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Industrial Internet of Things:

(IIoT) applications in underground coal mines

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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. U.S. National Institute for Occupational Safety and Health (NIOSH) researchers are investigating IIoT applications to identify the challenges of and potential solutions for transferring 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 percent 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 using 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 communication and tracking infrastructure.

Introduction

The U.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 communication 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 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, 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 (Atzori, Iera and Morabito,

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2010; Gubbi et al. 2013). 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: the Internet and things. The first word pushes toward 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, so things connected to the Internet are computers only. IoT extends the internet by allowing other generic things that are commonly found in daily life, such as refrigerators and cars, to be interconnected through the Internet, thus creating a bridge between the virtual world and the physical world.

According to Gartner's 2014 Hype Cycle (Gartner Inc., 2014), IoT was the most hyped emerging technology of the year. Companies such as Amazon, General Electric, Microsoft and IBM heavily investigated IoT and now offer commercially available IoT platforms to a variety of industries. Terms used to represent the concept of IoT include Internet of Everything (IoE), Industrial Internet, Industry 4.0 and 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 being deployed in underground mines to measure important operational and environmental parameters such as carbon monoxide concentration, methane concentration, airflow, temperature and belt-running conditions. They collect a massive volume of data daily. One challenge is processing the data to best improve mine safety and operational efficiency. Combining IIoT and Big Data analytics offers a unique solution to this challenge and is expected to bring unprecedented opportunities to the mining industry.

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 U.S. Mine Safety and Health Administration (MSHA)-approved wireless atmospheric monitoring systems (AMS) for coal-mining applications. There are also some wired monitoring systems, such as the PLC-controlled AMS network systems from Conspec Controls (Charleroi, PA). Compared with IIoT systems, these existing monitoring and control systems are generally proprietary systems and were not designed to interoperate or 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 Internet Protocol (IP) network structure. Transition to the 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, and there are specific considerations that must be taken into account to transfer concepts to mining in general. This paper provides theories and applications essential to accelerate the adoption of IIoT at underground mines, discusses the feasibility, potential and challenges for underground coal mines, and presents a practical example of a mining-specific application.

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 and equipment life-cycle management, and minimizing production costs. A report by Accenture (2015) said these priorities may open the door to IIoT in mining and revealed that 79 percent of the mining companies surveyed identified investing in data analytics and Industrial Internet as among their top three priorities.

The worldwide mining industry is already leveraging IIoT in wireless mining automation and connected mine projects. For example, Rio Tinto (2008) has been using autonomous, self-driving mining trucks to move ore around since 2008. Each self-driving truck has 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 are fed into a comprehensive mine automation system, which gives a system view of the entire mining operation, including 3D visualizations of work sites and predictive maintenance schedules.

Cisco has actively promoted two cases where IIoT technology has been successfully applied to improve the safety and efficiency of underground mines. In the first case, which is perhaps one of the best known IIoT mining examples and has been highlighted in Cisco’s IIoT initiatives (Cisco, 2014), 280 Cisco wireless access points were installed in the flagship gold mine of Dundee Precious Metals in Chelopech, Bulgaria, to provide wireless coverage along 50 km (31 miles) of tunnels. The IIoT solution implemented at this mine has helped to connect people, track the locations 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. The second case was presented through a partnership with Goldcorp (Cisco, 2015). In addition to communication and real-time tracking of people and assets, ventilation on demand (VoD) was implemented based on a multiservice IP network installed in one of Goldcorp’s mines.

In 2014, General Electric teamed up with mining equipment manufacturer Komatsu to implement IIoT solutions to improve the efficiency and service of mining operations (Vella, 2015). A joint venture called 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 technology can be used to provide data analytics on truck performance 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.

Engineers from the NTT Innovation Institute Inc. and Colorado School of Mines recently completed a pilot project using IIoT to provide VoD at the Edgar Experimental Mine (NTTi3, 2016). Based on the team's assessment, the program achieved 10 percent energy savings in the first two weeks.

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 limited. Some barriers to IIoT integration 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 taken initial steps to explore IIoT in underground coal mines.

