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Monitoring and assessment of underground climatic conditions using sensors and GIS tools

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ABSTRACT

Monitoring and assessment of underground climatic conditions are necessary to identify potential hazards and initiate remedial measures in advance that otherwise would lead to disastrous conditions. This paper discusses the concept of real-time monitoring and assessment of climatic conditions in a typical underground mine using sensors and GIS tools by utilizing a laboratory scale model. Typical ventilation parameters including temperature, humidity, and gas concentrations were monitored using sensors in a laboratory setting and various ratios and indices proposed by previous researchers for interpreting fire gases and spontaneous combustion conditions are predicted from the monitored data. GIS tools were used to display this information in real-time on a mine map that would help in creating a safe and comfortable working environment for personnel and equipment working underground.

1. Introduction

The underground mine environment has several challenges that are to be dealt with for safe mining. These include noxious gases, roof stability, fires, and explosions. Among other hazards, fires and gas outbreaks are two catastrophic events that could lead to injuries and fatalities in the mine. Fatalities in the United States underground mines ranged between 40 and 46 during the years 2001–2010 [1]. Universities and research organizations have undertaken research efforts to investigate impending health and safety issues in broad areas of mining engineering.

Several researchers have investigated the fire problems in underground mines. In 2016, Posser conducted a fire modeling study of Chuquicamata underground mine and made several recommendations to enhance the existing ventilation system at the mine [2]. Richard calculated the heat release rate from two types of mining vehicles for a fire scenario; this experiment was conducted in a non-active part of a dolomite mine and, it was observed that the airflow direction and the air volume flow rate in the mine drift had a significant effect on the fire behavior [3]. Duckworth investigated tunnel fires and developed a tunnel design criterion to mitigate its effects on personnel inside the tunnels. Fire analysis and detailed criteria for fire evaluation including fire-heat release rate and computational fluid dynamics techniques were considered in the study [4]. De Souza emphasized incorporation of a ventilation management program to enhance regulatory compliance, safety and operational efficiency [5]. Furthermore, in a different research study, De Souza presented a work to detect and manage heat stress in underground mines [6].

Risks associated with confined areas require predictive analytics to prevent the development of such conditions that otherwise would create disasters. Primarily underground mine involves confined airways, working miners, machinery, and hazards that could come into effect under proper conditions. Atmospheric monitoring systems are positioned in underground airways to achieve constant monitoring of hazards including noxious gas outbreaks, and fires. Research studies are conducted in the broad area of atmospheric monitoring systems and control. Raj et al. developed a smart monitoring and control system to address the issue of short-term over-exposure of airborne contaminants using ventilation controls, louvers, and auxiliary fans were used to control the contaminants to a tolerable limit [7]. Moridi et al. demonstrated the capability of the Zigbee network and GIS to achieve real-time monitoring of underground mines. Triggers based on a threshold value were established and connected to the system that activates the auxiliary fan and texting message functionality [8]. Pan et al. investigated the characteristics of cave parameters to resistance caused to airflow in underground headings of an experimental block cave model [9]. Additionally, several researchers have used experimental models and simulations to evaluate the effect of different ventilation parameters on underground mine environmental conditions [10–14].

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The main objective of this research study is to investigate the possibility of establishing an atmospheric monitoring system for a block cave mine and mitigate the effects of hazardous conditions through engineering controls. The concept of ventilation-on-demand was also investigated to assess mitigation strategies using ventilation devices. Atmospheric monitoring in real-time helps in obtaining different characteristics of the mine atmosphere that would help in optimizing and operating the existing ventilation system effectively.

In this study, a basic atmospheric monitoring system, Arduino microcontroller with carbon monoxide and temperature-humidity sensors, was developed for a proof of concept purposes; it was used in a laboratory setting and the data obtained from different atmospheric sensors were displayed on a geographic information system platform (GIS) that offered the ability to visualize the atmospheric conditions in a spatial context, predict potential risks, and implement appropriate mitigation techniques.

