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Smart Helmet–Based Wearable Intelligence for Interpreting Worker Health and Safety Conditions

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Abstract
Occupational safety in industrial sectors is often compromised by hazards such as toxic gases, high temperatures, sudden falls, and unnoticed health irregularities. To address these challenges, this paper proposes SafeHelmet-AI (Smart Artificial Intelligence–enabled Helmet for Industrial Safety), a real-time multimodal monitoring framework that integrates physiological, environmental, and motion sensing. The system incorporates a MAX30100 sensor for heart rate and SpO2 measurement, a MEMS accelerometer and gyroscope for fall and movement detection, gas sensors for hazardous substance monitoring, and a temperature sensor for heat stress evaluation. A CatBoost-based machine learning model is deployed to identify abnormal condi- tions such as irregular vital signs, elevated gas concentrations, fall incidents, and excessive thermal exposure. By combining multimodal sensing, machine learning with edge-level decision- making and ThingSpeak-based cloud remote monitoring, Safe Helmet-AI enhances data privacy, reduces latency, and offers a scalable, cost-effective solution for safeguarding workers in high- risk environments. This framework demonstrates the potential of AI-powered wearables to revolutionize occupational health and safety practices.

Keywords: SafeHelmet-AI, Smart Helmet, CatBoost, Occu- pational Safety, MEMS, Industrial IoT, ThingSpeak

I. INTRODUCTION

The increasing incidence of workplace accidents in indus- trial sectors has underscored the urgent need for intelligent, real-time safety systems. Workers in hazardous environments are routinely exposed to risks such as toxic gas leaks, excessive heat, falls, and undetected health irregularities, all of which can lead to severe injuries or fatalities if not addressed promptly. SafeHelmet-AI (Smart Artificial Intelligence–enabled Hel- met for Industrial Safety) is designed to address these lim- itations by integrating multimodal sensing with intelligent decision-making for proactive worker protection. The system embeds a MAX30100 sensor to monitor heart rate and SpO_2, a MEMS accelerometer and gyroscope to capture falls and unusual motion patterns, gas sensors for hazardous substance detection, and a thermal sensor to track exposure to high temperatures. These heterogeneous signals are collected in real time, preprocessed, and transmitted to a local server for analysis. To achieve robust anomaly detection, SafeHelmet-AI lever- ages a CatBoost-based machine learning model, which classi- fies abnormal physiological and environmental patterns indica- tive of potential hazards. Unlike traditional cloud-dependent frameworks, the system operates locally, ensuring low-latency inference, improved data privacy, and reduced reliance on network bandwidth. By combining physiological, environ- mental, and motion-based indicators, the proposed frame- work offers a comprehensive approach to workplace safety monitoring. With its modular architecture and human-centric design, SafeHelmet-AI enables scalable deployment in diverse industrial environments, thereby enhancing occupational safety and reducing accident response time.

II. LITERATURE REVIEW

Previous studies on rider and worker safety have primar- ily focused on conventional helmet compliance techniques, alcohol sensing mechanisms, and simple IoT-based moni- toring frameworks [1]–[6]. Early implementations relied on infrared-based helmet detection and alcohol sensors to restrict vehicle ignition, emphasizing regulatory enforcement rather than intelligent safety management. Several IoT-based helmet prototypes integrated GSM and GPS modules to transmit acci- dent notifications, while construction-oriented helmet systems employed accelerometers and gyroscopes to detect falls and impact events [7]–[10]. Nevertheless, most of these systems were reactive in nature, relied on limited sensing modalities, and lacked intelligent data interpretation capabilities. In addi- tion, dependence on centralized cloud processing introduced communication delays, limiting their effectiveness for real- time safety interventions [11].

More recent research has explored AI-enabled smart helmet architectures that integrate environmental sensing, physio- logical monitoring, and behavioral analysis [12]–[14]. Con- temporary IoT helmet systems incorporate vibration, impact, thermal, gas, and motion sensors to enhance hazard detection in both industrial and transportation domains. Machine learn- ing and deep learning approaches have been investigated to forecast accident risks, identify abnormal user behavior, and improve safety decision-making. Furthermore, edge computing frameworks have been proposed to perform local data pro- cessing, thereby minimizing latency and improving real-time responsiveness [15].

In this context, the proposed AI-powered Smart Helmet presents a multimodal sensing architecture that fuses physio- logical signals, environmental parameters, and motion data. By integrating edge-based analytics with wireless communication, the system aims to provide early risk prediction, enforce safety compliance, and generate immediate emergency alerts. This design strengthens preventive safety mechanisms and supports intelligent supervision for both riders and industrial workers, offering a more reliable and efficient alternative to existing safety systems.

