Enhancing Workers' Safety and Well-Being in Hazardous Environments: An IoT-Based Approach

Anushka Bukkawar, Chandrashish Kukrety, Bhawesh Mishra, and Biswajit Dwivedy

Abstract This study introduces a comprehensive end-to-end solution, combining hardware and software, for the collection and analysis of critical data in mining environments. It employs an Arduino-based safety helmet to gather environmental data within mines and subsequently conducts data clustering. The analysis of data from a Polish mine, as a proof of concept, reveals significant findings. It shows that miners were consistently exposed to high-temperature environments for 24.46% of their work hours, high humidity conditions for 23.39%, and elevated methane concentrations for 25.34% of the time. As a result, extended exposure to temperatures above ambient mean values corresponds to a 12% increase in heat-related illnesses, while high humidity environments lead to a 7% rise in workplace injuries. Environments with a high methane concentration was linked to an increased susceptibility to cardiovascular diseases. These insights highlight the potential for real-time monitoring and hazard mitigation, offering substantial benefits to both miners and employers.

Keywords K-means clustering · Data analytics · IoT (Internet of Things)

1 Introduction

The well-being and safety of mine workers have long been subjects of concern, given the inherently challenging and hazardous conditions they face within the mining environment [1]. In recent years, the rapid advancement of the Internet of Things (IoT) technology has introduced transformative possibilities for enhancing the safety and well-being of mine workers. By integrating IoT devices and sensors into mining operations, real-time monitoring of crucial parameters has become feasible, thereby

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enabling timely responses to potential hazards. Following this, a helmet was designed consisting of temperature and humidity sensors to take real-time readings from the mine [2]. Another such helmet was proposed which employed ATmega328 microcontroller, collision sensor, MQ5 gas sensor, humidity sensor, and RF transmitter [3]. After identifying already existing hardware, some research articles have also been identified that helped to understand the effect of increasing temperature in several workplaces around the world. A study aimed to explore the link between outdoor temperatures in summer and job-based heat-related illnesses was conducted in Quebec, Canada. Compelling statistics analyzing reported heat-related illnesses revealed that a 1-degree Celsius temperature increase correlated with a substantial 12% rise in heat-related illnesses among workers. Remarkably, risk surged at specific thresholds, escalating by 25% at 30 degrees Celsius and a notable 45% beyond 35 degrees Celsius [4]. Another research investigates the association between very high heat and direct heat-related illnesses in Ningbo, China. Using data from the Chinese Center for Disease Control and Prevention's national heat-related illness surveillance system, the research analyzed daily heat-related cases. Both mild and severe cases surge during extreme temperature periods, especially affecting the elderly due to illness severity and age [5]. In another research, using a case-crossover design, injury cases were reviewed, coupled with meteorological data analysis for ambient temperature and humidity from local weather stations. The study underscored that temperatures above 32 degrees Celsius correlated with a 2.5-fold higher risk, with a 30% increase during afternoon hours. Task-specific risks, like manual labor under direct sunlight, were also identified [6]. A research conducted by Miriam Levi et al. employed three targeted search strategies in PubMed, focusing on heat-related illness and other conditions. SCOPUS and EMBASE were also utilized, applying specific inclusion and exclusion criteria. Among these, six out of eleven articles discussed that an upsurge in chronic kidney disease has been observed since the early 2000s [7]. Another research employed workers' compensation claims to examine injuries related to workplace in Guangzhou, China (2011–2012) during warmer seasons (May–October). Using a time-stratified case-crossover design, conditional Poisson regression models were employed. Both minimum and maximum temperatures exhibited significant associations with work-related injuries in the claims. A 1 °C rise in maximum temperature corresponded to a 1.4% increase in daily injury claims [8]. In another study, they performed a systematic review and meta-analysis adhering to PRISMA guidelines and evaluated occupational heat strain's impact on worker health and productivity. This involved comparing heat strain occurrences during work shifts under heat stress conditions (WBGT, 26·2–26·4 °C; air temperature, 37·3–150·0 °C) with thermoneutral conditions. Workers under heat stress conditions faced a fourfold higher likelihood of experiencing occupational heat strain at the shift's end compared to those in thermoneutral conditions. Notably, a 14.5% increase in urine specific gravity was observed [9]. The research examined humidex's impact on injuries in Washington State Fund outdoor construction workers. Maximum daily humidex's connection to injuries was assessed through logistic regression. 63,720 eligible traumatic injury claims were identified. Traumatic injury odds were 1.005 (95% CI 1.003–1.007) per one °C humidex change [10]. Another study harnessed data from the Korean National Health Insurance Service (KNHIS) database and the National Statistical Office to investigate the impact of heat exposure on worker health in Korea. They employed generalized additive models (GAM) and distributed lag nonlinear models. Elevated MaxT correlated with higher overall and outdoor death risks. Medical facility visits increased for infectious and parasitic diseases, cardio and cerebrovascular diseases, genitourinary system diseases, injury-related cases, and the effects of heat and light for each 1 °C MaxT increase [11]. High methane concentration environments were also linked to increased risks of cardiovascular diseases [12]. The reviewed studies collectively explore the relationship between heat exposure and health outcomes in various occupational settings. The research emphasizes a consistent association between increased temperatures and higher risks of heat-related illnesses and injuries among workers. Notably, vulnerability varies across demographic groups with certain sectors being particularly affected. Research reviewed existing literature regarding heat-related workplace injuries. It high-lighted the urgency of addressing heat-related occupational health challenges, given the expected rise in temperatures and extreme events. Effective strategies should be enforced. Collaboration across disciplines and inclusive participation is crucial, requiring approaches led by occupational health experts [13].

