Preprint 17-076

INDUSTRIAL INTERNET OF THINGS (IIOT) APPLICATIONS IN UNDERGROUND COAL MINES

C. Zhou, National Institute for Occupational Safety and Health, Pittsburgh, PA
N. Damiano, National Institute for Occupational Safety and Health, Pittsburgh, PA
B. Whisner, National Institute for Occupational Safety and Health, Pittsburgh, PA
M. Reyes, National Institute for Occupational Safety and Health, Pittsburgh, PA

ABSTRACT

The industrial Internet of Things (IIoT)—a concept that combines sensor networks and control systems—has been employed in several industries to improve productivity and safety. NIOSH researchers are investigating IIoT applications to identify challenges of and potential solutions for transferability of IIoT from other industries to the mining industry. Specifically, NIOSH has reviewed existing sensors and communications network systems used in U.S. underground coal mines to determine whether they are capable of supporting IIoT systems. The results show that about 40% of the installed post-accident communication systems as of 2014 require minimal or no modification to support IIoT applications. NIOSH researchers also developed an IIoT monitoring and control prototype system based on low-cost microcontroller Wi-Fi boards, to detect a door opening on a refuge alternative, activate fans located inside the Pittsburgh Experimental Mine, and actuate an alarm beacon on the surface. The results of this feasibility study can be used to explore IIoT applications in underground coal mines based on existing communications and tracking infrastructure.

INTRODUCTION

The nation's approach to health and safety in mining has historically been reactive in the sense that health and safety regulations and mandates have traditionally been passed as a result of tragic mining accidents. An example of this is the Mine Improvement and New Emergency Response Act (MINER Act) of 2006, which was passed as a result of several mining accidents where tracking of and communications with underground personnel were severely limited. While this reactive approach has led to the development and implementation of highly impactful safety interventions and safety practices, there currently exists a technological revolution that can shift the paradigm toward a proactive approach based on preventative methods: Internet of Things (IoT).

IoT is the network of physical objects or "things" embedded with electronics, software, sensors, and connectivity to enable that network to achieve greater value and service by exchanging data with the manufacturer, operator, and/or other connected devices [1, 2]. It should be noted that IoT has been defined from various perspectives, and hence numerous definitions exist in the literature. The apparent ambiguity of the IoT definition might be due to the fact that IoT is syntactically composed of two terms: internet and things. The first one pushes towards a network-oriented vision, while the second tends to put the focus on generic objects. The traditional internet can be viewed as an internet of computers —i.e., "things" connected to the internet are computers only. IoT "extends" the internet by allowing other generic things that are commonly found in our daily life, such as refrigerators and cars, to be interconnected via the internet, and thus creates a bridge between the virtual word and the physical world.

According to the 2014 release of Gartner's Hype Cycle, IoT was the most hyped emerging technology of the year [3]. Companies such as Amazon, General Electric (GE), Microsoft, and IBM have heavily investigated this new technology, and now offer commercially available IoT platforms to a variety of industries.

In the past few years, different terms have been used to represent the concept of IoT. Examples of terms include:

- Internet of Everything (IoE)
- Industrial Internet
- Industry 4.0
- Web of things (WoT)

Currently, many IoT technologies are integrated into consumer applications, such as smart homes, connected cars, and smart wearables. The industrial applications of IoT, or Industrial IoT (IIoT), however, is anticipated to have the capability to transform many industries, including manufacturing, oil and gas, agriculture, and mining.

With advances in sensing technologies, more and more sensors are now being deployed in underground mines to measure important operational and environmental parameters. These deployed sensors collect a massive volume of data on a daily basis. The challenge is how to process those data in order to best improve mine safety and operational efficiency. The combination of IIoT and big data analytics offers a unique solution for this challenge, and will bring unprecedented opportunities to the mining industry.

It should be noted that, though not under the term IIoT, the mining industry has been deploying programmable logic controller (PLC) and supervisory control and data acquisition (SCADA) systems for monitoring and controlling for decades. For example, there exist a number of commercially available, MSHA-approved, wireless atmospheric monitoring systems (AMS) for coal mining applications. In addition to wireless monitoring systems, there are some wired monitoring systems such as the PLC controlled AMS Network systems from Conspec controls. Compared to IIoT systems, these existing monitoring and control systems are generally proprietary systems, and were not designed to interoperate/interconnect with other systems. The major difference between IIoT-based systems and legacy monitoring systems is that IIoT systems are based on an open, highly connected IP network structure. Transition to more open network architectures and data sharing of IIoT may bring opportunities to the mining industry that will enable it to move toward the next generation of smart mining and automation.

