety training by providing immersive and interactive simulations. The study explores how VR environments replicate realistic mining scenarios, allowing workers to experience hazardous conditions in a controlled and safe setting. This enhances their ability to respond appropriately during actual emergencies.

The paper emphasizes that traditional training methods often fall short in preparing workers for the unpredictable and high-risk nature of underground mining. VR overcomes this limitation by offering repeatable, scenario-based modules that engage multiple senses and promote experiential learning. Users can practice emergency protocols, such as evacuation and gas leak response, without real-world consequences.

Moreover, the study highlights how VR training improves knowledge retention and decision-making skills. It provides immediate feedback, enabling trainees to learn from mistakes in a risk-free environment. Implementing VR as part of safety training contributes to a proactive safety culture, reducing the likelihood of accidents and enhancing overall mine preparedness.

2.10 The Design of Warp Tension Embedded Intelligent Control System Based on µC/OS and ARM :H. M. Zhu and L. Zhang

This research paper [10] shows that embedded intelligent control systems can be effectively designed using µC/OS and ARM architecture to enhance automation and precision in industrial applications. Although primarily focused on warp tension control in textile machinery, the concepts of real-time monitoring and embedded automation are applicable to mine safety systems as well.

The paper discusses the integration of sensors with ARM-based microcontrollers running a real-time operating system (RTOS) to manage dynamic industrial processes. The use of μC/OS allows the system to execute multiple tasks concurrently—such as data acquisition, feedback control, and system alerts—making it highly efficient for safety-critical applications.

From a mining perspective, this architecture could be adapted for intelligent sensor networks in helmets or monitoring stations. The ability to run complex control logic in real-time ensures prompt responses to hazardous changes in mine environments. The study provides foundational insights into how robust embedded control frameworks can support the development of autonomous, reliable safety solutions.

2.11 Smart Sensor for Underground Coal Mine Based on ZigBee Protocol: L. Ma and H. Guo

This research paper [11] shows that smart sensors using the ZigBee protocol can provide a cost-effective and scalable solution for monitoring underground coal mines. The system is built around a ZigBee wireless sensor network (WSN) that collects data on temperature, gas concentration, and structural integrity in real-time, transmitting it to a central hub for analysis.

The study demonstrates how ZigBee's mesh networking capabilities enable sensors to communicate across long distances despite underground obstacles. This ensures network stability and redundancy, which are critical for continuous operation in safety-critical environments. The sensors operate on low power, extending operational lifespan and minimizing maintenance.

Importantly, the research validates the robustness of ZigBee-based WSNs for adverse and dynamic underground conditions. It suggests that the system can be integrated into wearable devices like smart helmets or fixed installations across mine shafts. This approach not only enhances environmental awareness but also supports proactive risk mitigation strategies.

2.12 Monitoring and Controlling of Mining Using IoT: M. P. Archana, S. K. Uma, and T. M. R. Babu

This research paper [12] shows that IoT technologies can transform mining safety through advanced monitoring and control capabilities. The system proposed integrates various sensors (gas, temperature, vibration) with microcontrollers and cloud computing platforms. Data is collected from mining sites and uploaded to IoT dashboards in real-time for remote supervision.

The paper emphasizes bidirectional communication, where commands can be issued back to the mining equipment or alerts sent to on-site personnel based on live data analytics. This creates a responsive feedback loop that significantly improves operational safety and decision-making. The system supports anomaly detection and predictive maintenance, minimizing equipment failures that may lead to accidents.

Moreover, the study underlines the scalability of IoT systems. The architecture can be expanded to include wearables like smart helmets, drones for structural inspections, and automated ventilation systems. Overall, it presents a blueprint for intelligent, networked mining operations that prioritize worker safety and process efficiency through continuous environmental surveillance.

The literature reviewed demonstrates significant progress in the development of smart helmets, incorporating various sensors and communication technologies to enhance worker safety in the mining and construction industries. These innovations have led to improved real-time monitoring, hazard detection, and emergency response capabilities. However, several critical gaps remain unaddressed.

Firstly, there is a lack of unified integration of multiple safety features into a single, compact smart helmet. Most existing solutions focus on individual components such as gas detection, temperature monitoring, or fall detection, without offering a comprehensive system that includes biometric monitoring (e.g., heart rate, oxygen levels), noise detection, fatigue assessment, and two-way communication. Secondly, energy efficiency and power management are often overlooked, with limited discussion on power optimization or the use of sustainable energy sources like solar or kinetic energy harvesting—both crucial for prolonged operation in remote areas. Thirdly, the absence of standardization across communication protocols, microcontrollers, and software limits interoperability, hindering widespread implementation across different mining operations. Lastly, ergonomic and user-centered design is frequently neglected, resulting in bulky and uncomfortable helmets that may hinder adoption and long-term usability among workers.

CHAPTER 3

TOOLS AND TECHNIQUES

This chapter presents the foundational tools and methodologies employed in designing, developing, and validating the SentinelGuard helmet. It outlines the integrated technologies, hardware components, software platforms, and testing protocols that collectively enabled the creation of a responsive and reliable industrial safety solution.

3.1 Hardware Components

This section focuses on the physical components that constitute the SentinelGuard system. It highlights the microcontrollers, sensors, and supporting modules used for sensing environmental parameters, processing data, and enabling real-time alerts. Each hardware choice was guided by parameters such as efficiency, power consumption, integration ease, and suitability for wearable industrial applications.

3.1.1 Microcontroller

The SentinelGuard helmet employs a dual-microcontroller architecture combining the ESP32 and ESP8266 modules. These microcontrollers were carefully selected based on their hardware capabilities to meet the real-time data processing, wireless communication, and power efficiency requirements of a wearable industrial safety device. This section describes their features and justifies their selection by comparing them with other commonly available microcontrollers.

The ESP32 functions as the primary controller, responsible for acquiring and processing data from multiple sensors including toxic gas detectors (MQ-135, MQ-7, MQ-6), ECG monitoring, temperature and humidity sensors, and an IR-based obstacle detection system. Additionally, it manages real-time data transmission over Wi-Fi. The ESP32 incorporates a dual-core 32-bit Tensilica processor, which facilitates efficient multitasking and parallel processing. It includes integrated Wi-Fi and Bluetooth (Classic and BLE) modules, thereby eliminating the need for separate communication hardware. The microcontroller offers numerous GPIO pins, analog-to-digital converters (ADC), and supports standard digital communication protocols such as I²C, SPI, and UART, allowing seamless integration with various sensors. Its low-power operating modes, including deep sleep and light sleep, are especially suited for energy-constrained wearable applications. Furthermore, the ESP32 provides adequate flash memory and SRAM for buffering sensor data and storing complex control logic.

The choice of the ESP32 over alternatives is well justified. Arduino Uno and Nano boards use the ATmega328P microcontroller, which lacks built-in wireless connectivity, has limited GPIO pins, slower clock speeds of 16 MHz, and minimal RAM of approximately 2 KB. Employing additional Wi-Fi modules such as the ESP8266 or NRF24L01 to compensate for wireless communication increases power consumption and the physical footprint, both critical disadvantages in compact wearable systems. Although the Arduino Mega offers more I/O pins, it still lacks native wireless support and operates at slower processor speeds, making it less suitable for real-time wireless sensor data processing. Raspberry Pi, despite its powerful computational capabilities, consumes significantly more power, is larger in size, and does not provide the real-time response needed for sensor monitoring within helmet-mounted applications. Hence, the ESP32 was selected for its superior processing power, integrated wireless modules, compact form factor, and power efficiency, all essential for the high-performance and real-time safety functions of SentinelGuard.

The ESP8266 acts as a supporting microcontroller, tasked with managing auxiliary sensors and serving as a backup communication node. This secondary controller offloads non-critical tasks from the ESP32, enhancing overall system efficiency and modularity. The ESP8266 is equipped with an 80 MHz 32-bit processor and integrated Wi-Fi (802.11 b/g/n). It offers sufficient GPIO pins and supports standard communication protocols such as I²C, SPI, and UART. Its compact size and lightweight nature make it ideal for fitting within the limited space available in wearable hardware enclosures. Additionally, the ESP8266 consumes low power, which contributes to extended battery life when handling secondary system tasks.

The justification for choosing the ESP8266 over other options such as Arduino Nano or ATtiny boards lies in its native Wi-Fi capability and greater computational power, which reduce the need for additional modules and thus conserve power and space. Its cost-effectiveness and small physical footprint make it well suited for modular roles in the system architecture. When system tasks are limited to lightweight communication or single-sensor control, the use of the ESP8266 prevents overloading the primary ESP32 microcontroller and improves overall system reliability.

3.1.2 Gas Sensors : MQ-135 (Air Quality Monitoring)

Monitoring air quality is vital in industrial environments to protect workers from prolonged exposure to toxic and hazardous gases. The SentinelGuard helmet incorporates the MQ-135 gas sensor (Figure 3.1) to ensure real-time detection of harmful airborne substances. The MQ-135 was selected after evaluating several gas sensors based on detection range, responsiveness, supported gases, power requirements, cost, and ease of integration [19].

The MQ-135 operates using a chemical-sensitive layer whose resistance changes in the presence of specific gases. This change in resistance causes an analog voltage variation, which is then used to determine gas concentration. The sensor is capable of detecting various gases such as ammonia (NH_3), nitrogen oxides (NOx), carbon dioxide (CO_2), alcohol, benzene, and smoke.

Sensor Specifications:

- Operating Voltage: 5V DC
- Detection Range: 0.5 – 1000 ppm
- Preheat Time: ~24 hours for stable operation
- Response Time: < 10 seconds
- Power Consumption: ~90 mW
- Output Type: Analog voltage
- Operating Temperature Range: -10°C to 50°C
- Target Gases: NH_3, NOx, CO_2, alcohol, benzene, smoke

The advantages of the MQ-135 include its ability to detect a wide range of harmful gases, affordability, wide availability, moderate power consumption, and simple analog output interfacing. It is also compatible with microcontrollers like ESP32 and ESP8266.

The MQ-135 was chosen for the SentinelGuard helmet because of its multi-gas detection capability, affordability, and seamless compatibility with microcontroller-based systems. Although it has a relatively long preheat time, its operational stability and widespread adoption in IoT air quality monitoring systems make it an ideal choice for industrial-grade wearable applications.

Alternative gas sensors considered included the Figaro TGS 2600, which uses a metal oxide semiconductor responsive to methane, propane, and air contaminants. Despite its high responsiveness, it was rejected due to its narrower gas detection profile, higher cost, and limited community support. The Micro-Electro-Mechanical Systems (MEMS)-based MiCS-5524 sensor offers compact design and multi-gas sensing capabilities but was rejected due to the need for precise calibration, complex circuitry, and higher cost. The MQ-2 and MQ-9 sensors, which detect LPG, smoke, methane, and CO respectively, were rejected because of their limited overlap with the gases of concern and lower accuracy for NOx and ammonia.

Overall, the MQ-135 sensor stands out as a versatile and dependable option for monitoring air quality in hazardous industrial environments. Its broad detection range aligns well with industrial safety requirements, while its cost-effectiveness and simple hardware integration make it suitable for a compact helmet-mounted safety system. Furthermore, its stable performance under continuous use and extensive documentation reinforce its suitability for the SentinelGuard project.

