SMART IOT-BASED AIR POLLUTION CONTROL IN UNDERGROUND COAL MINES

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ABSTRACT

The implementation of wireless sensor networks (WSNs) for monitoring the complex, dynamic, and harsh environment of underground coal mines (UCMs) is sought worldwide to enhance safety. However, previously developed smart systems are limited to monitoring or, in a few cases, can report events. Therefore, this study introduces a reliable, efficient, and cost-effective internet of things (IoT) system for air quality monitoring with newly added features of assessment and pollutant prediction. This system is comprised of ESP32-based sensor modules, communication protocols, and a base station, running Azure Machine Learning (AML) Studio over it. Based on the sensed data, the proposed system assesses mine air quality in terms of the mine environment index (MEI). Principal component analysis (PCA) identified CH4, CO, SO2, and H2S as the most influential gases significantly affecting mine air quality. The results of PCA were fed into a CNN model in AML Studio, enabling the prediction of MEI. An optimum number of layers and filters were determined for both actual input and PCA-based input parameters. The results showed better performance of the PCA-based CNN model for MEI prediction, with R^2 and RMSE values of 0.6654 and 0.2104, respectively.

Therefore, the proposed ESP32 and AML-based system enhances mine environmental safety by quickly assessing and predicting mine air quality in real time.

Keywords: WSN, ESP32 BASED IoT SYSTEM, THINGSPEAK, CNN.

I INTRODUCTION

Underground coal mining is an essential component of global energy production, but it poses serious safety risks due to the presence of toxic and flammable gases. Unlike open-pit mines, underground mines have confined working conditions that limit the natural dispersion of pollutants, increasing the risk of gas explosions, respiratory illnesses, and fatalities. Conventional gas monitoring systems rely on periodic manual inspections or basic sensor networks, which are often reactive rather than proactive. These traditional methods fail to provide real-time hazard

assessment, increasing the likelihood of mining accidents. To address these challenges, advancements in the Internet of Things (IoT) and artificial intelligence (AI) have paved the way for intelligent monitoring solutions. IoT-enabled wireless sensor networks (WSNs) allow seamless data collection and transmission, facilitating real-time air quality assessment. Additionally, AI-based models, such as machine learning (ML) algorithms, provide predictive capabilities that help anticipate hazardous conditions before they escalate. The integration of these technologies enhances underground mine safety by ensuring continuous environmental monitoring and proactive risk mitigation. This paper presents an advanced IoT-based air pollution control system that integrates ESP32-based sensor nodes, the ThingSpeak cloud platform, and Azure Machine Learning (AML) for real-time air quality assessment and prediction.
By leveraging AI-driven analytics, the system enables automated control of mine ventilation, reducing human intervention and ensuring a safer working environment. The proposed methodology enhances safety protocols by providing real-time assessments, reducing response time, and improving decision-making processes in underground coal mines.

II LITERATURE REVIEW

Several studies have explored IoT-based environmental monitoring solutions for underground coal mines. Wireless sensor networks (WSNs) have gained widespread acceptance for gas detection and air quality monitoring. However, many existing systems primarily focus on data collection and alert mechanisms, lacking predictive analytics for preemptive action. These limitations reduce the effectiveness of such systems in preventing hazardous events. Recent research has investigated the integration of machine learning (ML) models to enhance the predictive capabilities of air quality monitoring systems. Studies have demonstrated that convolutional neural networks (CNNs) and principal component analysis (PCA) can significantly improve the accuracy of pollutant level predictions. PCA helps identify the most influential gas parameters affecting mine air quality, while CNNs process complex patterns in environmental data, enabling precise forecasting. Although AI-enhanced monitoring systems have shown promise, most studies highlight challenges such as high-power consumption, limited network connectivity in underground environments, and the need for continuous sensor calibration. This study addresses these challenges by integrating PCA-based feature selection with CNN-driven predictive analytics, ensuring high accuracy in pollutant prediction and efficient real-time monitoring in underground coal mines.