While the health and safety implications of applying IIoT technologies go well beyond mining, introducing these technical advancements into the underground coal mine environment may be especially challenging. There are specific considerations that must be made to transfer concepts to mining. To that end, this paper provides theories and applications essential to accelerate the adoption of the IIoT concept to underground mines. Particularly, the feasibility, potential, and challenges of IIoT for underground coal mines will be discussed. Also, a practical example of an IIoT mining-specific application will be presented.

IIOT IN THE MINING INDUSTRY: STATE OF THE MARKET AND RELATED WORK

IIoT in metal/nonmetal mines

Due to the current economic climate in mining, mine operators are heavily focused on improving asset management, equipment life cycle management, and minimizing production costs. These priorities may open the door to IIoT in mining as discussed by an insights report published in 2015 on the benefits of the industrial internet [4]. The report revealed that 79% of the mining companies surveyed identified investing in data analytics and industrial internet to be within their top three priorities. In the following, we highlight some examples of IIoT in mining applications found in the literature:

The worldwide mining industry is already leveraging IIoT in wireless mining automation and connected mine projects. For example, the Rio Tinto mine has been using autonomous, self-driving mining trucks to move ore around since 2008 [5]. Each self-driving truck is loaded with more than 200 sensors, a GPS receiver, and a radar guidance system. The fleet is managed from an operations center located more than a thousand miles away. At the operations center, data from the vehicles and other equipment, on-site personnel, and geological instruments are fed into a comprehensive Mine Automation System, which gives a real-time, big-picture view of the entire mining operation, including 3D visualizations of work sites and predictive maintenance schedules.

Also, Cisco has actively promoted two cases where IIoT technology has been successfully applied to improve safety and efficiency of underground mines. The first case was with Dundee Precious Metals (DPM). It is reported that 280 Cisco Wireless Access Points were installed in DPM's flagship gold mine in Chelopech, Bulgaria, to provide wireless coverage along 50-km tunnels. The IIoT solution implemented at this mine has helped to connect people, track the location of miners and vehicles, monitor vehicle status, and automate building controls. In addition, the blasting system of the mine is connected to the personnel location tracking system to improve miner safety. This DPM case is perhaps one of the best known IIoT mining examples and has been highlighted in Cisco's IIoT initiatives [6]. A second case was presented through a partnership with the Goldcorp [7]. In addition to communication and real-time tracking of people and assets, ventilation on demand (VoD) has been implemented based on a multiservice IP network installed in one of the Goldcorp mines.

In 2014, GE teamed up with Komatsu, a mining equipment manufacturer, to implement IIoT solutions for improving efficiency and service of mining operations [8]. A joint venture partnership, Komatsu and GE Mining Systems, LLC, was established to develop the next generation of mining solutions where IIoT and big data analytics are anticipated to play an important role. For example, the GE Remote Monitoring & Diagnostics (RM&D) technology can be used to provide data analytics of the truck performance data to prevent unnecessary maintenance events and, by extension, reduce the costs associated with replacing failed components and maintenance downtimes through automation of predictive maintenance schedules.

Another example is based on the research by a team of engineers from the NTT Innovation Institute Inc. and the Colorado School of Mines. The team recently completed a pilot project using IIoT to provide "ventilation on demand" (VoD) at the Edgar Experimental Mine [9]. Based on the team's assessment, the implemented IIoT-based VoD program achieved 10% energy savings in just the first two weeks of the program [9].

IIoT in coal mines

While IIoT solutions have been successfully implemented in metal/nonmetal mines, the application of such technology in coal mines has been very limited. Some of the barriers affecting the integration of IIoT in coal mines may be attributed to intrinsic safety requirements enforced in underground coal mines, the complexity of integrating full coverage into a mine infrastructure, and the initial overhead costs associated with integrating sensor networks and automation. Despite these barriers, some manufacturers and mine operators have started taking an initial step to explore IIoT in underground coal mines.

Although still at its infancy in terms of implementation, IIoT in coal mines has been a hot research topic since early 2000 and has been widely investigated, particularly in China. An extensive number of papers on this topic have been published in academic and technical journals since 2000. For example, IIoT has been proposed in China for coal mine disaster warning [10], intelligent mine monitoring [11], mining equipment management [11], environmental sensing [12], real-time positioning [13], coal seam water monitoring [14], and accident analysis [15]. In addition to specific applications, some published papers focus on IIoT system overview and architecture design [16-21].

In contrast to the literature available from China, there have been limited studies on IIoT in coal mines reported in other countries. However, some related studies, such as those researching mine-wide monitoring systems, have been reported in the U.S. and abroad for many years. For example, a technical report comparing different mine monitoring systems in underground mines was published by the U.S. Bureau of Mines in the 1980s [22]. In addition, Nutter and Aldridge published an article on the status of mine monitoring and communications in 1987 [23]. It should be noted that mine monitoring is a part of the IIoT though, on its own, does not encompass the concepts of a complete IIoT solution.