Fig. 3.1: Pin configuration of the MQ135 gas sensor module [19]

3.1.3 Gas Sensor Selection: MQ-7 (Carbon Monoxide Monitoring)

Carbon monoxide (CO) is a highly toxic and potentially lethal gas commonly found in industrial environments due to combustion processes, engine exhausts, and chemical operations. Continuous monitoring of CO is critical to ensure occupational safety. For this reason, the SentinelGuard helmet integrates the MQ-7 gas sensor (Figure 3.2) specifically for detecting carbon monoxide exposure. This sensor was selected after evaluating several options based on its detection capability, accuracy, response time, power requirements, and ease of integration [20].

The MQ-7 sensor functions using a tin dioxide (SnO_2) semiconductor layer whose resistance varies in the presence of CO gas. It requires an alternating heater voltage cycling between 1.4V and 5V to maintain proper detection performance. The sensor operates at 5V and has a detection range from 20 to 2000 parts per million (ppm). Its response time ranges between 60 to 90 seconds, and it also requires a preheat time of 24 hours. The output is an analog voltage proportional to the CO concentration.

Sensor Specifications:

- **Operating Voltage:** 5V DC
- **Detection Range:** 2 – 2000 ppm (CO)
- **Preheat Time:** ~24 hours for stable readings
- **Response Time:** 60 – 90 seconds
- **Heater Voltage Cycle:** 5V (60s), 1.4V (90s) alternating
- **Heater Power Consumption:** ~350 mW
- **Output Type:** Analog voltage
- **Target Gas:** Carbon Monoxide (CO)
- **Operating Temperature Range:** -10°C to 50°C

The MQ-7 provides effective CO detection at a relatively low cost and is widely available in the market. Its simple analog output, compact design, and low weight make it easy to incorporate into microcontroller-based wearable devices such as those using the ESP32 or ESP8266.

Alternative sensors considered for CO detection included the ZE07-CO, an electrochemical sensor known for accurate and stable measurements with minimal interference from other gases. However, it was rejected due to its significantly higher cost and complex communication protocols (UART/I2C), which are less suitable for wearable hardware. The MiCS-5524 sensor, though small and capable of detecting multiple gases, was excluded because of its calibration complexity, higher cost, and power demands. The MQ-9 sensor, which detects CO along with other combustible gases, was not selected due to lower CO detection reliability in environments with gas mixtures.

The MQ-7 was ultimately chosen for its reliable CO detection capability, affordability, and compatibility with ESP-based microcontrollers, making it a suitable component for the SentinelGuard helmet. It enables timely alerts for carbon monoxide exposure, enhancing worker protection in high-risk environments.

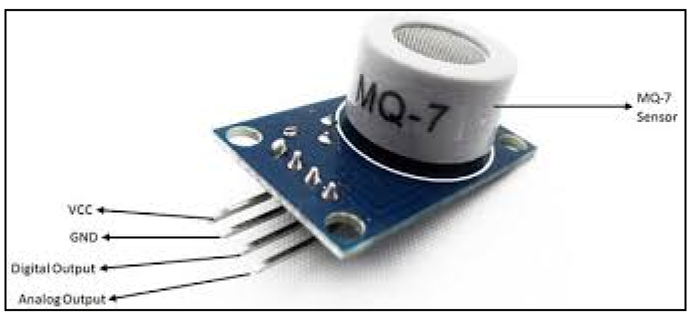

Fig. 3.2: Pin configuration of MQ7 Gas Sensor [20]

3.1.4 Gas Sensor: MQ-6 (LPG and Flammable Gas Detection)

In industrial settings, flammable gases such as Liquefied Petroleum Gas (LPG), propane, and butane present significant fire and explosion hazards. Real-time monitoring of these gases is essential for workplace safety. The SentinelGuard helmet integrates the MQ-6 gas sensor (Figure 3.3) to detect these combustible gases and provide timely alerts in case of leaks or hazardous gas accumulation in confined spaces [21].

The MQ-6 sensor employs a tin dioxide (SnO_2) semiconductor that changes electrical resistance when exposed to flammable gases. This resistance variation translates into an analog voltage proportional to the gas concentration. It primarily targets LPG but also responds to propane, butane, methane, hydrogen, and smoke.

Sensor Specifications:

- Operating Voltage: 5V DC
- Detection Range: 1 – 10,000 ppm
- Preheat Time: ~20 seconds
- Response Time: ≤ 10 seconds
- Power Consumption: Approximately 150 mW
- Output Type: Analog voltage
- Operating Temperature Range: -10°C to 50°C
- Target Gases: LPG, propane, butane, methane, hydrogen, smoke

The MQ-6 was selected for its effective detection of LPG and related flammable gases commonly found in industrial and construction environments. Its low power consumption, compact size, and straightforward analog interfacing make it well-suited for wearable continuous gas surveillance systems.

Alternatives considered included the MQ-2, which detects a broader range of gases including LPG and methane. However, it was rejected due to its lower selectivity and higher likelihood of false positives for specific gas detection. The Figaro TGS2611, a sensor targeting methane and natural gas, was dismissed because of its higher cost and need for complex circuitry. The miniaturized MEMS-based MiCS-5525 sensor offers multiple gas detection but was rejected due to its expense and engineering complexity, which conflicted with the project's goals for simplicity and affordability.

Ultimately, the MQ-6 sensor provides an effective and practical solution for flammable gas detection in hazardous environments. Its focus on LPG detection, low cost, ease of integration, and proven performance in safety applications make it the optimal choice for the SentinelGuard helmet's wearable industrial safety system.

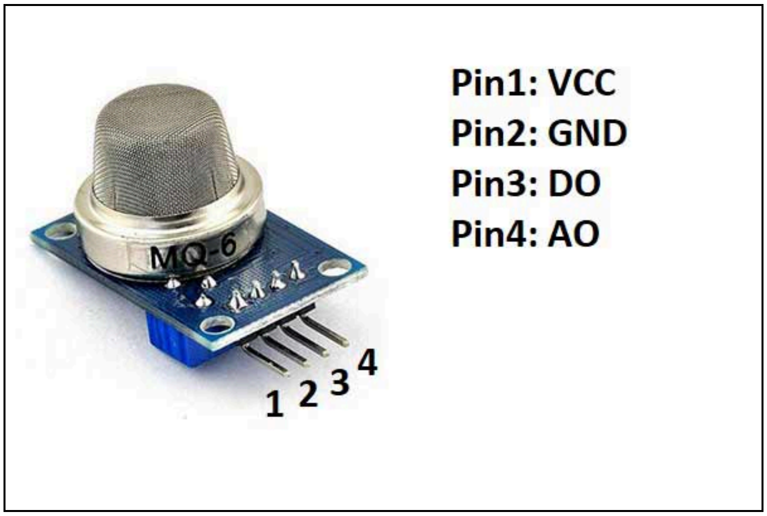

Fig. 3.3: Pin Configuration of MQ6 Gas Sensor [21]

3.1.5 Temperature & Humidity Monitoring Sensor - DHT22 sensor

Monitoring temperature and humidity is vital in industrial safety systems to prevent heat stress, ensure worker comfort, and maintain optimal environmental conditions. The SentinelGuard helmet incorporates a sensor capable of providing continuous and accurate real-time measurements of these parameters, which are critical for safeguarding workers in variable climates [22].

The DHT22 sensor (Figure 3.4), a digital temperature and humidity sensor, was selected for this purpose. It operates within a temperature range of -40°C to +80°C and measures humidity levels from 0% to 100% relative humidity (RH). The sensor provides temperature accuracy of ±0.5°C and humidity accuracy between ±2% to ±5% RH. Communication with microcontrollers is facilitated through a single-wire digital interface, enabling straightforward integration with low-power devices such as the ESP32. The sensor responds within five seconds, supporting real-time monitoring requirements.

The DHT22 offers several advantages including a wide operating range suitable for industrial environments, good measurement accuracy, low power consumption, and cost-effectiveness. Its compatibility with common microcontrollers and extensive open-source library support make it an efficient solution for embedded systems. Furthermore, the sensor's robustness and reliability meet the environmental monitoring standards necessary for workplace safety applications.

Alternative sensors considered include the DHT11, which was rejected due to its limited temperature (0°C to 50°C) and humidity (20% to 90% RH) ranges and lower accuracy. The AM2301 sensor, with specifications similar to the DHT22, was also evaluated but dismissed due to less widespread community support and documentation. The SHT31 sensor provided higher accuracy and faster response times with I2C communication but was excluded because of its higher cost and increased integration complexity, which conflicted with project constraints.

The DHT22 sensor was selected based on its optimal balance between performance, affordability, ease of integration, and reliability under industrial conditions. Its ability to provide accurate environmental data while operating efficiently in harsh environments aligns with the safety objectives of the SentinelGuard system.

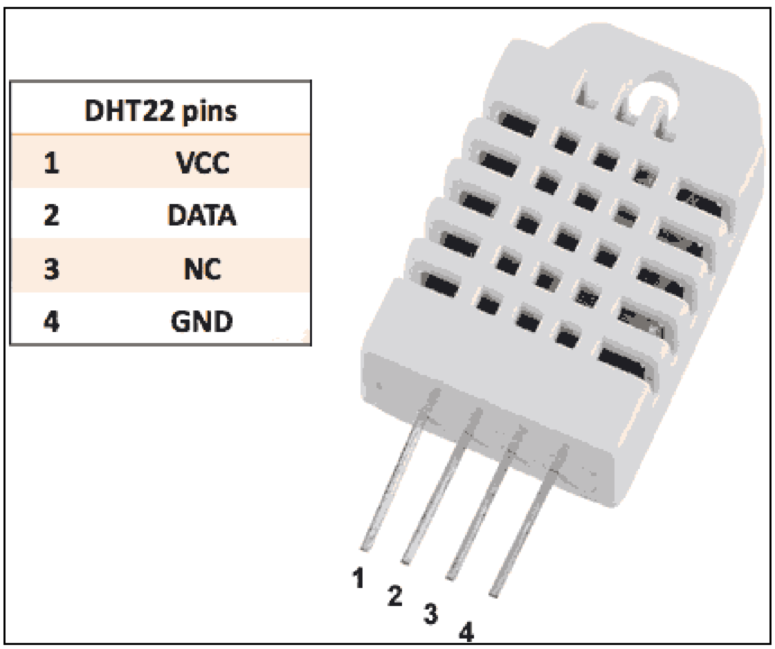

Fig. 3.4: Pin configuration of DHT22 temperature and humidity sensor [22]

3.1.6 Obstacle Detection Sensor Selection - IR Sensor

Reliable obstacle detection is essential in industrial environments to prevent accidents caused by collisions, particularly in confined or hazardous workspaces. The sensor integrated within the

SentinelGuard helmet must provide immediate feedback on nearby objects, maintaining worker safety without compromising comfort or system efficiency [23].

An infrared (IR) sensor (Figure 3.5) was selected for obstacle detection due to its emission and reflection principle, where emitted infrared light reflects off objects and is detected to measure proximity. This method enables short-range detection typically within 2 to 30 centimeters. The sensor interfaces easily with microcontrollers like the ESP32 through simple analog or digital outputs, allowing seamless integration into the wearable system.