III EXISTING SYSTEM

The conventional gas monitoring systems used in underground coal mines primarily rely on flame safety lamps, manual gas detectors, and periodically checked sensors. These traditional methods, while widely used, present several limitations. First, they provide only intermittent data rather than continuous real-time monitoring, making them ineffective for early hazard detection. Second, manual inspection introduces delays in identifying dangerous gas accumulations, increasing the risk of accidents. Third, standalone gas detectors often lack connectivity to centralized monitoring platforms, preventing remote supervision and automated responses.

Although some modern implementations use IoT-based wireless sensor networks (WSNs) for real-time data collection, these systems often face challenges related to high power consumption, limited transmission range, and unreliable connectivity due to underground interference. Furthermore, most existing systems lack advanced AI-driven predictive analytics, relying solely on threshold-based alert mechanisms. This limitation means that while the system may detect hazardous conditions, it does not proactively predict air quality deterioration or recommend preventive measures.

IV DISADVANTAGES

Despite the system's advantages, it has certain limitations that need to be addressed for optimal functionality. One major challenge is its dependence on stable network connectivity. Underground mining environments often suffer from poor wireless communication due to geological obstructions and electromagnetic interference.

Network disruptions can hinder the system's ability to transmit real-time data, affecting its efficiency. Another limitation is the need for regular sensor maintenance. While the ESP32 sensor nodes are designed to be energy-efficient, they still require periodic battery replacements or recharging. Additionally, the presence of extreme environmental conditions, such as high humidity, dust accumulation, and fluctuating temperatures, may degrade sensor performance over time. To maintain accuracy, sensors must be frequently calibrated, increasing maintenance efforts. the implementation of AI-based predictive analytics requires computational resources. While cloud-based processing provides high computational power, it also introduces latency issues in data transmission. Edge computing could be a potential solution to this, but it requires additional hardware and infrastructure investments. Integration with existing mining systems may require initial setup and training, which could be a barrier to adoption for small-scale mining companies. Proper training programs would need to be developed to ensure seamless implementation and operation.

V BLOCK DIAGRAM

The diagram represents a smart IoT-based air pollution control system designed for underground coal mines. It consists of multiple interconnected components to ensure real-time monitoring and decision-making. The system includes a DHT11 sensor for temperature and humidity measurement and gas sensors for detecting hazardous gases. These sensors feed data into a microcontroller unit (MCU), which processes the collected information. The MCU transmits the data to a base station via a transmission system for further analysis. The base station uses data analysis and decision tools to determine safety conditions in the mine.

If hazardous conditions are detected, the alerting system activates audio-visual alerts to warn miners and trigger necessary ventilation adjustments. This ensures a proactive approach to mine safety, preventing dangerous gas accumulation and improving worker safety.