The National Institute for Occupational Safety and Health (NIOSH) has conducted intramural research in areas directly related to IIoT technologies. One of the key elements for underground IIoT is the communication backbone for connecting things in the underground to the surface. In 2010, NIOSH launched a five-year research project to investigate radio propagation mechanisms for different frequencies that are commonly used by existing underground communications and tracking (CT) systems. Theoretical models were developed to predict underground communications and tracking system performance and validated through extensive measurement results [24, 25].

In 2014, NIOSH engineers reviewed the Emergency Response Plans (ERPs) of 306 active coal mines in the U.S., as part of its efforts under a project on communications and tracking. The post-accident communications and tracking system installation information for the 306 active coal mines was extracted and analyzed [26]. One of the major results, as shown in Figure 1, was a comprehensive overview of communication and tracking systems installed in U.S. underground coal mines in 2014. The list was used to evaluate the state of post-accident CT systems being used throughout the United States and to explore the capabilities and limitations of these systems in handling the data transmission and infrastructure required to operate an IIoT network.

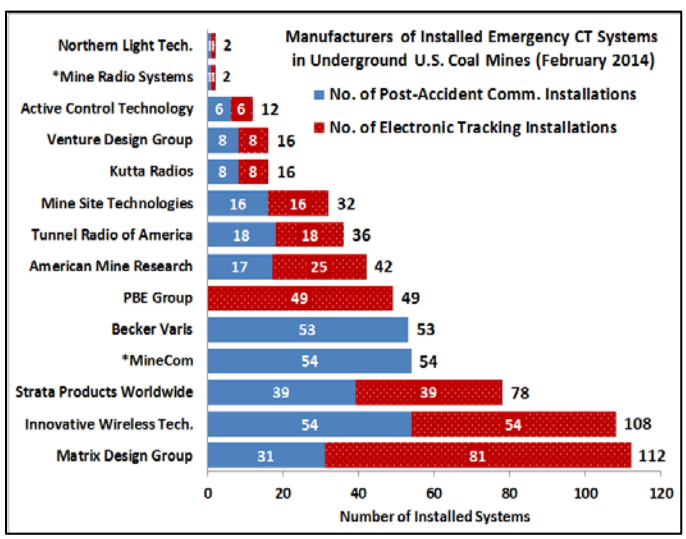

Figure 1. An overview of communication and tracking systems installed in US underground coal mines.

FEASIBILITY OF IIOT IN COAL MINES

To answer the question of whether it is feasible to implement IIoT technologies in coal mines, one must understand the major components of IIoT systems and compare them to those that already exist in coal mines. By examining the IIoT technologies used in other industries, the following system core components have been identified:

- Things: e.g., machines and people equipped with sensors, services, and actuators
- Networks: To connect things together
- Systems/platforms: To process data from/to things, often deployed in the cloud

System of systems

IIoT comprises a large scale of smart things and is often referred to as a "system of systems." Figure 2 illustrates some examples of existing underground systems that can potentially be integrated to form a new IIoT system, as detailed below.

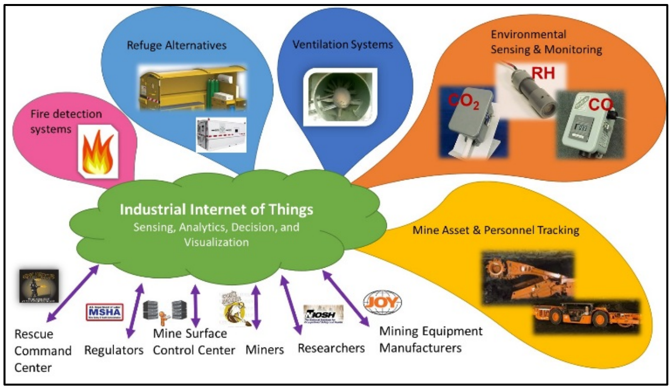

Figure 2. An example of an IIoT system in coal mines.

Ventilation and fire detection systems: Fires and explosions have been two serious safety concerns since the advent of mining. Ventilation systems are crucial for maintaining non-explosive and non-toxic atmospheres. The progression of technology has allowed mine monitoring techniques to become more sophisticated, and various advanced sensors for monitoring dust, oxygen, methane, CO, CO_2, temperature, and air velocity have been developed and deployed throughout the mining industry. In an IIoT system, these sensors could potentially be connected to a network to form a mine-wide monitoring system capable of collecting data and automatically transferring it to the surface through the existing communication backbone. The data can then be used to provide decision-making information and automatic actions. If an abnormal condition is detected, the local sensor node could be configured to simultaneously set off an alarm locally and in the monitoring and control center on the surface. Depending on the conditions detected, the system would then enact automatic measures to mitigate the hazard. For example, if the sensor data indicates a fire is occurring underground, the system may automatically activate fire suppression systems in the point of origin while taking additional measures to prevent it from spreading.