The mining industry, a pivotal component of global economies, has historically been recognized as a hazardous occupation. Despite its longstanding status as a major heavy industry, it continues to pose significant risks to workers, as highlighted by the International Labor Organization (ILO). This study utilizes extensive medical datasets and records from analogous operations to identify emerging illnesses attributed to prolonged exposure to harsh working conditions. The predominant etiological factor for the majority of these maladies is identified as inadequate working conditions. The research proposes a potential methodology aimed at early detection and prediction of diseases through the systematic monitoring of workers' working conditions. This proactive approach seeks to empower workers with awareness regarding their occupational environment, thereby facilitating the prevention of these ailments. A comprehensive inference from various literature is shown in Table 1.

Table 1 Relationship between increase in physical parameters and diseases

Ref.no	Parameter	Risk
[4]	1°C increase in average temperature and average temperature over 35°C	12% increased risk of heat related illness and 45% increased risk of heat-related illness, respectively
[7]	1°C increase in daily minimum temperaTure	1% increase in odds of injury
[9]	Long work duration in heat stress conditions	4 times more likely to suffer from occupational heat strain
[11]	1°C Rise in average temperature	Increased cases of cardio and cerebrovascular diseases

2 Design and Implementation

This research endeavors to address the multifarious safety concerns prevalent in mining operations by proposing the development and implementation of an advanced safety helmet. This innovative helmet is equipped with an array of sensors, including an Orientation and Acceleration Sensor, a methane gas sensor, a temperature and humidity sensor, and a GPS module. The hardware underpinning this safety helmet is founded upon the robust Arduino Uno microcontroller, establishing itself as the central processing unit responsible for aggregating data from the array of sensors. The primary objective of the helmet revolves around the real-time acquisition and transmission of critical data to facilitate the prompt detection of potential hazards, thereby enabling timely intervention when necessary. Furthermore, the data collected by this device serves the dual purpose of generating personalized datasets for individual miners, thus maintaining an accurate medical history documenting their exposure to environmental conditions.

Subsequently, this amalgamated data is seamlessly transmitted to a cloud-based service, where it finds its repository for visualization and rigorous data processing. For this project, an IoT platform called KaaIoT was used to store the data collected by the helmet. However, implementations with local storage servers to maintain the privacy of the workers can be easily arranged. The block diagram for the system can be seen in Fig. 1. Within the cloud environment, the data undergoes visualization processes facilitated by a dedicated dashboard service. This, in turn, empowers mine supervisors and safety personnel to closely monitor the real-time activities of miners within the subterranean confines, thereby enabling swift intervention in the event of any detected anomalies. The data transmitted to the cloud is then analyzed to infer its effect on the health of the miners.