The IR sensor is characterized by its compact size, lightweight design, and low power consumption, which are crucial for wearable applications. It provides fast response times necessary for real-time detection and alerts. These features ensure that the sensor does not impose significant demands on the helmet's power budget or physical design constraints.

Alternatives such as ultrasonic sensors were considered but dismissed due to their larger form factor, higher power consumption, and susceptibility to interference from environmental noise prevalent in industrial settings. Ultrasonic sensors also present challenges in mounting within a compact helmet design, making IR sensors a more practical choice.

The IR sensor was chosen for its suitability for short-range proximity detection in a compact, energy-efficient package. Its ease of integration, fast response, and low cost fulfill the requirements for immediate obstacle detection, contributing to the overall safety and usability of the SentinelGuard helmet.

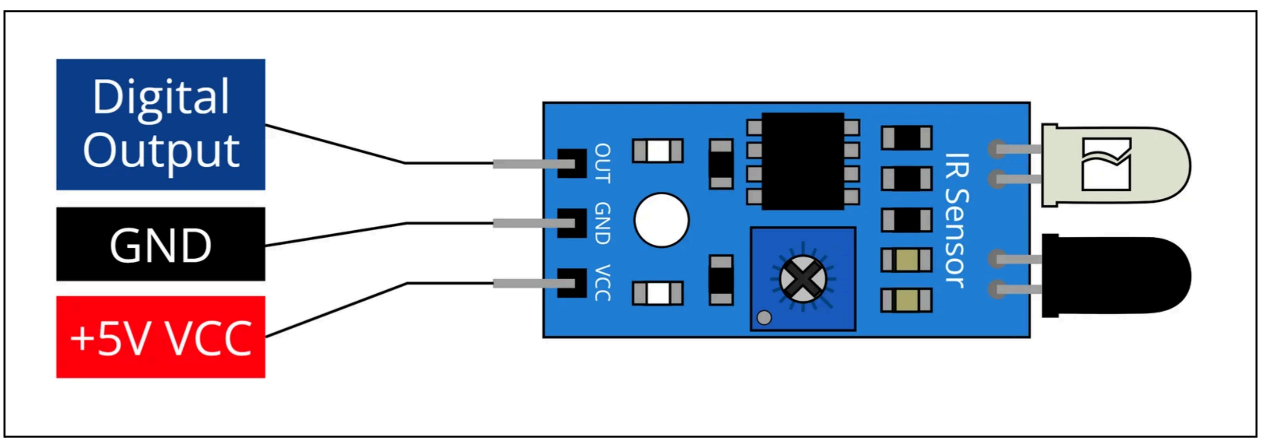

Fig. 3.5: Pin configuration of Infrared (IR) Sensor [23]

3.1.7 GPS Module - NEO-M8N

Accurate real-time location tracking is critical in hazardous work environments to enhance worker safety and facilitate timely emergency response. The SentinelGuard helmet integrates a GPS module capable of delivering precise positioning data continuously, supporting centralized monitoring and rapid rescue operations when necessary [24].

The NEO-M8N GPS module (Figure 3.6) was chosen because it can connect to multiple satellite systems, making it more accurate and reliable. This multi-system support improves satellite visibility and positioning accuracy, especially in challenging environments such as urban canyons or obstructed industrial sites. The module provides position accuracy up to 2.5 meters Circular Error Probable (CEP) and supports an update rate of up to 10 Hz, enabling smooth and frequent location updates. Time-To-First-Fix (TTFF) performance is approximately 26 seconds under cold start conditions and about 1 second for hot starts. Interfaces include UART, SPI, and I2C, facilitating flexible integration with microcontrollers like the ESP32. The module’s typical power consumption ranges from 20 to 25 mA during active tracking, suitable for battery-operated wearable systems.

Advantages of the NEO-M8N module include its high positioning accuracy enhanced by multi-GNSS support, rapid satellite acquisition, and reliable performance even in environments with partial signal obstruction. Its relatively low power consumption makes it appropriate for continuous use in wearable devices without excessive battery drain. Moreover, its widespread use and compatibility with ESP32 platforms contribute to simplified integration and development.

Alternative GPS modules evaluated included the NEO-6M, which offers affordability and ease of integration but suffers from lower sensitivity, single-GNSS support, and slower fix times. The Quectel L86 module was considered for its compact design and multi-GNSS capability but was found to have higher power consumption and less extensive documentation and community support. The SIM28ML was also reviewed but was deemed unsuitable due to its lower accuracy, poor update rate, and limited GNSS functionality, rendering it inadequate for high-precision, safety-critical applications.

The selection of the NEO-M8N GPS module was based on its combination of high accuracy, robust multi-GNSS support, and power efficiency. These characteristics ensure continuous and precise location tracking, enabling centralized monitoring and rapid emergency response. The module's performance meets the stringent requirements of industrial safety systems, making it an appropriate and effective choice for integration into the SentinelGuard helmet.

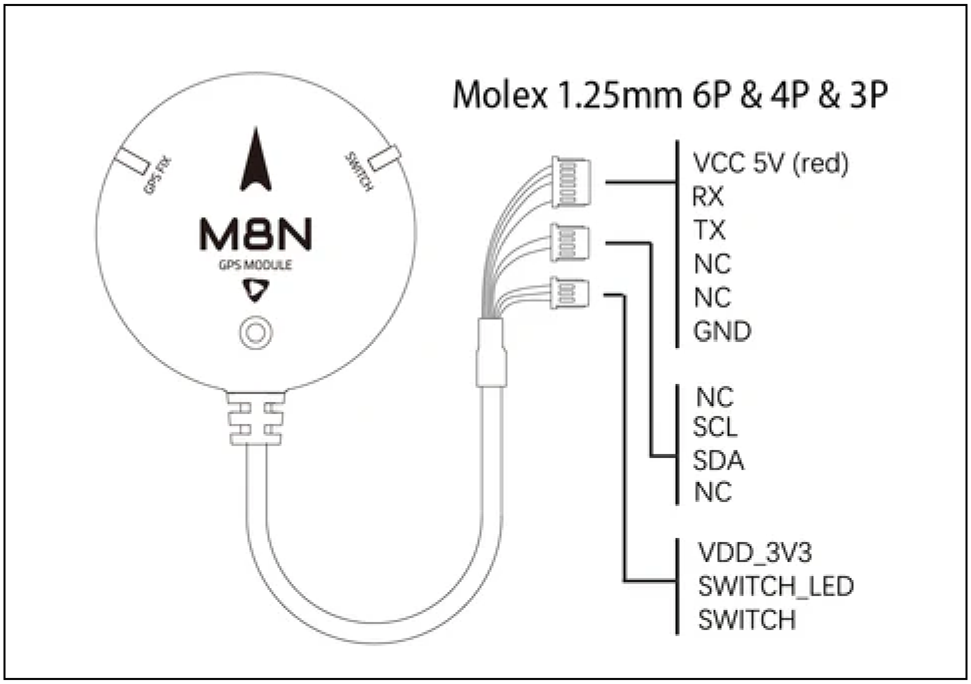

Fig. 3.6: Pin configuration of NEO-M8N GPS Module [24]

3.1.8 Audible Alert Module Selection - Passive Buzzer

Auditory alerts play a vital role in industrial safety systems by providing immediate notification of hazardous conditions, especially in environments where visual cues may be obscured or workers face physical limitations. The SentinelGuard helmet incorporates a passive buzzer to serve as the primary source of audible warnings, ensuring timely and clear communication of safety alerts [25].

The passive buzzer (Figure 3.7) selected is a compact PCB-mounted component operating within a voltage range of 1.5V to 15V, with a typical current consumption of approximately 25 mA. Its dimensions (15 mm × 19.7 mm × 10 mm) allow it to be embedded comfortably within the limited space of a safety helmet. Control of the buzzer is achieved via Pulse Width Modulation

(PWM) signals generated by the ESP32 microcontroller, enabling software-driven modulation of tone and frequency to deliver customizable alert patterns.

The passive buzzer offers several advantages that align with the requirements of wearable industrial safety devices. Its capability to generate variable tones and frequencies through software allows the system to issue distinct alerts for different hazard scenarios, enhancing situational awareness. Low power consumption supports extended use in battery-powered applications, while its compact and lightweight form factor ensures ergonomic integration without compromising comfort. Additionally, the buzzer's design exhibits durability to withstand industrial vibrations and environmental stresses, making it suitable for harsh working conditions. Cost-effectiveness further supports its selection by providing reliable performance at a lower price point compared to advanced multi-tone alarm systems.

Alternative audible alert components were evaluated. Active buzzers, which internally generate a fixed tone upon power supply, offer simplicity but lack the ability to vary tone or frequency, limiting alert customization. Piezo sirens provide loud output suitable for large industrial spaces but are generally bulky, power-hungry, and costly, rendering them impractical for helmet integration. Electromagnetic buzzers produce loud sounds at low voltage but do not support frequency modulation and suffer from mechanical reliability issues under prolonged industrial use.

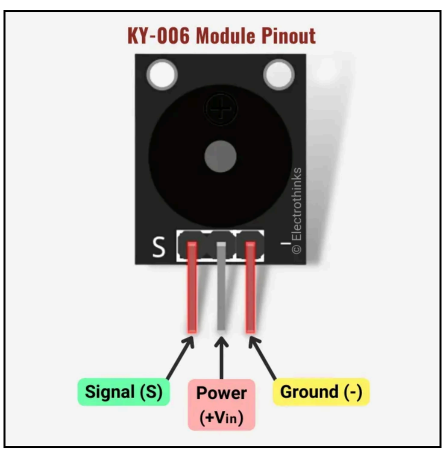

Fig. 3.7: Pin configuration of Passive Buzzer [25]

The passive buzzer’s combination of customizable alert capability, energy efficiency, compactness, and robustness makes it well suited for continuous deployment in wearable safety systems. These attributes enable the SentinelGuard helmet to deliver clear and adaptive auditory warnings, enhancing worker safety through reliable and effective hazard communication.

3.1.9 Visual Display Module Selection

Real-time visual feedback is a critical component in industrial safety systems, allowing users to maintain continuous awareness of environmental hazards, system status, and emergency notifications. The SentinelGuard helmet incorporates a 16x2 alphanumeric LCD screen to provide immediate, on-device display of essential safety information.

The chosen 16x2 LCD display (Figure 3.8) supports 16 characters per line over two lines and operates primarily at 5V. It offers flexible interfacing options through a parallel connection with the HD44780 controller or via an I2C module for simplified wiring and reduced pin usage. The display supports the creation of custom characters and symbols, enhancing the versatility of the information presented. Its high contrast and optional backlight ensure readability under low-light conditions commonly encountered in industrial environments. Power consumption remains low, typically between 1 to 2 mA when the backlight is disabled, making it suitable for battery-powered wearable devices [26].

The display is employed to present critical parameters such as temperature, humidity, and gas concentration levels (e.g., methane and carbon monoxide). It also conveys obstacle proximity alerts, GPS coordinates for location tracking, and system diagnostics. In emergency scenarios, the screen is capable of displaying prominent alert messages, thereby supporting rapid user response.