Although still in its infancy in terms of implementation, IIoT in coal mines has been a hot research topic since early 2000 and has been widely investigated in China. For example, IIoT has been proposed in China for coal mine disaster warning (Hu et al., 2014), intelligent mine monitoring (Hu et al., 2013), mining equipment management (Tan et al., 2013), environmental sensing (Chen et al., 2012), real-time positioning (Wang, Zhou et al., 2011), coal seam water monitoring (Meng, Wang and Gao, 2012), and accident analysis (Sun, 2015). In addition to specific applications, some published papers focus on IIoT system overview and architecture design (Ke, 2010; Wei, Zhu and Du, 2011; Wang, Zhao et al., 2011; Zhang et al., 2012).

Reports on studies of IIoT in coal mines in other countries have been limited, but some related studies, such as those on minewide monitoring systems, have been reported in the United States and abroad. For example, the U.S. Bureau of Mines (1984) published a technical report comparing different mine monitoring systems in underground mines, and Nutter and Aldridge (1988) investigated the status of mine monitoring and communication. More recently, U.S. National Institute for Occupational Safety and Health (NIOSH) researchers conducted an MSHA data survey and found that 204 carbon monoxide systems and 33 AMS systems had been installed in producing coal mines in the United States (Rowland, III, Harteis and Yuan, 2017). Mine monitoring is a part of the IIoT, though it does not encompass the concepts of a complete IIoT solution on its own.

NIOSH has conducted intramural research in areas directly related to IIoT technologies. One of the key elements of underground IIoT is the communication backbone for connecting things underground. In 2010, NIOSH launched a five-year research project to investigate radio propagation mechanisms for the different frequencies that are commonly used by existing underground communications and tracking systems. Theoretical models were developed to predict underground communication and tracking system performance and were validated through extensive measurement results (Zhou, Waynert et al., 2015; Zhou, Plass et al., 2013).

In 2014, NIOSH engineers reviewed the emergency response plans of 306 active coal mines in the United States as part of a project on communication and tracking. The mines' post-accident communication and tracking system installation information was extracted and analyzed (Damiano, Homce and Jacksha, 2014). One of the major results (Fig. 1) was a comprehensive overview of the communication and tracking systems installed in U.S. underground coal mines in 2014. The list was used to evaluate the state of post-accident communication and tracking 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.

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 with those that already exist in coal mines. By examining the IIoT technologies used in other industries, the following system core components are identified: (1) things, such as machines and people equipped with sensors, services and actuators, (2) networks, to connect things together, and (3) 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 shows some examples of existing underground systems that can potentially be integrated to form a new IIoT system.

Ventilation and fire detection systems—Fires and explosions have been serious safety concerns since the advent of mining. Ventilation systems are crucial for maintaining nonexplosive and nontoxic atmospheres. The progression of technology has allowed mine monitoring techniques to become more sophisticated, and various advanced sensors for monitoring dust, oxygen, methane, carbon monoxide, carbon dioxide, temperature and air velocity have been developed and deployed throughout the mining industry (Rowland, III, Harteis and Yuan, 2017). In an IIoT system, these sensors could potentially be connected to a network to form a minewide 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 indicate a fire is occurring underground, the system may automatically activate fire suppression systems in the point of origin while taking additional measures to prevent the fire from spreading.

Personnel and asset tracking systems—With the 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 locations of those important assets along with the locations of all 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 locations of underground personnel. Many of those 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 MSHA-approved sensors are gas sensors, including those for methane, oxygen and carbon monoxide; airflow sensors; temperature and humidity sensors; vibration sensors; smoke sensors; and alarm sensors. There also exist approved sensors for monitoring other parameters, such as ventilation fan speed, pump water level, power status, and conveyor-belt conditions like speed and slip detection.