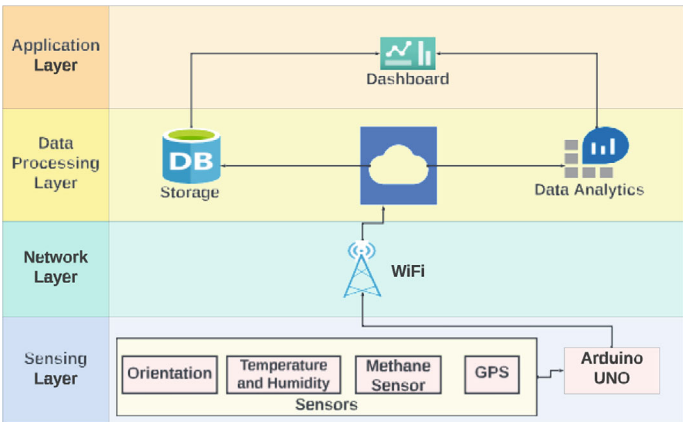

Fig. 1 Block diagram of the proposed safety helmet system for miners

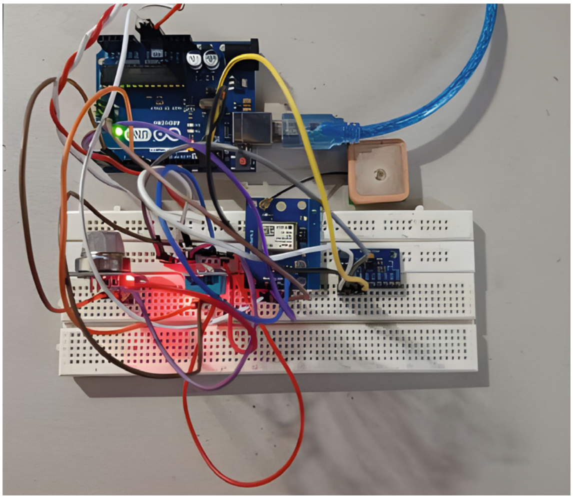

Fig. 2 Prototype circuit of the proposed helmet system

The designed helmet is not used to generate a dataset. Even though the circuit of the helmet has been tested in real time, the entire system has yet to be tested in a mining application. All the components used in the circuit have a standard operating range from –40 °C to 75 °C, which makes them to be used in mining conditions. Rather, a similar dataset from a mine in Poland was utilized to be used for the deployment of the clustering algorithm-based analysis. The dataset features readings that were recorded at a frequency of 1 Hz over a period spanning 107 days. The focus within this dataset was directed toward a select subset of readings obtained from a single temperature sensor named TP1721, one humidity sensor named RH1712, and a methane sensor named MM261.

The daily data is subjected to the K-means clustering algorithm. The optimum number of clusters is calculated using the Gap-Statistic method where the within-cluster variation of the data is compared for different values of k (the number of clusters) with the expected variation under a null reference distribution. The optimal number of clusters is typically the one where the gap statistic is maximized.

Post-clustering, clusters were discerned based on their respective centroid values. The first and third quartile values for each of the three centroid fields namely humidity, temperature, and methane concentration were calculated. Subsequently, centroids were assigned categorical labels, namely "High," "Medium," or "Low," contingent upon their positioning relative to the third quartile value, within the inter-quartile range, or below the first quartile value, respectively.

The categorized clusters visualized in Figs. 3, 4, and 5 were subsequently prepared for utilization in the identification and correlation with diseases. This application entails the use of pre-existing datasets, as well as the potential inclusion of novel datasets intended for classifying diseases arising from prolonged exposure to specific environmental conditions.