Several alternative display technologies were evaluated. OLED displays provide high contrast, compact size, and graphic support but suffer from limited readable area, higher power consumption, and increased cost. These factors limit their effectiveness for quick, glanceable alerts in demanding field conditions. TFT color displays offer advanced graphical capabilities and dynamic user interfaces but introduce significant complexity, elevated power requirements, and are not optimal for the straightforward textual information needed in a wearable safety system. Simple 7-segment displays were also considered; however, their inability to convey textual or descriptive information restricts their usefulness for comprehensive safety monitoring.

The 16x2 LCD display was selected for its optimal balance of readability, cost-effectiveness, ease of integration, and low power requirements. Its proven reliability in embedded applications and compatibility with microcontroller platforms such as the ESP32 contribute to seamless integration into the SentinelGuard helmet. Furthermore, its compliance with human-machine interface standards ensures that critical safety data is accessible and visible without dependence on external devices, enhancing the immediacy and effectiveness of safety communications.

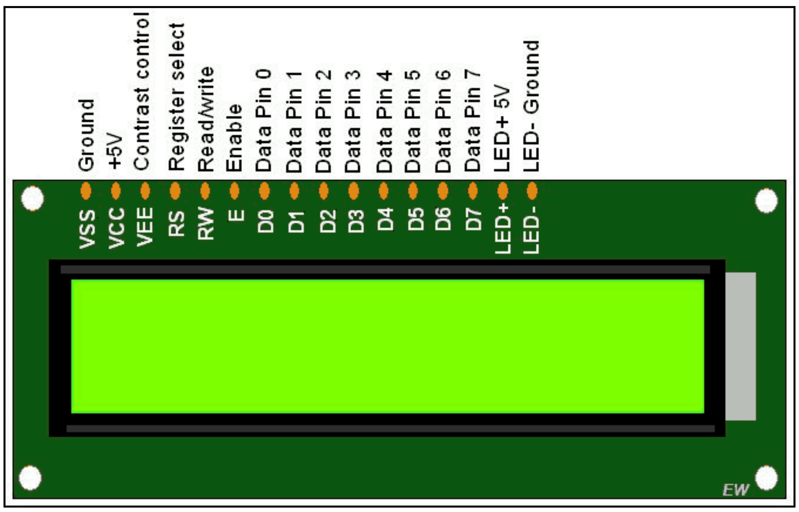

Fig. 3.8: Pin configuration of 16x2 LCD Display [26]

3.1.10 Rechargeable Battery & Power Management Circuit

A dependable and efficient power supply is fundamental for wearable safety systems to maintain uninterrupted operation of sensors, communication modules, and alert mechanisms. The SentinelGuard helmet employs a Lithium-Ion (Li-Ion) rechargeable battery (Figure 3.9) to fulfill these demands.

The selected Lithium-Ion battery features a nominal voltage of 3.7V and a typical capacity ranging from 2200 to 3000 mAh. Its high energy density facilitates a compact and lightweight form factor, critical for integration within a wearable helmet. The battery supports approximately 300 to 500 full charge-discharge cycles, ensuring longevity over repeated use. Rechargeability is enabled via a standard USB interface, providing user convenience and supporting sustainable operation by eliminating disposable battery waste. [27]

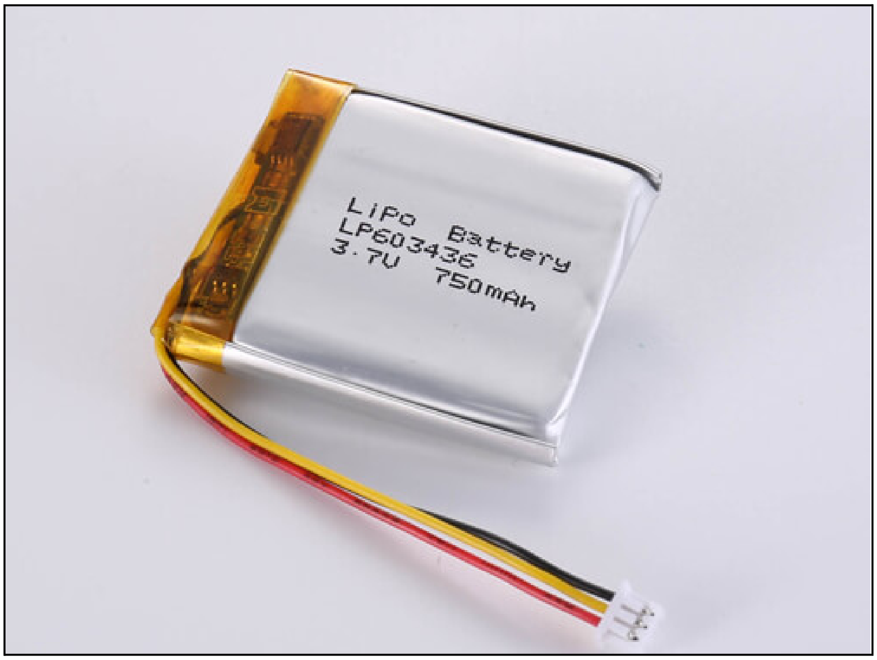

Fig. 3.9: 3.7V Li-Ion Battery [27]

Alternative power solutions considered include alkaline batteries, nickel-metal hydride (NiMH) rechargeable batteries, and lithium-polymer (Li-Po) batteries. Alkaline batteries, while readily accessible, were deemed unsuitable due to their non-rechargeable nature, bulkiness, and environmental impact. NiMH batteries offer rechargeability and safety advantages but are limited by lower energy density and increased weight, resulting in less efficient space-to-power ratios for compact helmet integration. Lithium-Polymer batteries present benefits in weight and flexibility; however, their increased sensitivity to physical damage and stricter charging requirements reduce their suitability for rugged industrial applications.

The Lithium-Ion battery was selected for its superior energy density, lightweight profile, and rechargeability—attributes essential for wearable safety equipment. This configuration delivers reliable power, aligning with industrial-grade standards for safety and performance. The approach ensures extended operational duration and efficient power usage, meeting the stringent demands of continuous worker protection in hazardous environments.

3.1.11 Heart Rate Monitor Kit with AD8232 ECG sensor module

In industrial environments, where physical exertion, high stress, and exposure to hazardous conditions are common, monitoring workers' physiological parameters—particularly heart activity—is essential for ensuring health and safety. The SentinelGuard helmet integrates the AD8232-based Heart Rate Monitor Kit (Fig. 3.10) to provide real-time electrocardiogram (ECG) data and heart rate measurements, enabling early detection of cardiovascular anomalies such as arrhythmias, tachycardia, or bradycardia.

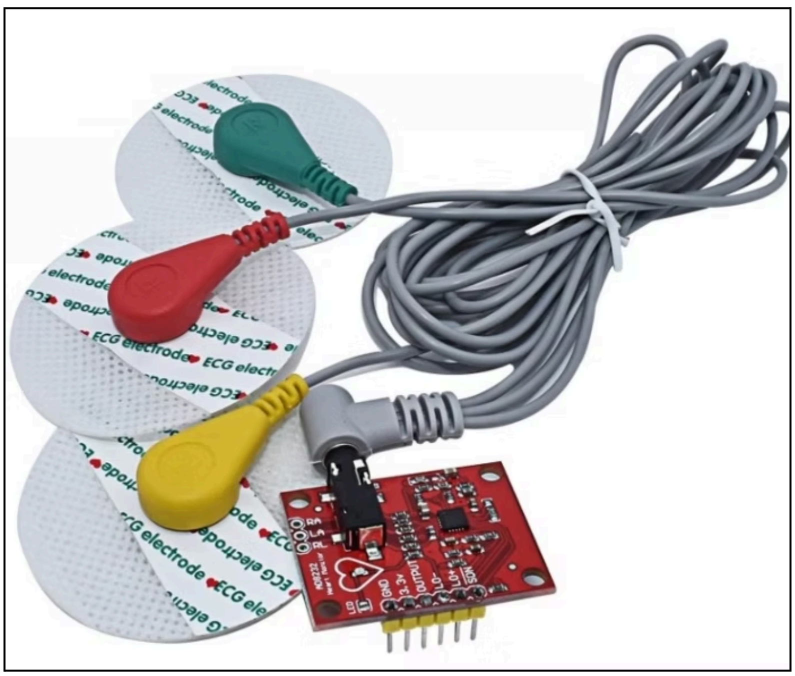

Fig. 3.10: Heart Rate Monitor Kit with AD8232 ECG sensor module [28]

The AD8232 ECG sensor is an integrated signal conditioning block designed for ECG and other biopotential measurements. It functions by amplifying and filtering the tiny electrical signals generated by the heart, even in noisy environments. The sensor connects via analog output to a microcontroller, which processes the signals and forwards the data to a cloud platform for visualization and analysis.

Sensor Specifications:

- **Operating Voltage:** 3.3V – 5V DC
- **Lead Configuration:** 3-lead ECG
- **Output Type:** Analog voltage (ECG waveform)
- **Typical Gain:** 100x
- **Low-Pass Filter Cutoff Frequency:** 40 Hz
- **High-Pass Filter Cutoff Frequency:** 0.5 Hz
- **Operating Temperature Range:** -40°C to +85°C
- **Size:** Compact and wearable

The AD8232 module was selected for its compact design, reliable ECG waveform output, and low power consumption, which are crucial in a wearable application like the SentinelGuard helmet. The ECG data collected is displayed on the Ubidots dashboard, which presents real-time heart rate values and waveform plots, allowing supervisors or safety officers to remotely monitor a worker's cardiovascular status.

Alternative solutions such as the MAX30003 and ADAS1000 offer multi-lead ECG measurements and higher precision but were excluded due to their complexity, higher cost, and increased power demands. Simpler pulse-rate sensors like the MAX30100 were also considered but rejected for lacking the waveform-level detail provided by the AD8232, which is essential for accurate cardiac monitoring.

Ultimately, the AD8232 ECG sensor module serves as a reliable, low-cost, and easy-to-integrate solution for real-time heart monitoring in high-risk occupational settings. Its role in the SentinelGuard system ensures that in addition to environmental safety, workers' health is continuously safeguarded through biomedical surveillance.

3.2 Software & Programming Tools

The digital tools, programming environments, and libraries utilized to build and control the SentinelGuard system are described in this section. These include platforms used for writing microcontroller code, interfacing with sensors, enabling cloud connectivity, and facilitating user interactions. The software tools were chosen based on their compatibility, flexibility, and capacity to support real-time operations and low-power performance.

3.2.1 Arduino IDE

The Arduino IDE is an open-source development environment used to write, compile, and upload code to microcontroller boards such as the ESP32. It features an integrated serial monitor for real-time debugging and supports a wide range of libraries and hardware modules.

In the project, the Arduino IDE was utilized as the primary platform for developing and uploading firmware to the ESP32. It enabled efficient debugging and iteration of code controlling sensor operations and wireless communication.

Its user-friendly interface and extensive community support significantly accelerated development. The availability of well-documented libraries also simplified integration with various sensors and modules.

3.2.2 Embedded C/C++

Embedded C/C++ is the standard programming language for writing firmware that interacts directly with hardware components. It provides precise control over memory and processing resources, making it ideal for real-time embedded applications.

The firmware for the ESP32 was written in Embedded C/C++. It controlled sensor initialization, data collection, real-time processing, and communication with external systems such as cloud databases and GPS modules.