2. Geographic information system and Arduino microcontrollers

2.1. Geographic information system (GIS)

GIS is a framework that is used for gathering, managing, and analyzing data [15]. It provides a platform to integrate diverse data sets and manage geospatial information. It helps to assimilate information from different sources, scales, accuracies, and formats into a single source that can be utilized for modeling, mapping, and spatial decision support (CFR). It has the ability to relate different data sets based on a common spatial attribute. These features are usually represented as points, lines, or polygons [16]. GIS is utilized in many applications relating to mining. GIS is used in the exploration phase, and data obtained in the form of geologic maps, hyperspectral and multispectral images are analyzed in the decision-making process. GIS was utilized in combining data from various sources including old paper maps, drafting on linen and various surveys, and CAD for re-opening a mine in Montana by converting various data forms on a single platform. GIS was used in providing the safety function of the mine such as placement of the refugee chamber in a mine (Geo-fencing). GIS was also used in the calculation of excavated volume, stability of an area near mine, and environmental changes in surrounding areas. In fact, the world's largest mining company, BHP Billiton, extensively uses GIS technology in all of its major operations worldwide [17]. Recently, GIS was used by Freeport-McMoRan to obtain real-time information on adverse road conditions, which was then used to direct drivers on best navigation routes. This relates to a saving of around $14 million in reduced wear and tear, and fuel cost [18]. GIS has a unique capability of interacting with different file sources including AutoCAD. The import between AutoCAD and GIS platform is straightforward especially in ESRI's, ArcGIS. Mine schematics are usually developed in AutoCAD and features such as headings, airways, sensor locations, and other prominent creations are marked at suitable locations (Fig. 1). Upon import, attributes such as length for headings, sensor locations are stored in the shapefiles.

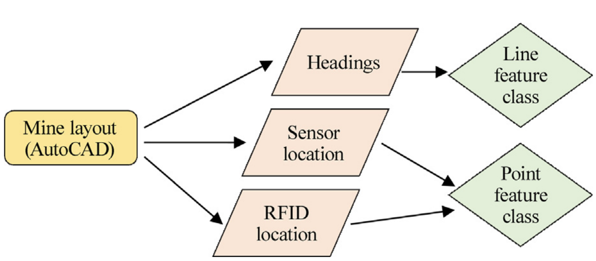


Fig. 1. Schematic representation of mine map import process in ArcGIS.

2.2. Arduino microcontrollers

Arduino is an open-source electronics platform based on easy-to-use software and hardware that is intended for making interactive projects [19]. Arduino microcontrollers are capable of connecting to different sensors and the collected data could be obtained on a software platform. These microcontrollers are inexpensive and allow the user to custom-build devices based on specific requirements. Creative projects that were developed using these microcontrollers include controlling home automation such as fingerprint door opener, temperature and humidity measurements, etc. [20]. These microcontrollers have a USB interface that allows for connection to a computer for the programming of sensors and data collection. Arduino software platform is used for programming features such as data collection frequency. The frequency of data collection was set at one second. ArcGIS has a python window with an interpreter that allows the implementation of geoprocessing tools and other functionality and is very helpful in automating different processes. Connections of the sensors to a microcontroller are accomplished using bread-board and jumper-wires. All the sensors require three different kinds of connections including ground, power-supply, and analog input. Fig. 2 shows an Arduino microcontroller connected with sensors.

3. Methodology

The main objective of this study is to prove that the concept of an integrated mine atmospheric monitoring system combined with GIS capabilities could be utilized for optimizing an existing ventilation system and for implementing appropriate mitigation techniques to create safe working conditions in underground block cave mines. Further, it is demonstrated that the data obtained from these sensors can be manipulated such that it can be utilized for ventilation on demand and improving rescue response. Broadly, this approach consists of two components: (1) sensor-based monitoring system, and (2) GIS-based data integration and manipulation. A basic flowchart for an integrated atmospheric monitoring system is shown in Fig. 3. One of the unique advantages of using GIS is that the mine layout or a particular section of mine network can be imported directly from AutoCAD for a better visual representation. There is no difference in data collection and manipulation for both approaches except for the visual representation.