Personnel and asset tracking systems: With increasing mining equipment and assets, such as boring machines, shearers, conveyors, hydraulic support, hydraulic pump stations, loaders, crushers, motor vehicles, ventilation fans, and water pumps used in underground mines, equipment management systems are often needed to provide a more convenient, efficient, and secure resource management platform. Through an IIoT network, the location of those important assets along with the location of all the underground personnel can be tracked. As mandated by the MINER Act, all U.S. underground coal mines now have installed wireless tracking systems to track the location of underground personnel. Many of those installed tracking systems are based on radio-frequency identification (RFID) technologies, and thus can be easily incorporated into the proposed IIoT network platform.

Sensors

To get an overview of legacy sensors used in underground coal mines, sensors approved for use in U.S. underground coal mines during 1996 to 2016 were examined. It was found that the major sensors used are:

- Gas sensors (e.g., CH_4, O_2, and CO)
- Airflow sensors
- Temperature and humidity sensors
- Vibration sensors
- Smoke sensors
- Alarm sensors

In addition, there exist other approved sensors for monitoring:

- Ventilation fan speed
- Water level for pumps
- Power status
- Conveyor belt condition (speed, slip detection, etc.)

Networks: Information collected by underground sensors should be readily accessible to underground miners as well as the dispatch personnel on the surface. Many mines have installed communication systems that have data backhaul capability; in these cases, an IIoT network may potentially be established based on existing mine communication systems, such as fiber optics systems, leaky feeder systems, and node-based systems. IIoT systems likely require a large communication bandwidth to support the transmission of the massive amount of data collected in the underground; therefore, from the bandwidth point of view, node-based systems with fiber optics as a communication backbone would be favorable for IIoT applications. In addition, a communication interface between the existing communications backbone and the sensors would need to be established. One method of accomplishing this is attaching an RF transceiver module to sensors or "things." Different communication protocols (e.g., Wi-Fi, Zigbee, Bluetooth, and BLE) should be investigated to identify the best one suited for underground mining applications.

As implied in the name, the internet is one of the key components of IIoT technologies. Although low-power, IIoT-dedicated networks have been developed, deploying a new network underground may be costly. Another solution would be to leverage existing communications and tracking networks as the backbone for these installations. As depicted in Figure 1, there are a number of communications systems that may be suited for sensor data transmission and controls. An examination of each of these systems found that 5 of 12 (42%) systems have the capability to provide internet to the underground with little or no modification. The five internet-capable communication system manufacturers in active U.S. underground coal mines are listed in Table I:

Table I. A list of internet-compatible system manufacturers in active U.S. underground coal mines in 2014.

Manufacturer	Technology
Mine Site Technologies (MST)	Node
Strata Worldwide	Node
American Mine Research (AMR)	Node
Active Control Technology	Node
Becker Varis	Leaky feeder

It is important to note that the number of manufacturers and availability of internet ready systems may have increased since the time of this survey, and additional technology review efforts may be required to obtain the most current data.

Platforms

Platforms are responsible for analyzing data, collected in real time, through modern high-performance computing systems and delivering optimized recommendations to operators and other type of users both in and out of mines. By leveraging a customizable and intuitive user interface, and with full mobile accessibility, users are able to gather insight into both mine safety and profitability over time. Platforms also make it possible for appropriate users to analyze historical and real-time data to deliver predictions or to forecast disaster. Big data analytics is increasingly becoming a critical component of IIoT in many industries, including mining. Applying big data analytics and predictive analytics effectively to the mining industry, based on the proposed IIoT network platform, can have a significant impact within the mining industry by processing massive amounts of data and streamlining the prioritization, automation, and resolution of day-to-day operations and mine hazards encountered.

POTENTIAL OF IIOT IN COAL MINES

Benefits of IIoT in coal mines

IIoT has the potential to boost both the safety and productivity of the mining industry to a new level by enhancing the collaborative operation between people, equipment, transportation tools, and the mining process. As shown in Figure 2, the primary end user of the IIoT system would be controlling centers on the surface. In addition to mining companies, the proposed IIoT systems also have the potential to influence mining equipment manufacturers, health and safety professionals, and worldwide researchers, by creating new network-based applications enabled by IIoT systems. Some of the key applications of the proposed mine-wide IIoT-based network systems may include the following.