3.2.3 Wokwi Simulator

Wokwi is an online simulator designed for prototyping and testing embedded systems, especially Arduino and ESP32-based projects. It allows simulation of sensors, microcontrollers, and circuits without physical hardware.

The Wokwi Simulator was used to validate the ESP32 firmware and circuit design virtually before actual hardware implementation. It simulated interactions with gas sensors, GPS modules, and other components to ensure correct behavior and functionality.

3.2.4 Lucidchart

Lucidchart is a cloud-based diagramming tool used for creating flowcharts, circuit diagrams, and system architecture designs. It supports collaboration and visualization of hardware and software integration.

In the project, Lucidchart was used to design the system architecture and detailed circuit diagrams. This ensured proper planning and clear communication for integrating sensors, the ESP32, and other modules.

3.2.5 Google Firebase (Real-Time Database)

Google Firebase is a cloud-based backend platform that offers real-time database capabilities, enabling synchronized data storage and retrieval across multiple clients. Firebase was integrated into the system to store real-time sensor data from the ESP32. It allowed cloud-based monitoring of gas levels, worker location, and safety alerts through a web dashboard, ensuring remote accessibility and real-time responsiveness.

3.2.6 Frontend Development (Web Interface for Monitoring)

Frontend development involves building the user interface and user experience of web applications. Bootstrap, a popular CSS framework, is commonly used to create responsive and consistent UI designs. A responsive web dashboard was developed using Bootstrap to display real-time data from the ESP32. It included visual elements like sensor readings, alert messages, and maps showing worker locations, offering an intuitive interface for monitoring system status.

3.2.7 Backend Development (Server & Data Processing)

Backend development focuses on server-side logic, database operations, and API development. RESTful APIs are widely used to enable communication between client interfaces and server-side resources.

In the project, REST APIs were created to facilitate data exchange between the ESP32 and the cloud database. The backend processed sensor data, handled alert conditions, and served endpoints to fetch real-time and historical information for the frontend interface.

3.3 Testing & Validation Techniques

3.3.1 Gas Exposure Chamber (Modified Setup)

Testing is conducted using an enclosed chamber with sealed edges to provide a controlled environment for gas exposure. The SentinelGuard helmet is placed inside this chamber to ensure accurate and consistent exposure of its sensors to test gases. Gases are generated externally using a flask-based reaction system and introduced into the chamber through a controlled inlet, enabling precise regulation of gas concentration during sensor evaluation.

3.3.2 Flask-Based Gas Generation

Specific chemical reactions are employed to produce the required gases for testing. The flask containing the reactants is connected to the gas exposure chamber through a controlled inlet, ensuring measured and reproducible gas exposure to the helmet's sensors. This setup allows for safe and controlled gas generation necessary for validating sensor performance under various hazardous conditions.

3.3.3 Gas Generation for Sensor Testing – SentinelGuard Helmet

To evaluate the performance of the gas sensors MQ-135, MQ-7, and MQ-6, controlled gas generation methods were employed. For carbon monoxide (CO) detection using the MQ-7 sensor, instead of generating CO chemically due to its toxic nature, smoke emitted from an industrial boiler was used as a safer and more practical source of CO.

For methane (CH_4) testing using the MQ-6 sensor, methane gas was generated by heating a mixture of sodium acetate and sodium hydroxide (soda lime), based on the decarboxylation reaction::

$$\mathbf{CH_3COONa + NaOH \rightarrow CH_4 + Na_2CO_3}$$

This reaction proceeds in a controlled manner, safely producing methane gas without the need for compressed cylinders. It offers a simple, non-flammable approach utilizing readily available and cost-effective chemicals.

Nitrogen dioxide (NO_2) gas for the MQ-135 sensor was generated by reacting a copper coin with concentrated nitric acid, following the reaction:

$$\mathbf{Cu + 4HNO_3 \rightarrow Cu(NO_3)_2 + 2NO_2 + 2H_2O}$$

This reaction produces nitrogen dioxide gas in a controlled manner, eliminating the need for gas cylinders and allowing adjustment of gas concentration by varying the amount of metal and acid used. All chemicals required are readily available from standard laboratory suppliers, facilitating safe and effective evaluation of sensor performance.

3.3.4 Wireless Communication Testing

The Wi-Fi and GPS modules integrated into the SentinelGuard helmet are tested to ensure reliable real-time data transmission. GPS tracking accuracy is validated by monitoring continuous location updates and movement detection, verifying the system's ability to provide precise positioning information during operational use.

3.3.5 Threshold-Based Alerts

Predefined safety limits are established for gas concentrations, temperature, and humidity based on industry standards and sensor specifications. The system continuously monitors these parameters and triggers auditory alerts via the buzzer and visual indicators through LEDs when any sensor readings exceed the preset thresholds, ensuring timely warning of hazardous conditions.

This chapter outlined the essential hardware, software, and testing methods used to develop and validate the SentinelGuard helmet. From sensor integration to gas generation techniques, each tool was selected for accuracy, safety, and cost-effectiveness. Together, these techniques ensured reliable performance in hazardous conditions.

The next chapter is Setup and Design that stands out as the most impactful, where the system truly came to life through practical implementation.

CHAPTER 4

SETUP AND DESIGN OF SENTINEL GUARD

This Chapter details the conceptualization, architecture, and implementation strategy behind the SentinelGuard Safety Helmet. Designed for deployment in hazardous and high-risk work environments, the system aims to significantly improve occupational safety through the integration of smart sensing technologies and responsive alert mechanisms.

The SentinelGuard is a sophisticated fusion of environmental sensors, gas detectors, physiological monitors, GPS tracking, and real-time communication modules. It has been specifically engineered to detect unsafe conditions, alert workers and supervisors, and enable immediate preventive action. This section outlines the complete system design—beginning from component layout and data flow architecture to physical assembly and remote data visualization—demonstrating how each element contributes to the operational effectiveness of the helmet in real-world scenarios.

4.1 Working Principle

The SentinelGuard operates as an integrated safety system designed to enhance worker protection in hazardous industrial environments. The primary working mechanism involves the continuous monitoring of environmental conditions and the health status of the worker through embedded sensors and wireless communication. Toxic gas sensors, namely MQ-135, MQ-7, and MQ-6, are strategically embedded in the helmet to detect harmful gases such as carbon monoxide, methane, and ammonia. Simultaneously, an electrocardiogram (ECG) module monitors the worker's cardiac activity to ensure physiological well-being.

The sensor data is collected and processed by an ESP32 microcontroller, which is equipped with an inbuilt Wi-Fi module to facilitate seamless real-time data transmission. Instead of relying on a local server, the processed data is transmitted to Google Firebase, a cloud-based platform, which enables centralized data storage and real-time accessibility. A dedicated front-end dashboard, connected to Firebase, fetches and displays this information, allowing safety supervisors to remotely monitor environmental parameters, toxic gas levels, and the health status of individual workers.

To ensure immediate hazard response, the system integrates a robust alert mechanism comprising both visual and auditory signals. An LCD display mounted on the helmet provides real-time feedback on sensor readings, while a buzzer generates an audio alert whenever unsafe conditions are detected. Furthermore, the helmet features an emergency SOS function, activated by a dedicated button. Upon activation, the worker's real-time GPS coordinates are also transmitted to Firebase, ensuring that safety personnel receive prompt location information during emergencies.

For optimized energy efficiency, sliding switches are incorporated to allow selective activation of specific sensors based on situational requirements, while the SOS button remains continuously operational to guarantee uninterrupted emergency communication.

By unifying environmental hazard detection, real-time health monitoring, wireless cloud data transmission, and proactive alert systems, the SentinelGuard offers a comprehensive and adaptive solution for mitigating occupational risks and safeguarding workers in hazardous conditions.

4.2 Block Diagram

The high-level architecture of the SentinelGuard system is comprehensively illustrated in the block diagram shown in Fig. 4.1, which was created using Lucidchart. This schematic offers a clear representation of both the transmitter and receiver components of the system. At the core of the transmitter side lies the microcontroller, which serves as the central unit interfacing with various sensors and modules. It integrates multiple gas sensors—MQ-135 for air quality, MQ-7 for carbon monoxide detection, and MQ-6 for LPG leakage—each connected through individual switches to ensure selective monitoring and modular control. Additionally, the DHT11 sensor monitors ambient temperature and humidity conditions, while the AD8232 ECG module is employed to track the wearer's cardiac activity in real time, contributing to vital health diagnostics.

To enhance situational awareness, an M8N GPS module provides real-time location data, which is particularly crucial in emergency scenarios. An IR sensor is used to confirm helmet usage, thus enforcing safety compliance. A 16x2 LCD display is connected to the ESP32 to provide immediate visual feedback to the wearer. For alerting purposes, a buzzer is activated when any of the sensor readings exceed predefined safety thresholds. An SOS button is also included for manual emergency alerts, ensuring the system is responsive even in unpredictable conditions. All sensor data is transmitted to a cloud server via Wi-Fi, enabling continuous monitoring. The cloud infrastructure then relays the information to a localhost web server, from which it can be accessed through an application device on the receiver side. This architecture ensures real-time visibility, robust monitoring, and quick response mechanisms to safeguard industrial workers in hazardous environments.

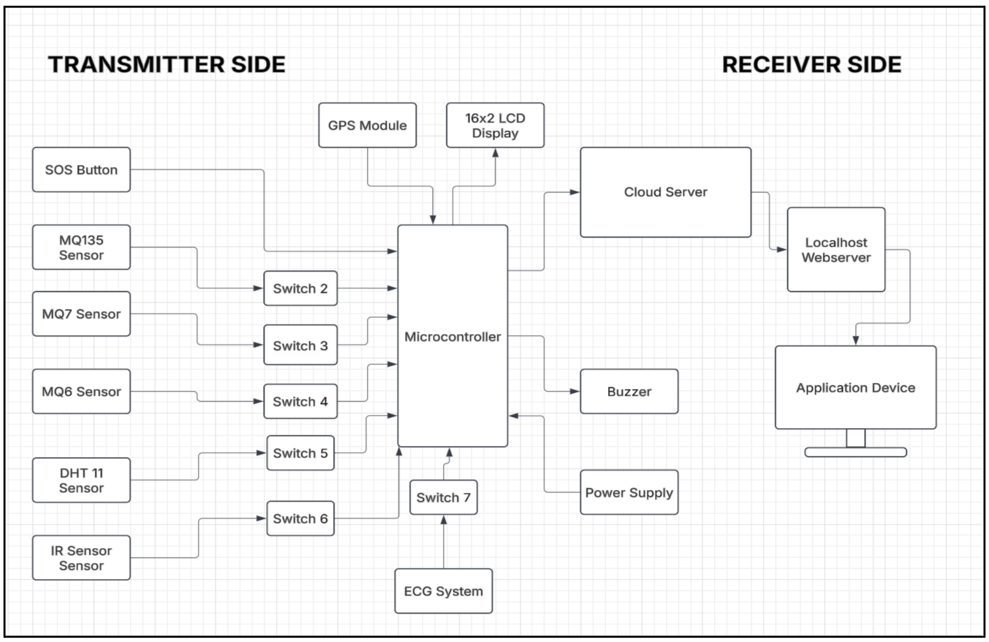

Fig. 4.1: Block Diagram Representation of the Transmitter and Receiver Side of SentinelGuard Helmet

4.3 Circuit Design and Simulation

To validate the functional interactions prior to hardware realization, a detailed circuit was designed and simulated using the Wokwi simulation platform. The simulation model, as illustrated in Fig. 4.2, effectively replicated the behavior of all critical components, including gas sensors, the DHT22 sensor, ECG module, GPS module, LCD display, buzzer, ESP32 microcontroller, and Firebase communication. This comprehensive simulation served as a reliable testbed for assessing system behavior under various conditions.