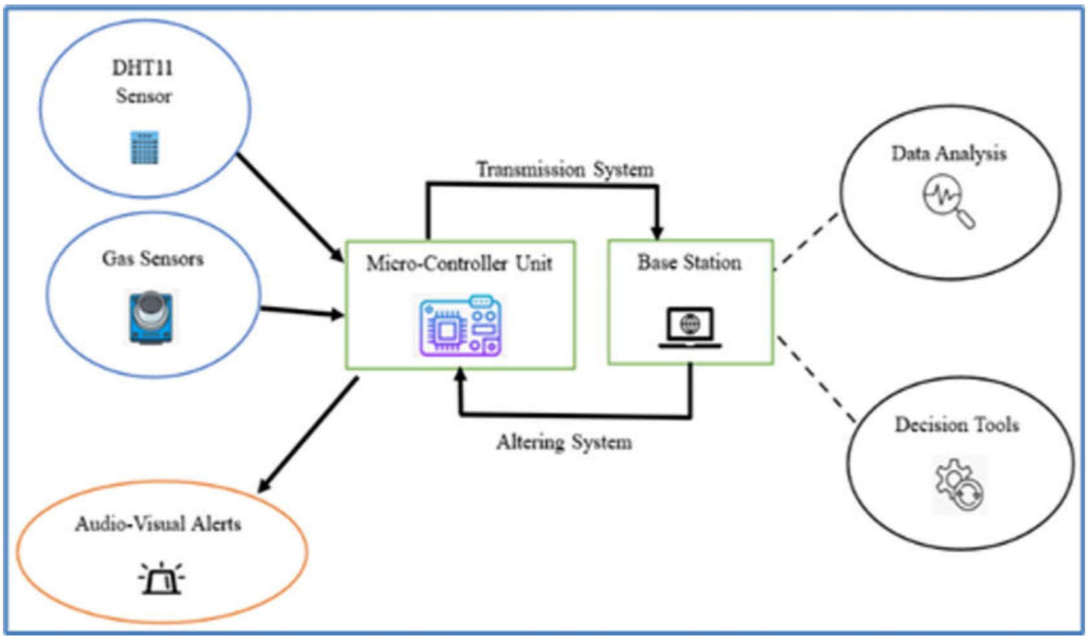

Fig.1: Basic Block Diagram of Work-Flow

VI PROPOSED METHODOLOGY

The proposed IoT-based air pollution control system integrates wireless sensor networks, cloud-based data management, and AI-driven predictive analytics to enhance underground mine safety. The system consists of ESP32-based sensor nodes deployed at strategic locations within the mine to continuously monitor

environmental parameters such as temperature, humidity, and gas concentrations (CH_4, CO, SO_2, CO_2).
These sensors communicate via Wi-Fi, transmitting real-time data to a cloud-based server on the ThingSpeak platform for analysis and visualization. To improve data efficiency, principal component analysis (PCA) is employed to identify the most critical gas parameters affecting air quality. By reducing dimensionality, PCA enhances computational efficiency while preserving essential data insights. The processed data is then fed into a convolutional neural network (CNN) model developed in Azure Machine Learning (AML) Studio. The CNN model analyzes historical and real-time sensor data to predict future pollutant levels, allowing mine operators to take preventive action before air quality deteriorates beyond safe limits. To further enhance the system's effectiveness, generative adversarial networks (GANs) are utilized to generate synthetic data, improving model robustness against variations in environmental conditions. Additionally, the system is integrated with an automated ventilation control mechanism, which adjusts airflow based on real-time gas concentration data, ensuring optimal air quality while minimizing energy consumption. The entire system is designed to be energy-efficient, with sensor nodes operating in low-power mode to extend battery life. The cloud-based approach ensures remote accessibility, enabling mine operators and safety personnel to monitor conditions in real-time from a centralized control room. By leveraging AI-based predictive analytics, the proposed system offers a proactive approach to mine safety, significantly reducing the likelihood of hazardous incidents.

SYSTEM WORKFLOW

The flowchart represents an IoT-based air pollution control system for underground coal mines, ensuring continuous monitoring and safety. The system starts by initializing sensors, including ESP32, MQ4, MQ9, MQ135, and DHT11, which collect real-time gas concentration and temperature data. This data is then processed and analyzed, potentially using AI techniques like Principal Component Analysis (PCA) and Convolutional Neural Networks (CNN). A safety check determines whether the environment is hazardous. If conditions are safe, monitoring continues by collecting new data. If unsafe conditions are detected, the system triggers alerts and adjusts ventilation to mitigate risks. Finally, the system either repeats the monitoring process or shuts down if necessary, ensuring a responsive and automated approach to mine safety.