- **Employee condition and environment monitoring systems**
  IIoT systems equipped with massive volumes of sensors and high connectivity make underground hazards more transparent to the surface, as well as to miners underground. This hazard transparency can help reduce or eliminate miners' exposure to hazards situations that can result in workplace injury and even death through networked, smart, wearable sensors. The transferability potential for smart sensors developed in other industries may have a significant impact on the health and safety of miners.

- **Mine resource management and equipment predictive maintenance**
  Several types of equipment are used in the underground for production and transportation purposes. These machines need to be regularly maintained in order to avoid unexpected failure or breakdown. Connected IIoT systems can monitor the conditions of the equipment, in real time, and use the data collected to predict failure. Parts or components can be issued against predicted failure to achieve predictive maintenance or even prescriptive maintenance.

- **Mine safety management and disaster forecasting**
  Mine safety management can be achieved through mine-wide monitoring such as atmospheric monitoring and ground stability monitoring. Advanced data analytics might be applied to identify possible areas of weakness in mine safety systems and to forecast potential disasters based on historical and current data collected. The system provides an audiovisual warning to alert corresponding people when a hazard is detected or forecasted so proper action can be taken to eliminate the hazard and/or to reduce the damage caused by it.

- **Mining automation**
  Mines may benefit tremendously from automation of mine equipment. For example, from a safety point of view, a good way to reduce mining injuries might be to remove miners from those extremely dangerous working places and replacing them with automated or remote-controlled machines. As a matter of fact, wireless mining automation is already being widely used, as discussed in the "IIoT in the Mining Industry: the State of the Market and Related Work" section of the paper. Automatically controlling equipment based on information monitored is the spirit of IIoT systems and may make a significant contribution toward the next generation of mining automation.

- **Predictive energy optimization (e.g., ventilation on demand)**
  Ventilation on demand is probably one of the most known applications of IIoT to the mining industry. However, the applications of IIoT are not limited to ventilation on demand. It is about energy optimization based on energy consumption monitoring and big data analytics.

- **Remote diagnostics and product performance monitoring**
  The open connectivity of IIoT systems would facilitate services such as remote diagnostics. This feature also allows equipment manufacturers to track the performance of their products in their lifetime after the products are sold and are being used underground. This valuable performance data can be used to improve product design.

- **Post-accident rescue coordination and accident investigation**
  When a disaster occurs, an IIoT system can provide a central place for rescue coordination and accident investigation. The system stores critical information—such as ERP plans, a list of first aid stations, trained rescue personnel along with their contact information, and place of duty during an emergency—and makes this information easily accessible to authorized staff. Through an integrated personnel tracking system, the IIoT system can provide the name of miners trapped underground along with their last known locations. Trapped miners may use handheld devices, such as tablets or smart phones, to check the mine-wide gas conditions provided by the mine-wide monitoring system, and select the best route for escape. When self-escape is not possible, trapped miners can search for the closest refuge alternative.

- **Smart Refuge Alternative (RA) systems**
  In the event of a disaster, miners are trained to escape from the mine with the available self-rescue apparatus first and then enter an RA when escape is cut off. RAs are intended to provide mine workers with breathable air, food, and water for 96 hours. Although RAs are only used in post-accident events, their functionalities should be checked periodically to make sure they work as expected when needed. Furthermore, there should be a mechanism to immediately signal the surface when an RA is activated following a disaster. One way to monitor occupancy status of an RA on the surface is to attach a sensor (e.g., a magnetic switch sensor) to the door of the RA and detect when the door of the RA is open. This door sensor could be linked to the network so the information can be relayed to the surface. The air quality and temperature information for both inside and outside of the RA could be continuously monitored on the surface. The equipment inside RAs can also be monitored and managed by the proposed IIoT-based network system.

IIOT IN COAL MINES: KEY CHALLENGES

Despite the promise and new opportunities brought by IIoT, there are a number of challenges that could hinder the adoption of IIoT technologies in coal mines. Examples of key challenges for implementing IIoT in coal mines include the following:

Security

Security due to connectivity to the global network is always a big concern for IIoT technologies, especially in the mining industry. According to a world economic forum industrial internet survey result reported in [4], 72% of the people surveyed believe that the security concern is the greatest barrier inhibiting business from adopting IIoT in North America. Given the novelty of IIoT and the pace of innovation today, people may believe that there is a need for a revolutionary security solution that can be uniquely tailored to mining applications and may want to wait for such a solution before implementing IIoT. However, traditional IT security controls that have evolved over the past decades can be effectively applied to IIoT in mining, provided that they can be adapted to the constraints of the sensors deployed in mining environments.

Similar to security, another concern caused by connectivity to the global network is the privacy of miners and confidentiality of the business process. IIoT promotes the sharing of information among connected things (including both equipment and personnel) and the information around them, which can lead to a privacy concern. This privacy concern, however, can be addressed by properly controlling access so that information is only available to authorized users.