The simulation results confirmed the efficient acquisition and processing of sensor data, demonstrating the system's capability to monitor both environmental and physiological parameters accurately. The ESP32 microcontroller successfully managed the integration and control of multiple peripherals, including environmental sensors, the buzzer, LCD display, IR obstacle detection sensor, and an SOS button. Moreover, the microcontroller facilitated stable and reliable wireless communication with the Google Firebase cloud platform, ensuring seamless real-time data transmission and remote accessibility.

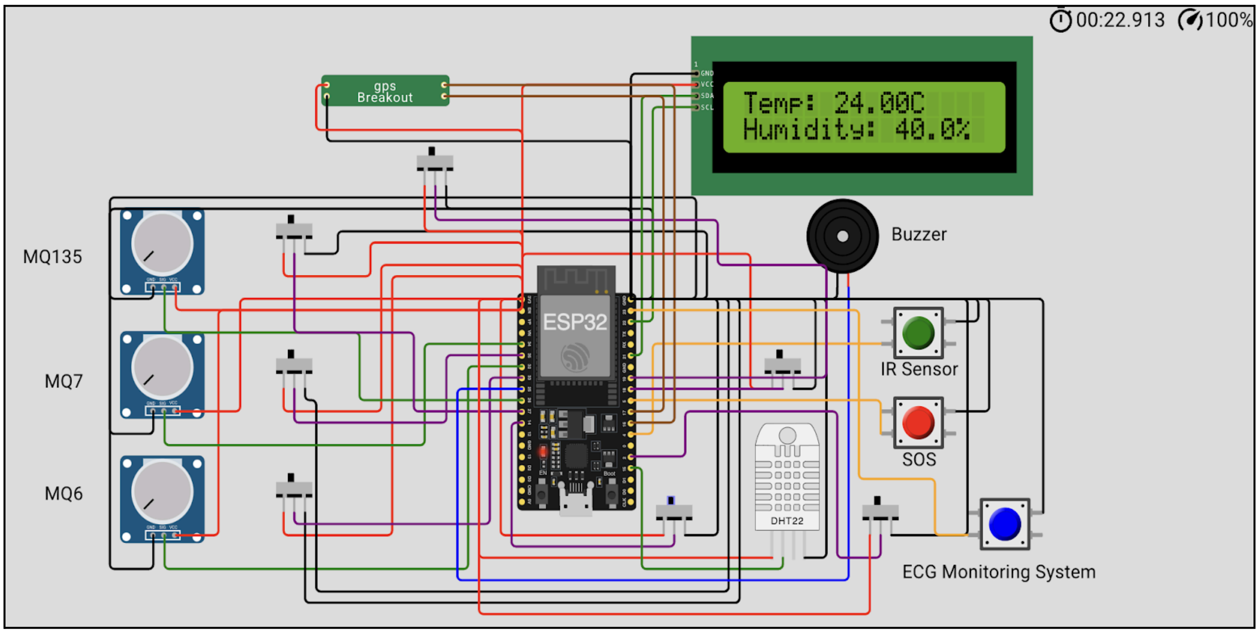

Fig. 4.2: Circuit Design of the SentinelGuard Helmet Developed and Simulated Using Wokwi Software

4.4 Hardware Development of SentinelGuard

Following the successful validation of the simulation model, the hardware implementation was undertaken with a focused approach toward modularity, reliability, and miniaturization. The architecture incorporated two dedicated microcontrollers to optimize functionality and performance. The ESP32 microcontroller was tasked with managing the gas sensors, IR obstacle detection sensor, buzzer, SOS button, and LCD display, while the ESP8266 microcontroller was exclusively assigned to handle GPS tracking and ECG monitoring. This strategic division of responsibilities ensured that critical health and location monitoring functions remained uninterrupted, even in the event of faults in other system components.

The separation of tasks between the two microcontrollers offered significant advantages. Reliability was notably enhanced by isolating ECG and GPS functionalities, allowing these essential services to continue operating independently of the rest of the system. Furthermore, the distribution of processing load between the ESP32 and ESP8266 helped prevent system bottlenecks and improved overall performance. This architecture also introduced fault tolerance into the design, ensuring that transmission of vital health and location data persisted even if non-critical sensors or subsystems experienced failure.

Each ESP module was powered through a dedicated, modular Li-Po based power supply. This design choice not only reduced the risk of total system shutdown due to battery issues but also allowed for independent and optimized power management for each microcontroller. To maintain compactness, all hardware components were carefully soldered onto a Vero Board. This resulted in a miniaturized and lightweight configuration, enabling seamless integration into a standard industrial safety helmet without compromising comfort or functionality.

Advanced components were chosen to enhance the system's capability. The M8N GPS module was selected for its commercial-grade performance, offering extended range and stable connectivity even in challenging environments such as underground mines. The AD8232 ECG module was employed for its ability to continuously and accurately monitor heart activity, enabling early detection of worker stress or fatigue, which is crucial in high-risk work environments.

The helmet body was painted according to color schemes recommended by the National Disaster Management Authority (NDMA) to improve visibility and ensure adherence to industrial safety standards. These comprehensive hardware design choices collectively contribute to the feasibility, operational reliability, and real-world applicability of the SentinelGuard system.

To implement the real-time sensing, data transmission, and wireless communication functionalities of SentinelGuard (Fig. 4.3), embedded firmware was developed for the ESP32 and ESP8266 microcontrollers using the Arduino IDE. The Arduino Integrated Development Environment offers a user-friendly and versatile platform for writing, compiling, and uploading code in Embedded C/C++, making it ideal for rapid prototyping and hardware-software integration.

Fig. 4.3: Assembled SentinelGuard showcasing sensor integration

ESP32 was primarily used for its robust processing capabilities and multiple GPIOs to interface with gas sensors, ECG modules, buzzers, and GPS units. Meanwhile, ESP8266 modules were utilized for establishing Wi-Fi connectivity and cloud communication due to their compact size and low power consumption. The code developed in this environment handles sensor data acquisition, threshold-based decision-making, alert generation, and real-time data transmission to Firebase, enabling continuous environmental and health monitoring.

4.5 Dashboard Development

To complement the hardware setup, a real-time remote dashboard was developed to visualize live sensor data retrieved from Google Firebase. This web-based interface provides continuous monitoring capabilities, allowing safety supervisors to oversee critical parameters and respond promptly to emergencies. The dashboard is designed to present a comprehensive view of the system's outputs in an organized and accessible manner, facilitating remote supervision and decision-making.

The interface displays real-time environmental metrics, including gas concentrations, temperature, and humidity, providing immediate insight into the surrounding working conditions. Additionally, physiological monitoring is supported through the integration of ECG data, as illustrated in (Fig. 4.4), enabling health status assessment of the individual wearing the helmet. The worker's precise GPS location is also visualized on an embedded interactive map, ensuring location tracking at all times, especially useful in large or complex industrial sites.

Fig. 4.4: Dashboard displaying ECG data acquired from a member of the group (member of the group)

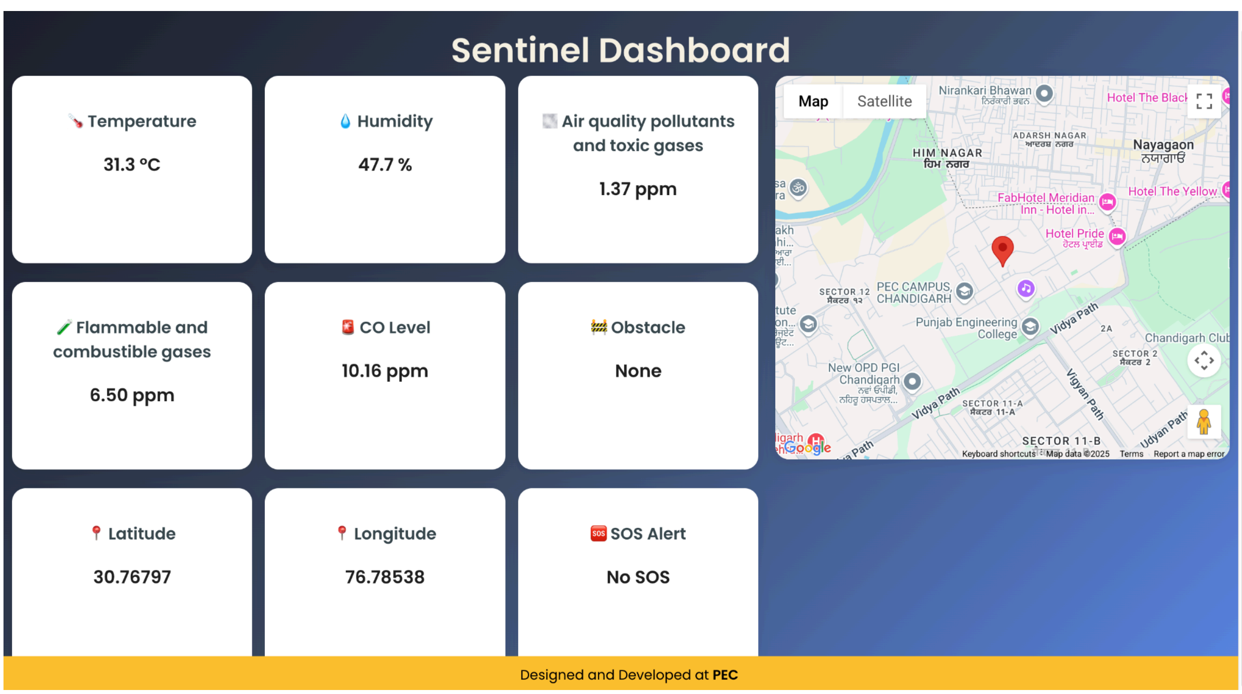

Fig. 4.5: Dashboard displaying real-time sensor data acquired from the hardware setup.

In critical situations, such as emergencies triggered via the SOS button, the dashboard immediately reflects alert notifications, allowing supervisors to initiate rapid interventions. As shown in Fig. 4.5, the dashboard serves as a vital tool for real-time situational awareness, enabling timely and informed responses to hazardous environmental conditions, health-related incidents, or position-based threats. This remote monitoring capability significantly enhances the overall safety infrastructure of industrial operations by combining live data visualization with cloud-based accessibility.

This chapter detailed the complete implementation of the SentinelGuard helmet, from circuit simulation and hardware integration to real-time dashboard visualization. The dual-microcontroller setup, sensor layout, and cloud connectivity were thoughtfully designed for reliability, safety, and user comfort in industrial environments.

The chapter showcases the true realization of the system-making it the most significant and transformative part of the project..The next chapter is Results and Analysis.It evaluates the system's performance through testing and data interpretation.