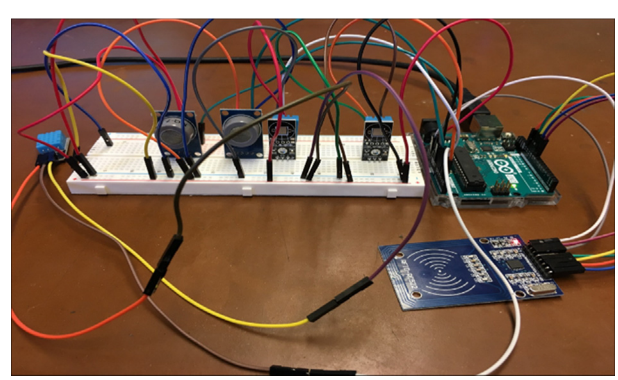


Fig. 2. Arduino microcontroller with temperature-humidity, carbon-monoxide, and RFID sensor.

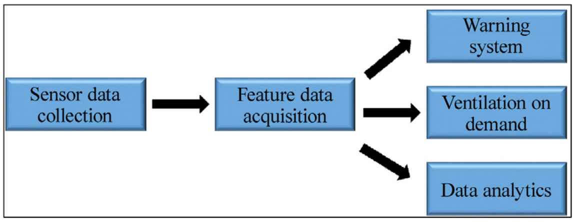


Fig. 3. Flowchart of an integrated atmospheric monitoring system.

Both of these approaches are discussed in this study. In the first approach, a mine schematic was drawn in AutoCAD and it was imported into ArcGIS including its features such as airways, drawbells, cave, exhaust fan, and sensor location that were displayed on the map, as shown in Fig. 4. This schematic shows a section of a block caving operation and provides a better representation of

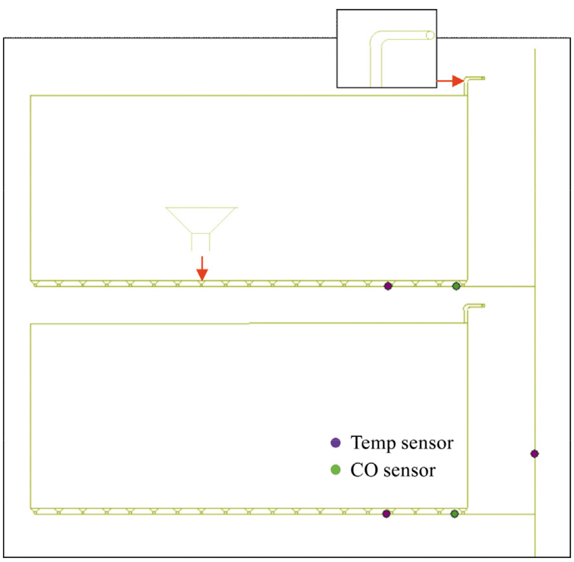


Fig. 4. Schematic of a block cave mine imported into ArcGIS.

headings, sensor location, and other features. The geospatial information related to all the feature class of mine was stored in GIS tables. This feature class provides an opportunity for data manipulation based on different conditions. In this study, two different sensors namely carbon-monoxide sensor, and temperature-humidity sensor were used for monitoring underground atmospheric conditions. These sensors are likely to provide detailed characteristics about the atmospheric conditions in underground mines. Other types of gas sensors can also be used and the data transfer and manipulation processes remain the same. Fig. 5 shows an attribute table in ArcGIS that contains the data obtained from sensors.

Further, Arduino-based sensors were activated, and the data (carbon-monoxide, and temperature) was transferred from the sensor to ArcGIS using a python code developed by the authors. Real-time data transfer was accomplished, wherein, data collected by all five sensors were directly stored in the feature class with the timestamp. Temperature and carbon monoxide sensors provide best indications if a potential risk of mine fire exists at a given mine site. Real-time monitoring of atmospheric conditions using these sensors would provide mine engineers the ability to predict potential risks and implement appropriate mitigation measures that otherwise would create disastrous conditions in underground mines. There were no time delays when converting the signal from analog to digital and conversion was achieved in microcontroller. The optimum sampling time for the data depends on the needs of the mine. However, for purpose of this research study, sampling at one-second intervals produced decent results.

For the second approach, a 3D mine layout of the block caving operation was developed and imported in ArcScene.

The process of import and manipulation was the same as the one followed for the first approach. Fig. 6 shows a 3D schematic of a block caving operation.