Harsh and gassy environments

Despite the fact that IIoT has been successfully implemented in other industries, special care must be taken to adapt the technology from the surface to the underground. First, due to the harsh nature of mining environments (e.g., extreme moisture, heavy coal dust), a rugged design is required for sensors and equipment used underground. Second, confined space and tunnel-like structures in mining environments cause some unique radio propagation behavior that must be taken into account in the design of wireless sensors and networks operated in such environments [25]. Third, the gassy underground atmosphere is potentially explosive, so intrinsic safety (IS) or explosion-proof (XP) technology is often required in underground coal mines. Electrical systems, including these IIoT sensors and communication nodes, should be designed in such a way that they do not contain any components that produce sparks or high surface temperatures, or components that can hold enough energy to produce a spark of sufficient energy to cause an ignition. As a result, IIoT systems used on the surface must be evaluated and approved by MSHA before they can be used underground. Sometimes systems on the surface cannot be used underground because they would need to be redesigned in order to be certified as permissible equipment by MSHA.

Network interoperability

The fundamental concept behind IoT is to connect a large scale of systems or things to a common network and infrastructure. This poses a challenge to the scalability and interoperability of the networks in the mining industry, as many existing networks are proprietary systems that are not designed to interoperate with each other.

Data analytics tailored to mining applications

Data analytics refers to examining large amounts of real-time and historical data to uncover patterns and correlations. Fast and agile data analytic specific to the mining applications may help mine operators make informed decisions on health and safety as well as production to prevent potential accidents and reduce costs. While data analytics has been widely used in other industries to help organizations turn data into useful information, it is still in its infancy in the mining industry.

IIOT FOR REAL-TIME MONITORING AND CONTROL: PRACTICAL EXAMPLES

To show the feasibility and potential of IIoT for mining applications, an IIoT prototype system using commercially available components was built and demonstrated in NIOSH's Experimental Mine in Pittsburgh, PA.

System description

As shown in Figure 3, the developed IIoT system consists of IIoT sensors, a communication network, a cloud-based data engine, and actuators. Some examples of IIoT sensors and actuators, built specifically for this application, are shown in Figure 4. These IIoT sensors were constructed by integrating the corresponding sensor with a miniature low-cost microcontroller board that has embedded Wi-Fi connectivity (ESP8266). The IIoT control unit (actuator) in Figure 3 consists of a Wi-Fi microcontroller board, similar to what would be used in IIoT sensors, and a power switch controlled by the Wi-Fi microcontroller board. For this demo, the Wi-Fi coverage in the underground was achieved by using an integrated cellular repeater system. The cellular signal coverage was extended from the surface to the underground work area by using a cellular amplifier. The input antenna of the cellular amplifier was placed on the surface and was connected to the amplifier located underground by a long, low-loss coaxial cable through a borehole. It should be noted that any system that can be connected to the internet using an open protocol could be used in place of the cellular repeater system here.

RA door-open detection demo

To demonstrate the monitoring and control ability of the developed IIoT system prototype, a door-open detection sensor was installed to monitor the door status of a built-in-place (BIP) RA located in the Experimental Mine. The sensor/microcontroller was programmed to conserve batteries so that it was dormant most of the time, and would only transmit data whenever a door-open event was detected. The user interface would then display the status of the door after it received messages from the sensor. A similar approach was taken for other controlled devices.

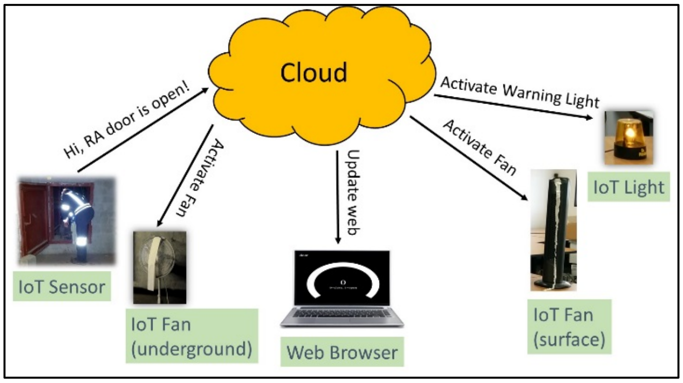

Figure 1. IIoT system used as a demonstration.