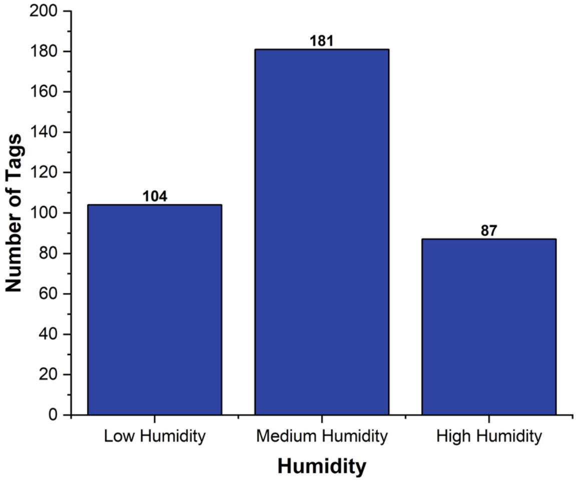

Fig. 3 Histogram plot of density of classification tag versus humidity data

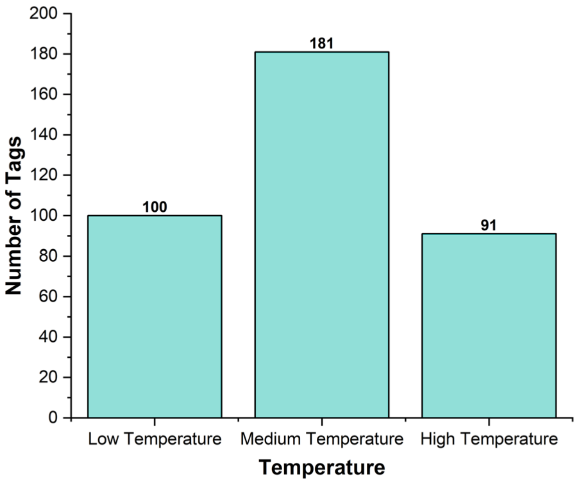

Fig. 4 Histogram plot of density of classification tag versus temperature data

Significantly, the findings uncovered a substantial increase in the risk of various disease manifestations as a consequence of prolonged exposure to elevated temperatures and heightened humidity levels.

3 Dataset Description

The dataset under scrutiny originates from an underground coal mine in Poland, spanning a period between March 2, 2014 and June 16, 2014, and comprising a substantial 9,199,930 data examples [14]. Each example is characterized by a timestamp,

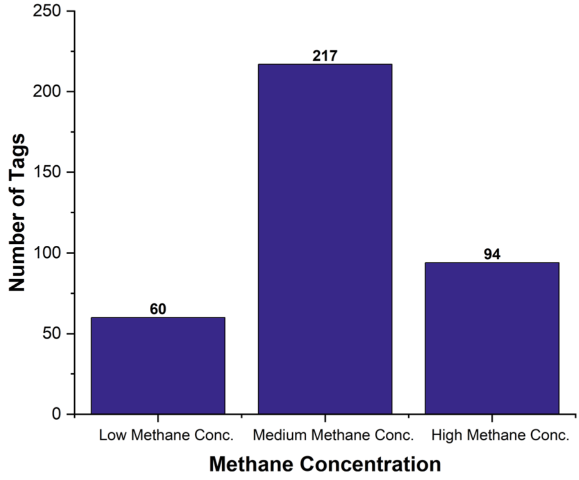

Fig. 5 Histogram plot of density of classification tag versus methane concentration data

Table 2 Sensors used for data analytics

Sensor name	Parameter	Minimum	Maximum
TP1721	Temperature	0 °C	27.9 °C
RH1712	Relative humidity	0%	86%
MM261	Methane concentration	0%	30%

consisting of six attributes (year, month, day, hour, minute, second), and measurements acquired from 28 distinct sensors. This data is meticulously sampled at one-second intervals and is presented in a CSV format. Three out of the 28 sensors have been selected to perform data analytical operations. The mentioned sensors are shown in Table 2. Standardization procedures were applied to ensure all measurements corresponded to one-second intervals, with missing cutter loader values replaced by "0" to signify no work, and missing sensor values substituted with the last known value. Importantly, there are no missing values in the continuous operation of the methane systems, reflecting the critical nature of maintaining uninterrupted data streams for safety and monitoring in underground coal mines.

4 Results and Discussion

The analysis of the clustered dataset has revealed several important findings. A sample plot depicting the clusters formed on 2014/04/01 is shown in Fig. 6. Similar clustering was performed on daily datasets, leading to multiple significant insights. A partial representation of the clustered dataset and its corresponding classification is displayed in Fig. 7. After the classification, it became evident that the mine

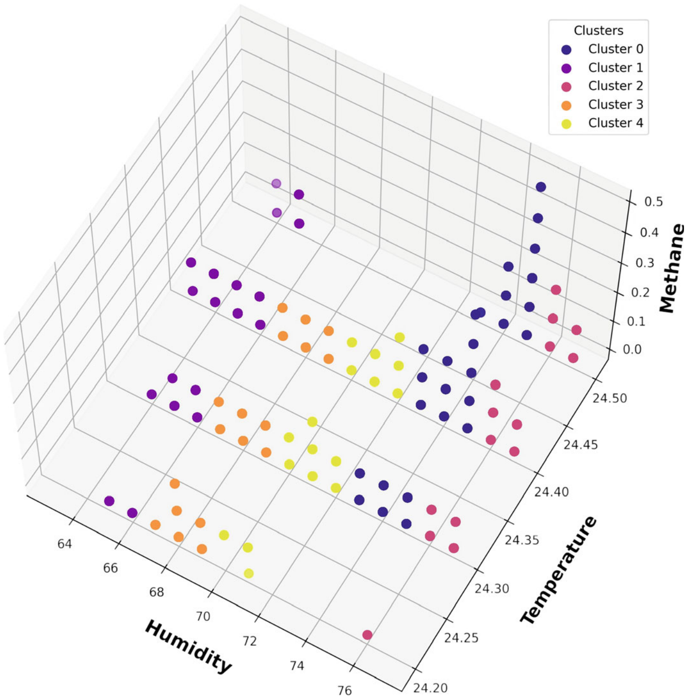

Fig. 6 Visualization of clusters for a typical day (2014/04/01)