Networks

Information collected by underground sensors should be readily accessible by underground miners as well as by dispatch personnel on the surface. Many mines have installed communication systems that have data back-haul capability. In these cases, an IIoT network may potentially be established based on existing mine communication systems, such as fiberoptics 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 underground. Therefore, from the bandwidth point of view, node-based systems with fiberoptics as a communication backbone would be favorable for IIoT applications. In addition, a communication interface between the existing communication backbone and the sensors would need to be established. One way to accomplish this is to attach a radio-frequency transceiver module to the sensors, or things. Different communication protocols, such as Wi-Fi, Zigbee, Bluetooth and BLE, should be investigated to identify the best protocol suited to 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. A solution would be to leverage existing communication and tracking networks as the backbone for these installations. As depicted in Fig. 1, there are a number of communication systems that may be suitable for sensor data transmission and controls. An examination of each of these systems found that five of 12 systems, or 42 percent, 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 1.

The number of manufacturers and availability of Internet-ready systems may have increased since 2014, 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 inside and outside of mines. By leveraging a customizable and intuitive user interface, and with full mobile accessibility, users are able to gather insight into 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 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 in the 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 the safety and productivity of the mining industry to new levels by enhancing the collaborative operation between people, equipment, transportation tools and the mining process. As shown in Fig. 2, the primary end users of a IIoT system would be controlling centers on the surface. Besides mining companies, the proposed IIoT systems 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 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 large 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 hazardous 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—Many types of equipment are used underground for production and transportation purposes. They need to be regularly maintained to limit unexpected failures or breakdowns. 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 minewide 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 the relevant 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 the automation of mine equipment. For example, from a safety point of view, a good way to reduce mining injuries might be to relocate miners away from extremely dangerous working places and providing them with automated or remote-controlled machines. As a matter of fact, wireless mining automation is already being used. Automatically controlling equipment based on information monitored is in the spirit of IIoT systems and may significantly contribute to the next generation of mining automation.

Predictive energy optimization, such as ventilation on demand—VoD is probably one of the most known applications of IIoT to the mining industry, but IIoT applications are not limited to VoD. 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 could also allow equipment manufacturers to track the performance of their products in their lifetimes 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 emergency response plans, a list of first aid stations, a list of trained rescue personnel along with their contact information, and place of duty during an emergency — and makes this information easily accessible by authorized staff. Through an integrated personnel tracking system, the IIoT system can provide the names 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 minewide gas conditions provided by the minewide 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 systems—In the event of a disaster, miners are trained to escape from the mine with the available self-rescue apparatus first, and enter a refuge alternative if escape is cut off. Refuge alternatives are intended to provide mine workers with breathable air, food and water for 96 h. Although refuge alternatives are only designed for use in post-accident events, their functionalities should be checked periodically to make sure they will work as designed in an emergency. Furthermore, there should be a mechanism to immediately signal the surface when a refuge alternative is activated following a disaster. One way to monitor the occupancy status of a refuge alternative from the surface is to attach a sensor, such as a magnetic switch sensor, to the door of the refuge alternative to detect when the door 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 the inside and outside of the refuge alternative could be continuously monitored from the surface. The equipment inside refuge alternatives can also be monitored and managed by the proposed IIoT-based network system.

Key challenges for IIoT in coal mines

Challenges

Despite the promise and new opportunities offered by IIoT, there are challenges that could hinder the adoption of IIoT technologies in coal mines.

Security and privacy—Security due to connectivity to the global network is always a concern for IIoT technologies, especially in the mining industry. According to the results of a World Economic Forum survey on IIoT (source details), 72 percent of the people surveyed believe that concern over security 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 they can be adapted to the constraints of the sensors deployed in mining environments.

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

Harsh and gassy environments—Although IIoT has been successfully implemented in other industries, special care has to be taken to adapt the technology from the surface to the underground. First, due to the harsh nature of mining environments, such as extreme moisture and heavy dust, 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 (Zhou, Plass et al., 2015). Third, the gassy underground atmosphere is potentially explosive, so intrinsic-safety or explosion-proof technology is often required in underground coal mines. Electrical systems, including the IIoT sensors and communication nodes, should be designed in such a way that they do not have 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 be interoperable.