In this study, the ArcGIS was used to manipulate the sensor data to provide the following information:

(1) Risk-based warning system: A computer code was developed to provide a visual warning on a mine map when the carbon-monoxide gas concentration exceeds the permissible limit. This code calculates the average of the last ten data obtained from the carbon-monoxide sensor and when the reading exceeds 100 ppm, a buffer ring is generated at the sensor location indicat-

Table
Block_caving_Temp

FID	Shape *	Date_Time	Temp_1	Temp_2	Temp_3
0	Point	23/07/2019 14:12:36	27	26	26
1	Point	23/07/2019 14:12:36	27	26	26
2	Point	23/07/2019 14:12:37	27	26	26
3	Point	23/07/2019 14:12:38	27	26	26
4	Point	23/07/2019 14:12:38	27	26	26
5	Point	23/07/2019 14:12:39	27	26	26
6	Point	23/07/2019 14:12:40	27	26	26
7	Point	23/07/2019 14:12:41	27	26	26
8	Point	23/07/2019 14:12:41	27	26	26
9	Point	23/07/2019 14:12:42	27	26	26
10	Point	23/07/2019 14:12:43	27	26	26
11	Point	23/07/2019 14:12:43	27	26	26
12	Point	23/07/2019 14:12:44	27	26	26
13	Point	23/07/2019 15:00:15	27	26	26
14	Point	23/07/2019 15:00:15	27	26	26
15	Point	23/07/2019 15:00:15	27	26	26
16	Point	23/07/2019 15:00:15	27	26	26
17	Point	23/07/2019 15:00:15	27	26	26
18	Point	23/07/2019 15:00:15	27	26	26
19	Point	23/07/2019 15:00:15	27	26	26
20	Point	23/07/2019 15:00:15	27	26	26
21	Point	23/07/2019 15:00:15	27	26	26
22	Point	23/07/2019 15:00:15	27	26	26

Table
Block_caving_CO_sensor

FID	Shape *	Date_Time	CO_1	CO_2
609	Point	23/07/2019 14:56:25	444	398
610	Point	23/07/2019 14:56:25	444	473
611	Point	23/07/2019 14:56:25	444	447
612	Point	23/07/2019 14:56:25	444	454
613	Point	23/07/2019 14:56:25	444	439
614	Point	23/07/2019 14:56:25	444	434
615	Point	23/07/2019 14:56:25	444	467
616	Point	23/07/2019 14:56:25	444	396
617	Point	23/07/2019 14:56:25	443	412
618	Point	23/07/2019 14:56:25	443	481
619	Point	23/07/2019 14:56:25	443	467
620	Point	23/07/2019 14:56:25	443	424
621	Point	23/07/2019 14:56:25	443	393
622	Point	23/07/2019 14:56:25	443	397
623	Point	23/07/2019 14:56:25	443	467
624	Point	23/07/2019 14:56:25	443	463
625	Point	23/07/2019 14:56:25	443	391
626	Point	23/07/2019 14:56:25	443	438
627	Point	23/07/2019 14:56:25	443	424
628	Point	23/07/2019 14:56:25	443	418
629	Point	23/07/2019 14:56:25	444	433
630	Point	23/07/2019 14:56:25	444	399
631	Point	23/07/2019 14:56:25	443	471

Fig. 5. Attribute table - data obtained from the Arduino sensors shown in ArcGIS.

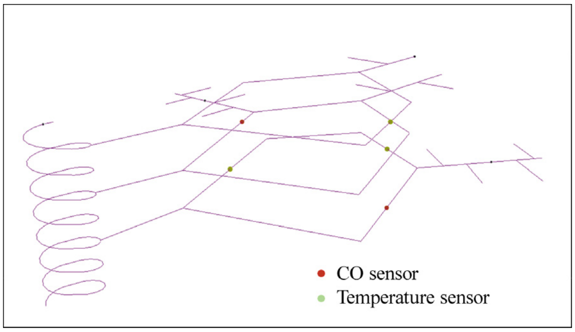


Fig. 6. 3D schematic of a block caving mine with sensors.

ing a hazardous condition. Also, similar code was developed to generate information in the form of the buffer under varied temperature conditions. Color codes including green, yellow, and red were incorporated in the code to indicate different conditions within the mine. Temperatures were specified in degrees Celsius, green buffer indicates a condition where the temperature is below 35 °C, yellow designates a temperature between 35 and 45 °C, whereas, red signifies temperature greater than 50 °C. This helps the mine engineer in knowing the state of the mine atmosphere, such that countermeasures can be initiated when required. Fig. 7 shows the buffer across the carbon-monoxide sensor that is generated in the event of excess gas concentration.