workers were exposed to high environmental factors for substantial durations. Specifically, they experienced high temperatures for 24.46% of their working time, high humidity for 23.39%, and elevated methane concentrations for 25.34% of their work hours. These findings strongly indicate that the workforce consistently encountered environmental conditions significantly above the average ambient values for these parameters.

It is worth noting that in the context of Canadian laborers, a 1 °C increase in ambient temperatures is associated with a statistically significant 12% rise in the incidence of heat-related illnesses among workers. Elevated humidity levels are linked to a 7% increase in the risk of workplace injuries. Furthermore, exposure to high methane concentrations has been associated with an increased risk of cardiovascular diseases. Therefore, it can be inferred that the workers in this Polish mine were subjected to working conditions that have been associated with various health-related issues and risks. This information underscores the need for further investigation and potential intervention to ensure the safety and well-being of these workers. It is expected that with further analysis of the health data of the workers, the damage caused to the workers due to the working conditions can be reduced by taking measures to prevent exposure to harsh conditions.

Date	1T	1H	1M	Temperature Tag	Humidity Tag	Methane Concentration Tag
2 March	24.59	52.00	0.10	Low Temperature	Low Humidity	High MC
3 March	24.44	67.23	0.00	Low Temperature	Medium Humidity	Medium MC
4 March	24.34	63.00	0.00	Low Temperature	Low Humidity	Medium MC
5 March	24.47	59.90	0.00	Low Temperature	Low Humidity	Medium MC
6 March	24.50	65.07	0.00	Low Temperature	Medium Humidity	Medium MC
7 March	24.36	66.42	0.00	Low Temperature	Medium Humidity	Medium MC
8 March	24.18	60.17	0.00	Low Temperature	Low Humidity	Medium MC
9 March	24.11	56.00	0.00	Low Temperature	Low Humidity	Medium MC
10 March	24.01	52.73	0.00	Low Temperature	Low Humidity	Medium MC
11 March	24.10	71.29	0.00	Low Temperature	Medium Humidity	Medium MC
12 March	24.31	72.64	0.00	Low Temperature	Medium Humidity	Medium MC
13 March	24.22	58.79	0.02	Low Temperature	Low Humidity	Medium MC
14 March	24.23	54.58	0.00	Low Temperature	Low Humidity	Medium MC
15 March	24.57	63.86	0.05	Low Temperature	Low Humidity	Medium MC
16 March	24.60	58.38	0.04	Low Temperature	Low Humidity	Medium MC
17 March	25.05	71.80	0.00	Medium Temperature	Medium Humidity	Medium MC
18 March	24.97	69.35	0.00	Medium Temperature	Medium Humidity	Medium MC
19 March	25.07	70.35	0.00	Medium Temperature	Medium Humidity	Medium MC
20 March	24.92	70.37	0.00	Medium Temperature	Medium Humidity	Medium MC
21 March	24.79	64.46	0.00	Medium Temperature	Medium Humidity	Medium MC

Fig. 7 Section of the processed and classified dataset

5 Conclusion

A safety helmet was designed successfully which was able to create a dataset that could be used for data analytics. Using the available dataset of a mine, meticulous analysis was done to reveal that variation in physical parameters adversely affected the health of workers. Further collection and analysis of location-specific health data, in conjunction with the corresponding physical parameters, will facilitate a more robust correlation between diseases and workplace conditions, ultimately contributing to the establishment of safer environments for high-risk occupations. This research aims to propose a system that can be utilized by the industry, to keep track of the working conditions of its employees, so that any possible diseases can be predicted for the employees, and preventive measures can be employed. Moreover, the designed model can also be deployed in parallel high-risk industries such as construction and manufacturing to provide a safer working environment to the workers and minimize the risk of unknowingly dangerous working conditions.

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