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

Refuge alternative door-open detection

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 refuge alternative located in the experimental mine. The sensor/micro-controller was programmed to conserve battery power, so it was dormant most of the time and would only transmit data whenever a door-open event was detected. The user interface would display the status of the door after it received messages from the sensor. A similar approach was taken for other controlled devices.

In this demonstration, one warning light and two fans were used to demonstrate the automatic actions enabled by the sensor network (Fig. 5). The actuators and sensors communicated with the server using the Message Queue Telemetry Transport (MQTT) protocol, which is a publish-subscribe lightweight messaging protocol designed for machine-to-machine 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 refuge-alternative door was open and turn them off when the door was closed.

Although a simple door-open detection sensor was used in the demonstration, other sensors can also be used as the event triggers. 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, the connected things in this demostration 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 can get the information.

Conclusion

This paper presented a discussion on the current state of IIoT in the mining industry, specifically, 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 exists 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, an example for a mining-specific IIoT application was presented by discussing a NIOSH prototype system that was developed based on low-cost, open-source micro-controller boards. The system was developed and installed in NIOSH’s experimental mine in Pittsburgh to monitor the door status of a built-in-place refuge alternative and to automatically turn on or turn 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.

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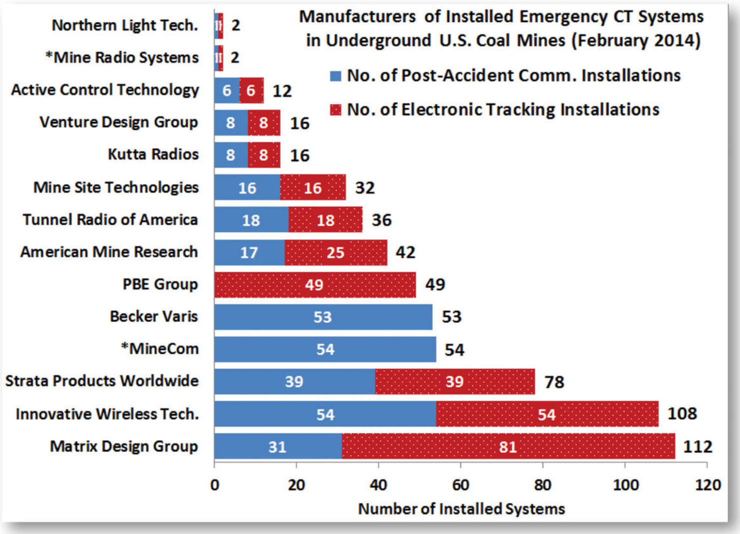

Figure 1.

Overview of communication and tracking systems installed in U.S. underground coal mines (Damiano et al., 2014).

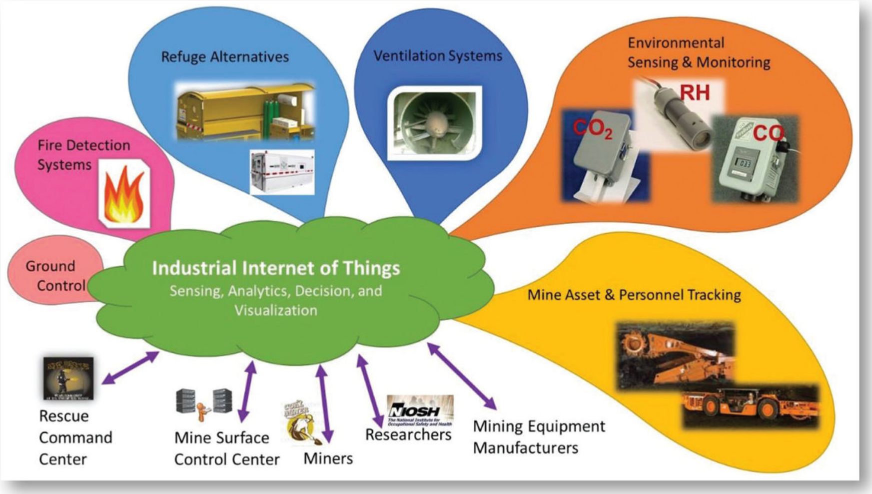

Figure 2.