(2) Ventilation-on-demand: The data obtained in ArcGIS was manipulated to fulfill the concept of ventilation-on-demand. Once the average value of carbon monoxide exceeded 100 ppm, the exhaust fan speed was increased such that gas concentration was diluted. The additional flow required to dilute gas concentration was calculated using the equation: $Qo = q/(C\text{-}B)$, where Qo is airflow requirement; B is the initial concentration of gas; C is the final concentration; and q is contaminant flow rate. Fans equipped with variable frequency drives can provide this additional quantity

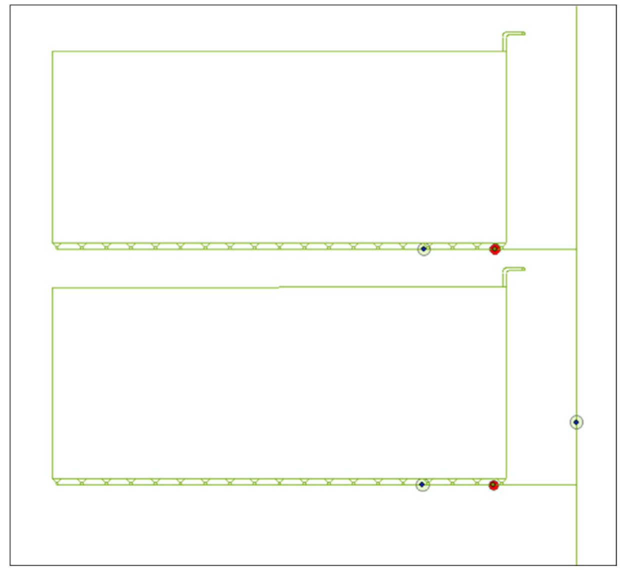
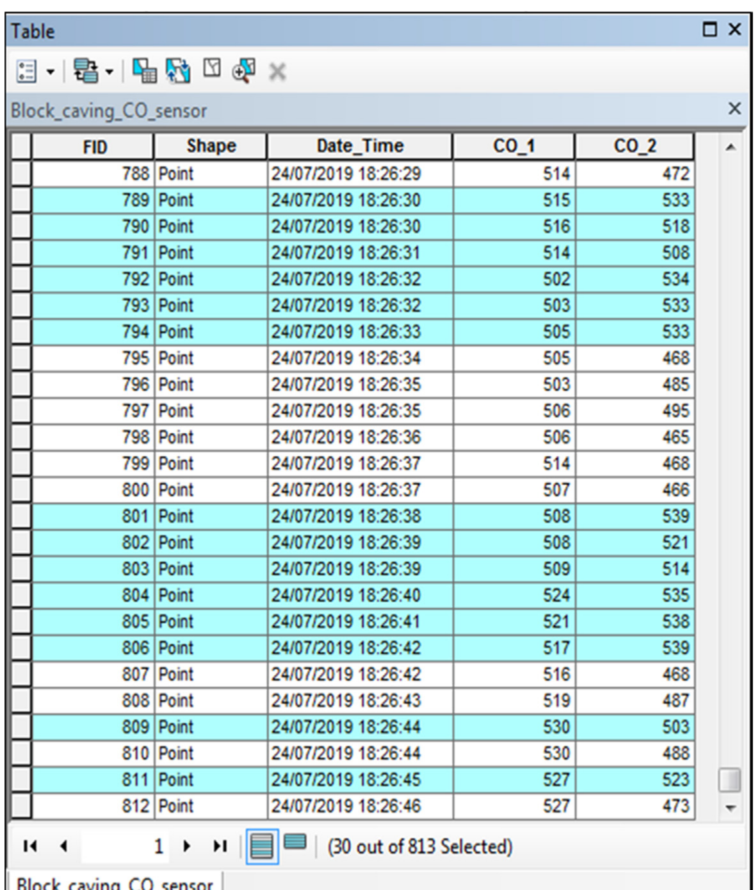


Fig. 7. Buffer across the sensors indicating different conditions.