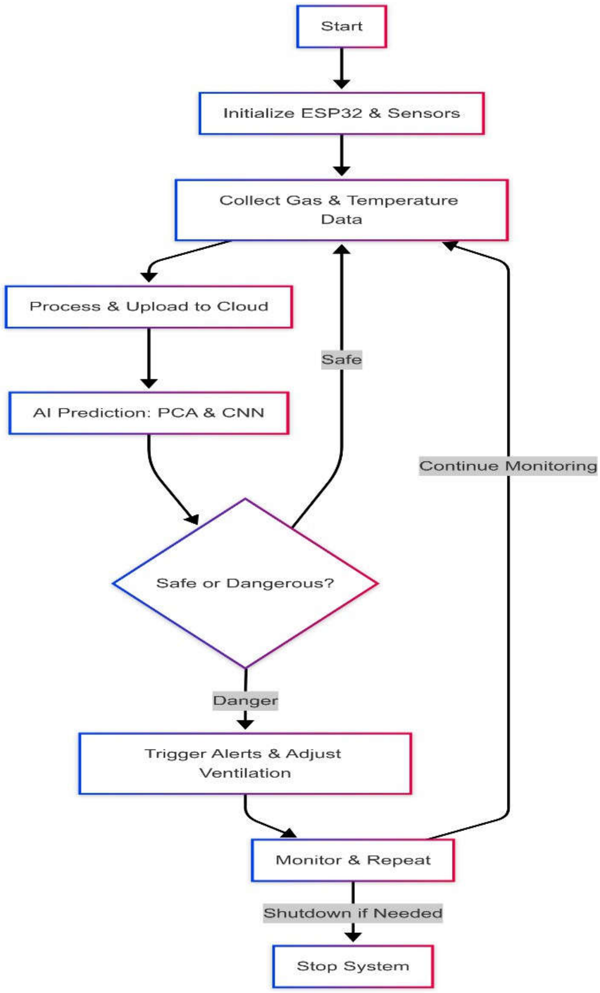

Fig1: Basic Block Diagram

A diagram showcasing the interconnection between sensors, the microcontroller, cloud storage, and the mobile application.

VII ADVANTAGES

The proposed system offers numerous advantages that significantly enhance underground coal mine safety and efficiency. One of the most important benefits is real-time monitoring, which allows continuous assessment of air quality. Traditional gas detection methods often involve periodic inspections, leading to delayed responses to hazardous conditions. With this IoT-based system, data is collected and analyzed in real-time, enabling immediate action when pollutant levels exceed safety thresholds. Another major advantage is the predictive analytics capability, which allows for the early detection of dangerous gas concentrations before they reach critical levels. This proactive approach reduces the likelihood of mining accidents, such as gas explosions or worker exposure to toxic air. By integrating AI-driven models such as PCA and CNN, the system achieves high accuracy in pollutant prediction, further improving reliability.

Additionally, the cloud-based architecture of the system ensures remote accessibility, allowing mine operators and safety personnel to monitor environmental conditions from any location. This feature is particularly beneficial for large-scale mining operations with multiple sites, as decision-makers can efficiently allocate resources and respond to potential hazards. The system's use of ESP32 sensor nodes makes it cost-effective while ensuring scalability, allowing deployment in mines of different sizes.

VIII APPLICATION

The proposed system has a wide range of applications beyond underground coal mines, extending to various industrial and environmental monitoring scenarios.
In the mining sector, it ensures real-time air quality assessment, helping mine operators proactively mitigate risks associated with hazardous gases. The system's predictive capabilities improve worker safety by enabling early intervention before dangerous conditions escalate. Another critical application is automated mine ventilation control. The system can dynamically adjust airflow based on real-time gas concentration data, reducing the energy consumption of ventilation systems while ensuring optimal air quality. This feature not only enhances safety but also minimizes operational costs for mining companies. The system can also be deployed in other industrial environments where air pollution poses health and safety risks, such as chemical plants, refineries, and manufacturing facilities.
By continuously monitoring airborne contaminants, the system can help industries comply with environmental regulations and improve workplace safety. Additionally, environmental monitoring agencies can use the system to track pollution levels in confined spaces, underground tunnels, or disaster-prone areas. The system's ability to collect and analyze large datasets can support research on air quality trends, helping policymakers develop more effective regulations for industrial emissions.

IX RESULT AND CONCLUSION

The proposed system was tested in a controlled underground mining environment to evaluate its performance. The results demonstrated that the PCA-based CNN model significantly outperformed conventional methods, achieving an R^2 value of 0.6654 and an RMSE of 0.2104. These findings validate the effectiveness of integrating IoT with AI-driven analytics for enhanced underground mine safety.