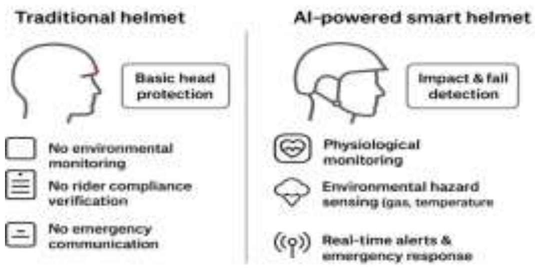

Fig. 1. Comparison of existing smart helmet and worker safety monitoring systems reported in literature.

III. Proposed System

The proposed system delivers a real-time safety monitoring and hazard detection framework by integrating multimodal sensing with AI-based analytics. The helmet incorporates sensors such as the MAX30100 (for heart rate and SpO_2), MEMS modules (accelerometer and gyroscope for fall and motion detection), gas sensors, and temperature sensors. These continuously capture physiological signals and environmental parameters during operation in hazardous sites.

The microcontroller unit collects and digitizes sensor inputs. Physiological readings are filtered to remove noise, while environmental signals are calibrated for accurate detection. Data preprocessing ensures normalization and synchronization before analysis. The CatBoost machine learning algorithm is employed to identify abnormal patterns, including toxic gas exposure, heat stress, abnormal vitals, or fall incident. Sensor data and prediction results are transmitted to the ThingSpeak cloud platform for real-time visualization and remote moni- toring.

A decision-level fusion mechanism integrates insights from multiple sensors to improve detection accuracy and reduce false positives. Critical events trigger two simultaneous re- sponses: a buzzer alert for the worker's immediate awareness and wireless notification to a supervisory web application for remote monitoring and intervention.

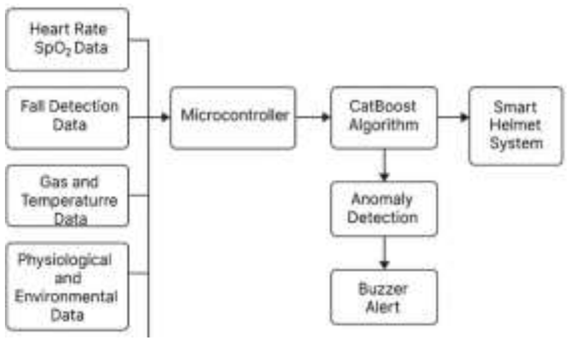

Fig. 2. Smart Helmet System: Multisensor Data Fusion and Anomaly Detection Flowchart

IV. Hardware and Software Setup

The proposed Smart Helmet system integrates multiple physiological, motion, and environmental sensors to ensure comprehensive safety monitoring. The sensing unit includes a MAX30100 sensor for measuring heart rate and blood oxygen saturation SpO_2, a MEMS-based accelerometer and gyroscope module for detecting motion patterns and fall events, gas sensors for identifying the presence of hazardous gases, and a DHT11 sensor for monitoring ambient temperature and humid- ity. These sensors collectively provide real-time insight into both worker health conditions and surrounding environmental risks.

A NodeMCU microcontroller is used as the central data acquisition and communication unit. It collects sensor read- ings, performs basic preprocessing, and transmits the data wirelessly to a remote processing system using Wi-Fi. Local alert mechanisms, including a buzzer, LED indicators, and a 16×2 LCD display, are integrated into the helmet to provide immediate warnings to the wearer when abnormal conditions are detected. This ensures that critical alerts are delivered even in the absence of network connectivity.

On the processing side, a laptop or personal computer performs multimodal data fusion, machine learning inference, and visualization tasks. The CatBoost algorithm is employed to classify sensor data into normal and abnormal safety states, enabling early detection of hazardous events such as gas exposure, heat stress, or sudden falls. The graphical user interface (GUI) provides real-time visualization of sensor readings and safety status, assisting supervisors in monitoring worker conditions remotely.

The software framework is developed using Python due to its flexibility and extensive machine learning ecosystem. NumPy and Pandas libraries are utilized for data preprocess- ing, normalization, and feature extraction, while CatBoost is used for classification due to its efficiency on structured sensor datasets. Tkinter or PyQt is employed to design the GUI for real-time monitoring and alert visualization. Communication between the helmet and the processing system is achieved through serial communication or Wi-Fi protocols, ensuring low-latency and reliable data transfer.

This integrated hardware–software architecture enables real- time safety assessment, intelligent anomaly detection, and effective visualization, making the system suitable for deploy- ment in industrial and construction environments.

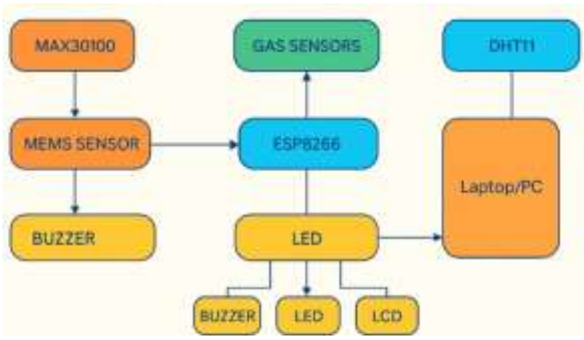

Fig. 3. Block diagram of the proposed smart helmet hardware architecture.