Example of IIoT system in coal mines.

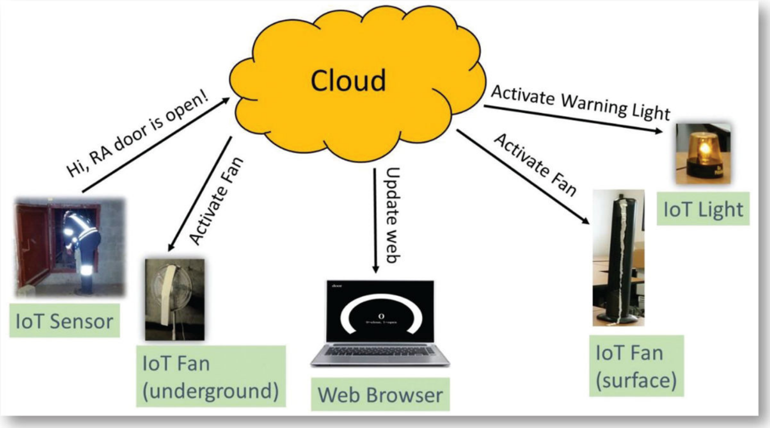

Figure 3.
IIoT system used for the demonstration in the Pittsburgh Experimental Mine.

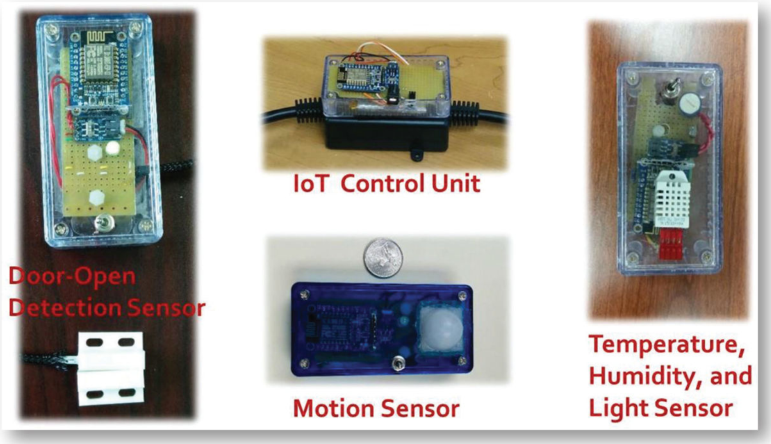

Figure 4.

Examples of IoT sensors and actuator.

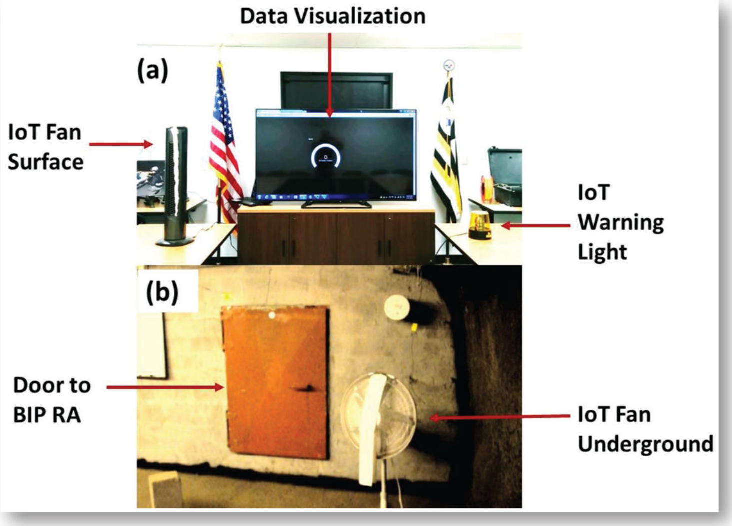

Figure 5.
IIoT demonstration setup in (a) a conference room (top) and (b) the Pittsburgh Experimental Mine (bottom).

Table 1

Manufacturers of Internet-compatible systems in active U.S. underground coal mines in 2014.

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