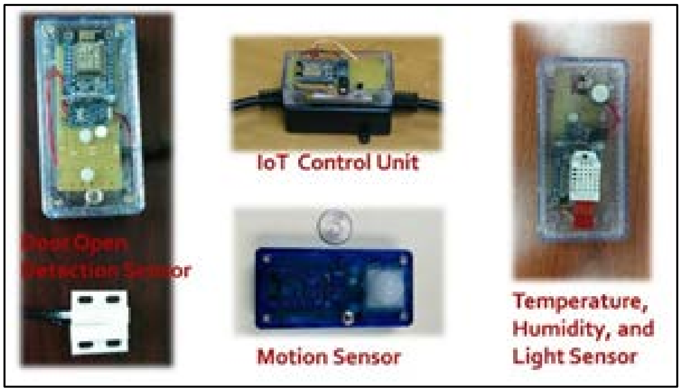

Figure 2. Examples of IoT sensors and actuator.

In this demo, researchers used one warning light and two fans to demonstrate the automatic actions enabled by the sensor network. The actuators and sensors communicated to the server through the Message Queue Telemetry Transport (MQTT) protocol, which is a publish-subscribe "lightweight" messaging protocol designed for Machine-to-Machine (M2M) communications. This messaging protocol is designed for "small code footprint" applications where the network bandwidth is limited. The system was programmed to activate a light and two fans when the RA door was open and turn off when the door was closed.

Although a simple door-open detection sensor was used in the demo, other sensors can also be used as the event trigger as well. The system can be configured to control one device with triggers from multiple sensors or to control multiple devices using a trigger from one sensor. Because the internet is a worldwide network, connected "things" in this demo can essentially be monitored and controlled anytime, from anywhere in the world where there is internet coverage. Even though the information can be accessed anywhere in the world, it could also be made local or even intranet-based, so only people with access to those intranet systems could get the information.

CONCLUSION

This paper presented a discussion on the current state of IIoT in the mining industry. Specifically, the paper discussed the feasibility and potential of applying IIoT to the mining industry, particularly to underground coal mines. The potential applications and benefits of applying IIoT to underground coal mines were summarized to highlight areas where IIoT may have an immediate impact based on current infrastructure that exist in underground coal mines. The research found that a large portion of the sensors and communication systems installed in underground coal mines can be potentially integrated into IIoT systems with little or no modification. In addition, a practical example for a mining-specific IIoT application was presented by discussing a NIOSH prototype system that was developed based on low-cost, open-source microcontroller boards. The system was developed and installed in the Experimental Mine in Pittsburgh, to monitor the door status of a BIP RA and automatically turn on/off equipment based on door status. The results of this paper can be used to further explore the transferability potential and feasibility of IIoT applications in underground coal mines based on previous research and advances in technologies.

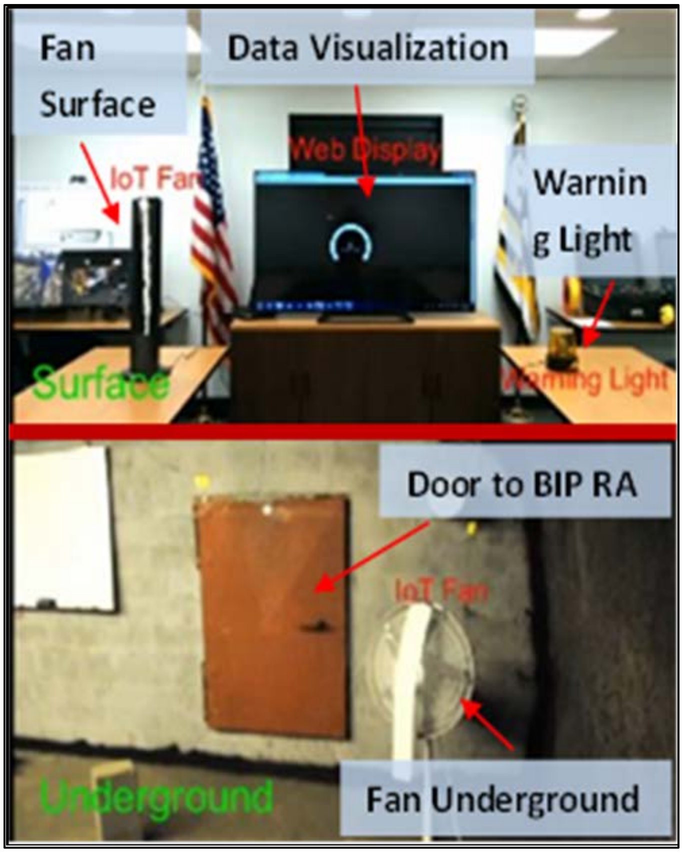

Figure 5. IoT demo setup: (a) in a conference room (top) and (b) in the Experimental Mine (bottom).

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Reference to specific brand names does not imply endorsement by the National Institute for Occupational Safety and Health.