CHAPTER 5
RESULTS AND ANALYSIS

The SentinelGuard Smart Safety Helmet system underwent extensive evaluation across multiple real-world safety dimensions to validate its integrated sensor suite, cloud-based monitoring, and emergency alert mechanisms. These tests were conducted in both ambient and simulated industrial environments to assess the system's reliability, responsiveness, and suitability for deployment in hazardous workplace conditions.

5.1 Gas Sensor Analysis and Performance

The core environmental sensing capability was tested using three primary gas sensors—MQ-6 (methane and LPG), MQ-7 (carbon monoxide), and MQ-135 (general air quality including ammonia and benzene). The system was exposed to controlled concentrations of these gases under laboratory conditions. All three sensors showed a proportional and accurate response to changes in gas concentration, proving their suitability for early detection of toxic or flammable gases. These readings were displayed in real-time via a cloud-integrated Sentinel Dashboard, which uses color-coded alerts to signal threshold violations. For example, methane readings above 1100 ppm, carbon monoxide exceeding 55 ppm, and nitrogen dioxide surpassing 60 ppm triggered immediate visual warnings (see Figures 5.1, 5.2, and 5.3). These features ensure timely alerts to prevent accidents and safeguard personnel in potentially explosive or toxic environments.

In addition to individual sensor performance, the system was validated for simultaneous multi-gas detection without noticeable cross-sensitivity or interference. Logged data was stored for trend analysis and compliance tracking, supporting informed decision-making and safety audits. Real-time alerts were reinforced through the SentinelGuard's buzzer and LCD display, while cloud integration enabled remote supervisors to receive mobile notifications instantly. This comprehensive alert mechanism ensures a robust early-warning framework ideal for high-risk industrial environments.

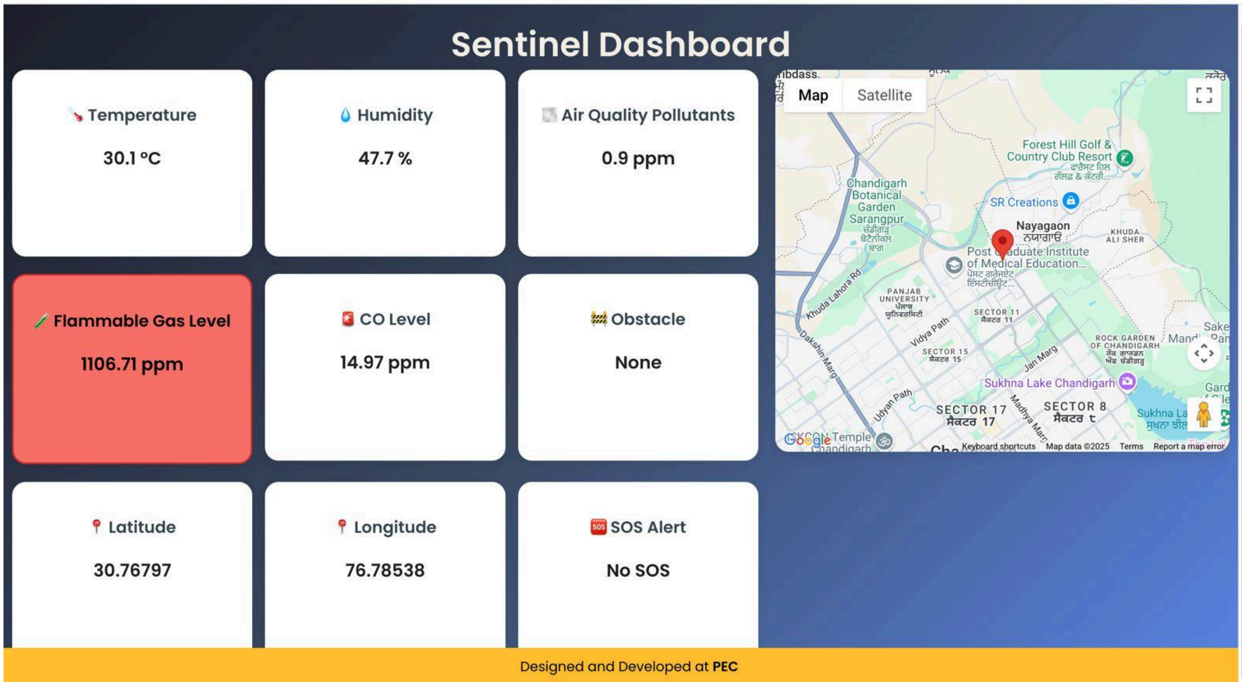

Fig. 5.1: Dashboard alert displaying methane level gas exceeding safety threshold (1100 ppm)

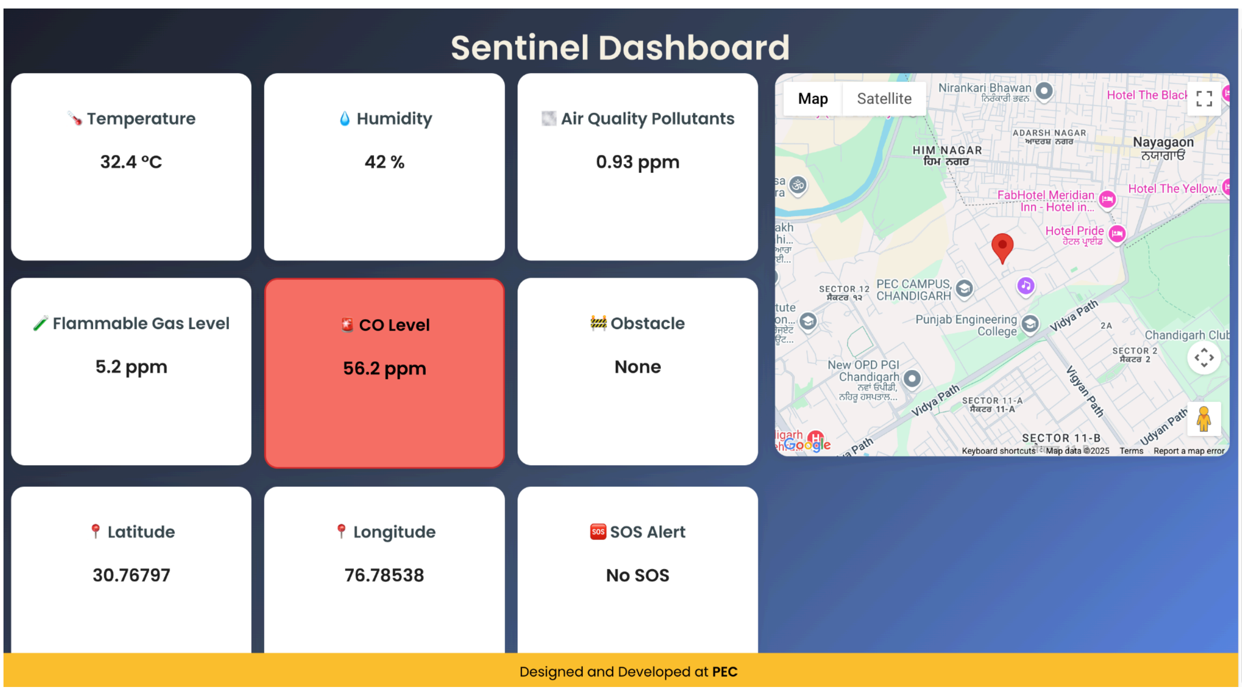

Fig. 5.2: Dashboard alert displaying carbon monoxide gas level exceeding safety threshold (55 ppm)

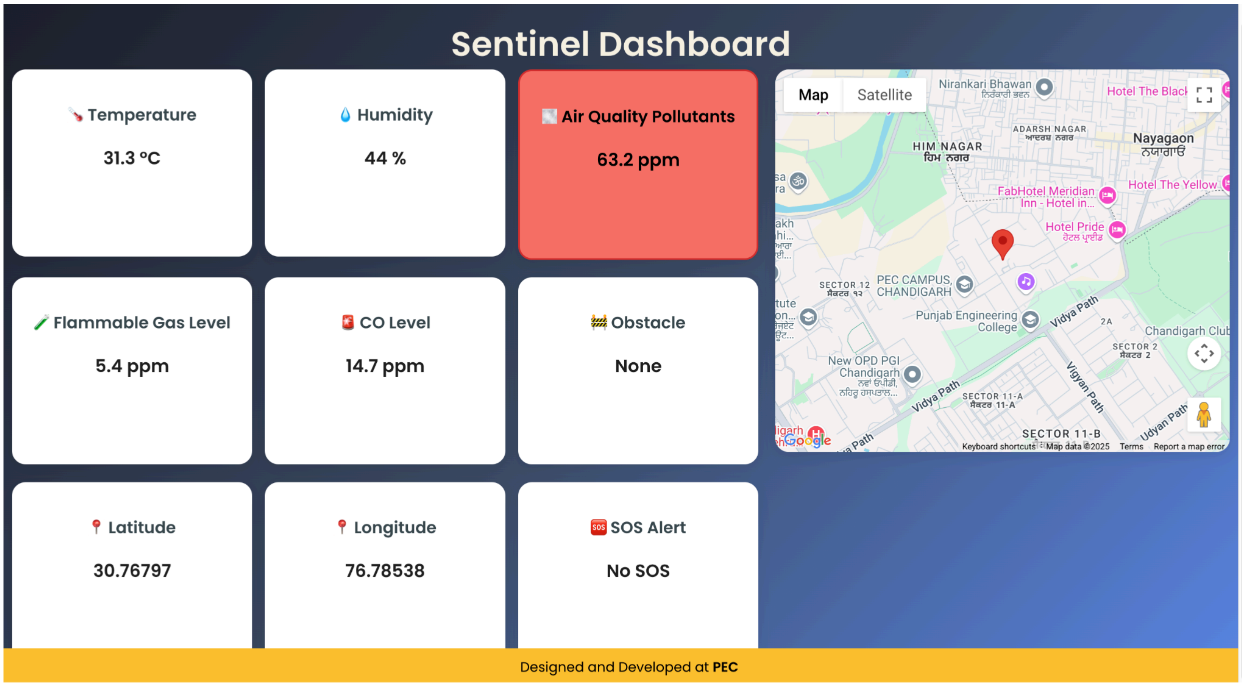

Fig. 5.3: Dashboard alert displaying nitrogen dioxide gas level exceeding safety threshold (60 ppm).