V. Experimental Design and Evaluation

The proposed Smart Helmet system was experimentally evaluated in controlled and semi-realistic environments to assess its sensing accuracy, communication reliability, and anomaly detection performance. The prototype integrated mul- tiple sensors, including the MAX30100 sensor for heart rate and SpO_2 measurement, MEMS-based accelerometer and gy- roscope modules for motion and fall detection, gas sensors for hazardous gas monitoring, and the DHT11 sensor for ambient temperature and humidity measurement. Sensor readings were processed by a NodeMCU microcontroller, displayed locally on a 16×2 LCD module, and transmitted wirelessly to a monitoring interface for real-time safety supervision.

To evaluate system intelligence, a CatBoost machine learn- ing model was trained using labeled datasets representing normal and abnormal safety conditions. Abnormal scenarios included simulated hazardous gas exposure, sudden falls, abnormal heart rate variations, and high-temperature stress conditions. The dataset was preprocessed to remove noise and normalize sensor values before training. The CatBoost model was selected due to its efficiency in handling structured sensor data and its robustness against overfitting.

During testing, the system successfully identified unsafe conditions with high detection accuracy and low latency. When an anomaly was detected, the system triggered immediate alerts through local indicators and remote wireless notifi- cations, enabling rapid response to potential hazards. The experimental results indicate that the proposed Smart Helmet provides a reliable proactive safety mechanism, outperforming traditional single-sensor safety systems by integrating multi- modal sensing and intelligent analytics.

Overall, the evaluation demonstrates that the AI-powered Smart Helmet is an effective solution for enhancing worker and rider safety through real-time monitoring, predictive risk assessment, and automated emergency alert generation.

VI. Results and Discussion

The integration of sensor-based health monitoring and AI- driven anomaly detection demonstrated significant improve- ments in workplace safety assessment. The performance of different sensing configurations was evaluated to analyze the impact of multimodal data fusion.

The classification accuracy achieved using only heart rate and SpO_2 sensors was 86.7%. Motion and environmental sensors alone achieved an accuracy of 84.5%. However, the proposed multimodal fusion framework achieved the highest accuracy of 93.6%, demonstrating the effectiveness of combin-ing physiological, environmental, and motion-based indicators. The combined system achieved a precision of 92.1%, recall of 93.0%, and an F1-score of 92.5%. Most misclassifications occurred under borderline conditions such as mild fatigue or early gas exposure, where sensor variations were minimal and difficult to distinguish.

The severity levels predicted by the CatBoost model closely aligned with expected physiological and environmental thresh- olds, enabling early and actionable safety decisions. The real-time graphical user interface (GUI) and web dashboard provided continuous monitoring and instant alerts, allowing supervisors to respond rapidly to emergency situations.

The experimental results confirm that the proposed smart helmet provides a robust, low-cost, and portable solution for proactive worker safety monitoring. Its layered architecture, combining on-site alerts with AI-powered remote monitoring, makes it suitable for deployment in industrial environments, construction sites, and hazardous workplaces.

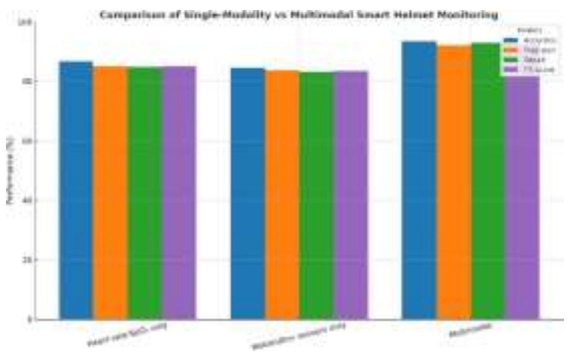

Fig. 4. Accuracy comparison of individual sensor modules and the proposed multimodal fusion model.

VII. Conclusion and Future Work

This work demonstrates the successful design and imple- mentation of an AI-powered Smart Helmet that integrates physiological, motion, and environmental sensing with ma- chine learning–based safety analytics. By combining heart rate and SpO_2 monitoring, motion and fall detection, gas sensing, and environmental condition monitoring, the system enables continuous assessment of worker safety in real time. The developed solution provides a dual-layer safety mecha- nism: immediate on-device alerts to warn the wearer during hazardous conditions and intelligent AI-driven monitoring for supervisors through a web-based interface. This layered approach enhances situational awareness and enables proactive intervention, significantly improving workplace safety man- agement.