REFERENCES

1. Atzori, L., A. Iera, and G. Morabito, *The internet of things: A survey.* Computer networks, 2010. **54**(15): p. 2787-2805.

2. Gubbi, J., et al., *Internet of Things (IoT): A vision, architectural elements, and future directions.* Future Generation Computer Systems, 2013. **29**(7): p. 1645-1660.

3. *GE to Open Up Predix Industrial Internet Platform to All Users*, in *GE Press Release*. 2014.

4. Accenture, *Industrial Internet Insights Report for 2015*. 2015.

5. Tinto, R. *Mine of the Future*. Available from: http://www.riotinto.com/australia/pilbara/mine-of-the-future-9603.aspx.

6. Cisco. *Mining Firm Quadruples Production, with Internet of Everything*. 2014; Available from: http://www.cisco.com/c/dam/en_us/solutions/industries/docs/manufacturing/c36-730784-01-dundee.pdf.

7. Cisco. *Goldcorp's Éléonore: Internet of Things Enables the Mine of the Future Today*. 2015; Available from: http://www.cisco.com/c/dam/en_us/solutions/industries/materials-mining/downloads/c36-goldcorp-cs.pdf.

8. Vella, H. *Using the Internet of Things to boost efficiency in mining operations*. 2015; Available from: http://www.mining-technology.com/features/featureusing-the-internet-of-things-to-boost-efficiency-in-mining-operations-4585946/.

9. NTTi3. *Using the Industrial Internet of Things to transform human safety and energy consumption in the mining industry*. 2016; Available from: http://www.ntti3.com/blog/iiot-industrial-internet-things-mining-industry-innovation/.

10. Hu, Y., et al. *Coal Mine Disaster Warning Internet of Things Intrusion Detection System Based on Back Propagation Neural Network Improved by Genetic Algorithms*. in *Applied Mechanics and Materials*. 2014. Trans Tech Publ.

11. Hu, S., et al. *Intelligent coal mine monitoring system based on the Internet of Things*. in *Consumer Electronics, Communications and Networks (CECNet), 2013 3rd International Conference on*. 2013. IEEE.

12. CHEN, Y., F.-w. MENG, and H.-c. GUO, *Design of detection system for mine oxygen concentration based on internet of things.* Electronic Design Engineering, 2012. **20**: p. 023.

13. Wang, X., T.-Z. Zhou, and D. Zhao, *Reaserch and Realization of Real Time Location System in Coal Mine Based on Internet of Things [J].* Coal Mine Machinery, 2011. **12**: p. 032.

14. Meng, X., J. Wang, and Z. Gao, *Research on coal seam floor water inrush monitoring based on perception of IoT coupled with GIS.* Engineering, 2012. **4**(8): p. 467.

15. Jiping, S., *Accident analysis and big data and Internet of Things in coal mine.* Industry and Mine Automation, 2015. **3**: p. 001.

16. Ke, H., *The Key Technologies of IOT with Development & Applications [J].* Radio Frequency Ubiquitous Journal, 2010. **1**: p. 012.

17. Qiuping, W., Z. Shunbing, and D. Chunquan, *Study on key technologies of Internet of Things perceiving mine.* Procedia Engineering, 2011. **26**: p. 2326-2333.

18. WANG, Y., et al., *Internet of Things Technology and Application in Coal Mine Industry [J].* Computer Knowledge and Technology, 2011. **33**: p. 095.

19. Yinghua, Z., et al., *Discussion on application of IOT technology in coal mine safety supervision.* Procedia Engineering, 2012. **43**: p. 233-237.

20. ZHANG, C.-j., Z.-j. YUANG, and L.-y. WANG, *IOT system for mine and its application.* Internet of Things Technologies, 2012. **9**: p. 028.

21. ZHANG, F.-g. and H.-y. WANG, *Sensing Coal Mines——Application of IOT Technology in Coal Mining [J].* Internet of Things Technologies, 2011. **5**: p. 029.

22. BoMStaff, *Underground communicaitons, control and monitoring*. 1984: US Bureau of Mines Information Circular (IC 8955).

23. Nutter, R. and M.D. Aldridge, *Status of mine monitoring and communications.* IEEE transactions on industry applications, 1988. **24**(5): p. 820-826.

24. Zhou, C., et al., *Attenuation constants of radio waves in lossy-walled rectangular waveguides.* Progress In Electromagnetics Research (PIER), 2013. **142**: p. 75-105.

25. Zhou, C., et al., *RF Propagation in Mines and Tunnels.* IEEE Antennas and Propagation Magazine, 2015. **57**(4): p. 88-102.

26. Damiano, N., G. Homce, and R. Jacksha, *A review of underground coal mine emergency communications and tracking system installations.* Coal Age, 2014. **119**(11): p. 34-35.