Table 5.1: Sensor Data Comparison between Normal and Industrial Environments

Sensors	Gas Exposed	Category	Normal Ambient Level (PPM)	Lab Tested Concentration (PPM)	Hazardous Concentration Threshold (PPM)	Reference
MQ-6	Methane (CH_4)	Flammable and Combustible Gases	~ 5 ppm	~ 1100 ppm	1,000 ppm (0.1%) 8-hour TWA **OR** 5% volume (50,000 PPM) – Lower Explosive Limit (LEL)	ACGIH and OSHA / NIOSH
MQ -7	Carbon Monoxide (CO)	Toxic Gases and Air Quality Monitoring	~ 15 ppm	~ 55 ppm	50 PPM (8-hr TWA) / 200 PPM (IDLH)	OSHA / NIOSH
MQ -135	Air quality (NO_2 ,NH_3)	Air Quality Pollutants and Toxic Gases (e.g. NO_2 ,NH_3,CO_2)	~ 1 ppm	~60 ppm	NO_2: 50 PPM (8-hr TWA) / CO_2: 5,000 PPM (TWA)	OSHA / WHO

5.2 GPS-Based Location Tracking

The system incorporates the NEO-M8N GPS module to provide continuous location data of the worker. In high-risk or remote work areas such as mines or construction zones, real-time location awareness is essential for safety supervisors. The SentinelGuard system successfully displayed latitude and longitude (Figure 5.3) coordinates in real time on the cloud dashboard, with Google Maps integration for visual geolocation tracking. This helps with rapid identification and rescue in emergencies. Additionally, geofencing capabilities can be implemented to alert supervisors if a worker moves beyond predefined safety zones. The GPS data is also logged periodically to maintain movement history, aiding in incident analysis and safety compliance.

5.3 Obstacle Detection via Infrared Sensor

To prevent physical injuries due to unseen obstacles, the helmet includes an IR sensor module that detects nearby objects or barriers. During practical testing, the system generated accurate proximity alerts, and these were promptly displayed on the dashboard interface (Figure 5.4). This feature is particularly useful in low-light or visually restricted industrial settings, adding another preventive safety layer.

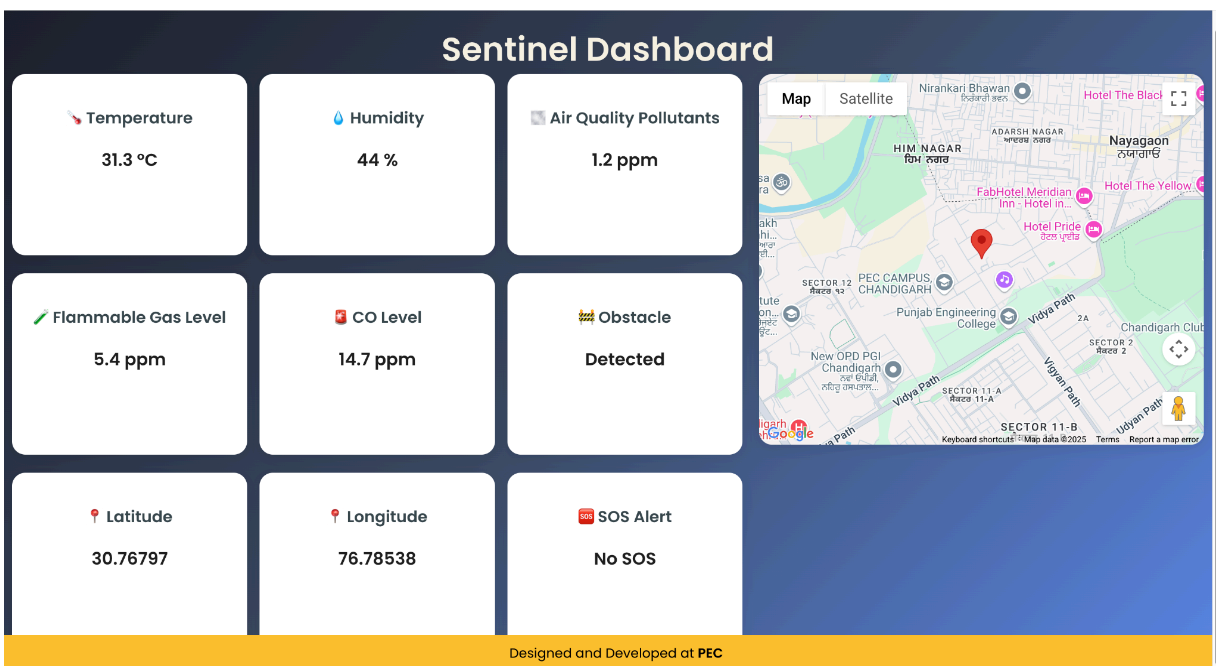

Fig. 5.4: Dashboard displaying obstacle alert

5.4 SOS Emergency Alert System

For scenarios requiring immediate help—such as gas poisoning, injury, or fainting—the helmet features a manual SOS alert mechanism. When triggered, the system immediately updates the dashboard with a red “SOS” warning (Figure 5.5) , sending an emergency alert to supervisors. This tested feature proved effective in ensuring timely notification and coordination of emergency response, highlighting the system’s role not just in monitoring but also in active incident response.

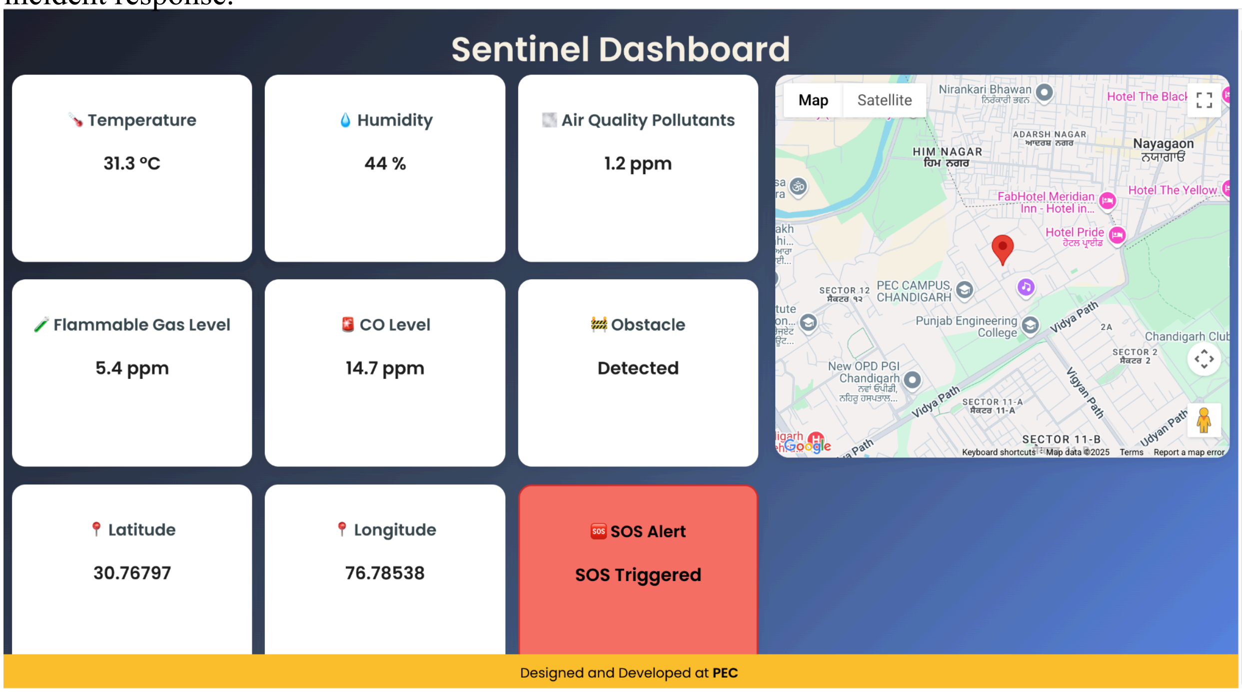

Fig. 5.5: Dashboard displaying SOS alert

5.5 Real-Time ECG Monitoring and Heart Health Tracking

In addition to environmental monitoring, the system is equipped with a Heart Rate Monitor Kit based on the AD8232 ECG sensor module, which enables continuous monitoring of the user’s cardiac activity. This biomedical module captures the user’s ECG waveform and heart rate, sending the data in real time to the Ubidots IoT cloud platform (Figure 5.6)

The Ubidots dashboard visualizes this health data through live ECG waveforms and numerical heart rate readings, ensuring that any abnormal cardiac activity—such as tachycardia, bradycardia, or irregular rhythm—can be promptly detected. During testing, the system accurately tracked dynamic heart rate changes across different activity levels, confirming the AD8232 sensor's precision and noise filtering capabilities. This integration provides a critical layer of physiological monitoring, which is especially useful for workers in high-stress or high-temperature environments where cardiac incidents may occur.

Fig. 5.6: Dashboard displaying ECG data acquired from a member of the group (member of the group)

The results from functional testing confirm that the SentinelGuard Smart Safety Helmet is a robust, real-time safety solution for industrial environments. The system effectively combines:

- Toxic gas monitoring with responsive alerting
- ECG and heart rate tracking using the AD8232 module and Ubidots cloud
- Live GPS-based location tracking
- Physical obstacle detection
- Manual SOS alert capabilities

The comprehensive and integrated Sentinel Dashboard and Ubidots interface ensures that workers' safety data—both environmental and physiological—are continuously visible to safety officers and emergency teams. These results affirm the system's readiness for deployment in hazardous industrial settings where continuous monitoring and rapid alerting are essential to protect human life.

This chapter validated the system's performance through controlled experiments simulating industrial hazards. The sensors reliably detected toxic gases, and alerts were accurately triggered, confirming the system's effectiveness. The dashboard provided real-time visibility, reinforcing the practicality of the helmet in real-world scenarios.

The next chapter is Conclusion and Future Scope. It summarizes the project and outlines directions for further development.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

The SentinelGuard Smart Safety Helmet represents a significant advancement in occupational safety, addressing the critical need for real-time hazard detection and health monitoring in high-risk industrial environments. Integrating gas sensors (MQ-6, MQ-7, MQ-135), ECG heart-rate monitoring, and GPS tracking, the helmet offers timely alerts through an onboard LCD and buzzer system. A dual-microcontroller architecture (ESP32 and ESP8266) ensures fault tolerance and continuous data streaming to Firebase and a cloud-based dashboard for supervisory oversight. Testing under simulated hazardous conditions demonstrated its reliability in detecting toxic gases and physiological anomalies, validating its responsiveness and robustness.

Importantly, the system overcomes limitations of existing solutions by combining continuous ECG-based monitoring with real-time cloud communication and a fail-safe design. Its modular, IoT-enabled architecture allows for scalable deployment across diverse industrial scenarios, making it a proactive and adaptable safety solution.

Looking ahead, the following enhancements can significantly broaden the SentinelGuard's capabilities and impact:

1. Integration of Artificial Intelligence and Predictive Analytics

Future iterations can incorporate artificial intelligence and machine learning to analyze sensor data for pattern recognition and predictive insights. This will enable proactive risk management and intelligent decision-making, reducing accident risks before they escalate.

2. On-Device Edge Computing

Enabling edge processing on the ESP32 microcontroller will reduce latency in alert generation, optimize power usage, and ensure data availability even in areas with poor connectivity—critical for battery-powered wearables.

3. Advanced Health Monitoring Capabilities

Beyond ECG, the system can be expanded to monitor SpO_2, body temperature, and heart rate variability, providing a more comprehensive view of worker health. Medical-grade sensor integration could enhance accuracy and real-time diagnostics.

4. Expansion of Communication Technologies

Incorporating LoRaWAN or 5G would extend communication coverage to remote or underground locations, ensuring reliable connectivity where Wi-Fi or GPS may fail.

5. Industrial IoT (IIoT) Integration

Aligning with IIoT standards allows for seamless integration into industrial control systems and enterprise dashboards, facilitating centralized monitoring, historical data analysis, and incident logging.

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