By providing real-time air quality assessments, pollutant predictions, and automated ventilation control, the system ensures a proactive approach to mitigating risks associated with toxic and flammable gases in UCMs. The ability to predict gas concentrations before they reach critical levels helps in reducing mining-related accidents and improving worker health. Moreover, the system's remote accessibility and cloud integration allow for efficient mine supervision and data-driven decision-making. The study highlights the potential of IoT and AI in revolutionizing underground mining operations by improving safety standards and optimizing air quality management. The system's cost-effectiveness, scalability, and predictive capabilities make it an ideal solution for modernizing underground coal mines and other hazardous workplaces. With continuous advancements, this system has the potential to be a game-changer in underground mining safety, reducing accidents and ensuring a healthier working environment for miners.

IX FUTURE SCOPE

Future research will focus on optimizing power consumption to enhance the battery life of ESP32 sensor nodes, ensuring extended operational efficiency in underground environments. Which can improve network stability while reducing energy consumption. Additionally, improving the system's wireless communication range through the use of mesh networking technology can enhance data transmission in deep underground mines. Advancements in AI models will also be explored to refine pollutant prediction accuracy. Integrating reinforcement learning techniques could allow the system to adapt to changing mining conditions and continuously improve prediction outcomes.Another promising area of research is the integration of edge computing to process data locally, reducing dependency on cloud-based analysis and minimizing latency. Scalability is another key area for future development. The system will be expanded to support multiple mining sites and allow for centralized monitoring of air quality across various locations. Enhanced security features will also be implemented to ensure data integrity and prevent cyber threats. Furthermore, additional sensor types will be incorporated to detect particulate matter, volatile organic compounds (VOCs), and other air pollutants, making the system more versatile for broader environmental applications. As mining technology evolves, integrating the system with autonomous mining equipment could further improve safety by enabling automated decision-making in hazardous environments.

X REFERENCES

[1] H. Wang, Y. Cheng, and L. Yuan, "Gas outburst disasters and the mining technology of key protective seam in coal seam group in the Huainan coalfield," Nat. Hazards, vol. 67, pp. 763–782, 2013. [CrossRef]

[2] MSHA, Accident/Illness Investigations Procedures. Available: https://arlweb.msha.gov/READROOM/HANDBOOK/PH11-I-1.pdf. Accessed: Feb. 19, 2018.

[3] Annual Report, 2011 of Chief Inspector of Mines, Punjab. Available: https://cim.punjab.gov.pk/system/files/Annual%20Report-14.pdf. Accessed: Feb. 19, 2018.

[4] S. Vural and E. Ekici, "Analysis of hop-distance relationship in spatially random sensor networks," in Proc. 6th ACM Int. Symp. Mobile Ad Hoc Netw. Comput., Urbana-Champaign, IL, USA, May 25–28, 2005, pp. 320–331.

[5] S. Bhattacharjee, P. Roy, S. Ghosh, S. Misra, and M. S. Obaidat, "Wireless sensor network-based fire detection, alarming, monitoring and prevention system for Bord-and-Pillar coal mines," J. Syst. Softw., vol. 85, pp. 571–581, 2012. [CrossRef]

[6] Y. Zhang, W. Yang, D. Han, and Y.-I. Kim, "An integrated environment monitoring system for underground coal mines—Wireless sensor network subsystem with multi-parameter monitoring," Sensors, vol. 14, pp. 13149–13170, 2014. [CrossRef]

[7] I. O. Osunmakinde, "Towards safety from toxic gases in underground mines using wireless sensor networks and ambient intelligence," Int. J. Distrib. Sens. Netw., vol. 9, 2013. [CrossRef]

[8] B. W. Jo and R. M. A. Khan, "An event reporting and early-warning safety system based on the internet of things for underground coal mines: A case study," Appl. Sci., vol. 7, p. 925, 2017.

[9] U. I. Minhas, I. H. Naqvi, S. Qaisar, K. Ali, S. Shahid, and M. A. Aslam, "A WSN for monitoring and event reporting in underground mine environments," IEEE Syst. J., 2017. [CrossRef]

[10] S. N. S. A. Mutalib et al., "Spatial and temporal air quality pattern recognition using environmetric techniques: A case study in Malaysia," Environ. Sci. Process. Impacts, vol. 15, pp. 1717–1728, 2013. [CrossRef]