FID	Shape	Date_Time	CO_1	CO_2
788	Point	24/07/2019 18:26:29	514	472
789	Point	24/07/2019 18:26:30	515	533
790	Point	24/07/2019 18:26:30	516	518
791	Point	24/07/2019 18:26:31	514	508
792	Point	24/07/2019 18:26:32	502	534
793	Point	24/07/2019 18:26:32	503	533
794	Point	24/07/2019 18:26:33	505	533
795	Point	24/07/2019 18:26:34	505	468
796	Point	24/07/2019 18:26:35	503	485
797	Point	24/07/2019 18:26:35	506	495
798	Point	24/07/2019 18:26:36	506	465
799	Point	24/07/2019 18:26:37	514	468
800	Point	24/07/2019 18:26:37	507	466
801	Point	24/07/2019 18:26:38	508	539
802	Point	24/07/2019 18:26:39	508	521
803	Point	24/07/2019 18:26:39	509	514
804	Point	24/07/2019 18:26:40	524	535
805	Point	24/07/2019 18:26:41	521	538
806	Point	24/07/2019 18:26:42	517	539
807	Point	24/07/2019 18:26:42	516	468
808	Point	24/07/2019 18:26:43	519	487
809	Point	24/07/2019 18:26:44	530	503
810	Point	24/07/2019 18:26:44	530	488
811	Point	24/07/2019 18:26:45	527	523
812	Point	24/07/2019 18:26:46	527	473

Fig. 8. Event selection using an SQL expression.

upon sensing the mine atmospheric condition. Additionally, energy savings can be achieved when fans deliver the air keeping in view of the atmospheric condition.

(3) Data Analytics: Atmospheric monitoring data is crucial in providing the detailed conditions and analytics at different sections of the mine. Aggravated atmospheric conditions can be sensed and reasons for the same can be outlined such that countermeasures can be initiated. Local events such as an increase in temperature or gas concentration at a particular section of the mine are recorded so that adequate planning measures are introduced. Specific events can be outlined using a SQL-based expression available in the feature class table. Fig. 8 shows the utility of SQL-based expression to identify events where the gas concentration for both the sensors was above 500 ppm. In addition, the data obtained can be analyzed to outline specific events and cause of their occurrence at a particular time. Moreover, the psychometric properties of the mine air can also be calculated using the data.

Underground mines utilize atmospheric monitoring systems to obtain information on the existing environmental parameters in underground mines. These commercial systems are usually custom-designed and installed at particular mine site and they fulfill different requirements in terms of monitoring systems. A detailed structure and literature of monitoring system could not be found upon extensive literature search. A GIS-based monitoring system has several advantages including easier inclusion and positioning of sensors, real-time data storage, and analysis, automation of process using python programming based toolbar. GIS is flexible in inclusion and positioning of new sensors such that different toolbars and features available can be used to accomplish the desired tasks. However, sometimes the GIS-based monitoring system does not respond to simultaneous real-time data display and storage with processes such as indication of high levels gas readings with alarms. This can be a problem with a particular GIS platform and may not exist in other platforms that are available for use.

4. Conclusions

An integrated atmospheric monitoring system with GIS capabilities was developed for a block caving operation. The ArcGIS capabilities were explored by integrating the Arduino microcontroller-based sensor data with GIS. Furthermore, several objectives were accomplished including the development of a risk-based warning system, ventilation-on-demand, and data analytics for mine atmosphere. ArcGIS offers visualization of mine map that includes locations of prominent features such as sensors. Two different approaches to visualization were included in the study, and data collection and manipulation was achieved. Python code was developed to transfer the sensor data from Arduino microcontroller to ArcGIS. In addition, these data were stored in an attribute table at the sensor location. Real-time transfer of sensor data was accomplished using five sensors including two carbon-monoxide sensors and three temperature and humidity sensors. Further, data obtained from these sensors were stored in the feature class table with time-stamp. A risk-based warning system was established using a python code that would create a buffer ring around the sensor in an event of an excess gas concentration or temperature. From this study, it was observed that the integrated atmospheric monitoring system is a useful tool for predicting potential risks and implementing appropriate mitigation measures to create safe and comfortable working conditions in underground mines.

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