Experimental evaluation confirmed the system's effective- ness in detecting abnormal conditions such as hazardous gas exposure, sudden falls, and thermal stress. The CatBoost- based anomaly detection model achieved reliable performance on multimodal sensor data, demonstrating the feasibility of integrating lightweight machine learning models in embedded safety systems. Additionally, the prototype was found to be portable, energy-efficient, and cost-effective, making it suitable for deployment in construction sites, industrial plants, mining operations, and other high-risk environments.

For future work, several enhancements can be explored to further improve the system's functionality and scalability. Cloud-based analytics can be integrated to enable large-scale data aggregation, long-term trend analysis, and centralized safety dashboards for enterprise-level monitoring. Edge AI techniques can be incorporated to perform faster on-device inference with reduced latency and minimal dependence on network connectivity. The sensing framework can be extended to include advanced fatigue and cognitive state monitoring using EEG sensors, eye-tracking modules, or facial analysis to detect drowsiness and reduced alertness.

Furthermore, large-scale field trials across diverse indus- trial environments should be conducted to evaluate system robustness under real-world conditions such as dust, vibration, and extreme temperatures. Future studies can also explore adaptive learning models that personalize safety thresholds based on individual worker profiles. These enhancements will contribute to building a comprehensive intelligent personal protective equipment (PPE) platform that ensures enhanced safety, reliability, and compliance in industrial workplaces.

REFERENCES

1. V. Maheshwari, T. Khandelwal, D. Gulati *et al.*, "Smart Helmet: A Com- prehensive Solution for Rider Safety," in *Proc. 3rd Int. Conf. Disruptive Technologies (ICDT)*, 2025, doi: 10.1109/ICDT63985.2025.10986370.
2. S. Akter, M. A. Yousuf, and K. M. R. Alam *et al.*, "A Cost-Effective Smart Helmet for Human Safety and Road Ac- cident Detection Using IoT," in *Proc. ICRPSET*, 2024, doi: 10.1109/ICRPSET64863.2024.10955923.
3. S. Somantri and I. Yustiana, "Smart Helmet Integrated with Motorcycles to Support Rider Awareness and Safety Based on IoT," in *Proc. ICISS*, 2022, doi: 10.1109/ICISS55894.2022.9915262.
4. M. S. Muneshwara, A. R., and T. Shivakumara *et al.*, "Advanced Wireless Techniques to Avoid Accidents Through Smart Helmet," in *Proc. ICICCS*, 2021, doi: 10.1109/ICICCS51141.2021.9432193.
5. V. T. Vaishnavi, G. Kumaravel, and G. Vijaya *et al.*, "SAFE-Net: Secure AI-Driven Forecasting Network for Smart Helmet Systems," in *Proc. RAEEUCCI*, 2025, doi: 10.1109/RAEEUCCI63961.2025.11048317.
6. N. Divyasudha, P. Arulmozhivarman, and E. R. Rajkumar, "Designing an IoT-Based Smart Helmet: A Cost-Effective Solution," in *Proc. ICIICT*, 2019, doi: 10.1109/ICIICT1.2019.8741415.
7. K. Venkatesh, J. Harshitha, and S. K. P *et al.*, "Enhancing Human Safety Through IoT-Integrated Smart Helmet Technology," in *Proc. ICOECA*, 2024, doi: 10.1109/ICOECA62351.2024.00097.
8. M. Ahmed, H. Al-Korki, and D. Al-Hazza *et al.*, "The Smart Hel- met System Towards Safer

Construction Work Sites," in *Proc. IEEE MECOM*, 2024, doi: 10.1109/MECOM61498.2024.10881715.
9. V. Hema, A. Sangeetha, and S. Navya *et al.*, "Smart Helmet and Accident Identification System," in *Proc. ASSIC*, 2022, doi: 10.1109/AS- SIC55218.2022.10088324.
10. V. Jayasree and M. N. Kumari, "IoT Based Smart Helmet for Construction Workers," in *Proc. ICSSS*, 2020, doi: 10.1109/IC- SSS49621.2020.9202138.
11. E. A. Merchan-Cruz *et al.*, "Smart Safety Helmets with Integrated Vision Systems," *Sensors*, 2025.
12. C. Pearkao *et al.*, "Development of an AI-Integrated Smart Helmet for Accident Prevention," *J. Multidisciplinary Healthcare*, 2025.
13. R. Patra, A. Roy, and P. Sen, "IoT-Enabled Smart Helmet for Accident Detection," in *Proc. IEEE ICCSP*, 2022.
14. "Trends in Smart Helmets With Multimodal Sensing for Health and Safety," *JMIR mHealth and uHealth*, 2022.
15. R. J. Patel, K. Bhalodia, and A. Shah, "Development of IoT-Based Smart Helmet Using Arduino," in *AIP Conf. Proc.*, vol. 2311, 2021.