Intelligent monitoring system for improved worker safety during plant operation and maintenance

by D. Parks, M. McNinch, R. Jacksha, H. Nickerson and A. Miller

Each year hundreds of mine workers are involved in machinery-related accidents. Many of these accidents involve inadequate or improper use of lockout/tagout (LOTO) procedures. To mitigate the occurrence of these accidents, new safety methods are needed. These methods should include the monitoring of access to hazardous areas around operating machinery, improving documentation/monitoring of maintenance activities which require shutdown of the machinery, and preventing of unexpected startup or movement during machine maintenance activities."

Of the hundreds of machinery-related accidents occurring every year in the mining industry, incidents involving stationary machinery at surface mines continue to be among the most frequent (MSHA, 2017). A U.S. National Institute for Occupational Safety and Health (NIOSH) study showed that the majority of fatal accidents involving stationary machinery at surface mines occurred at sand and gravel (38 percent) and stone (26 percent) operations. Of these accidents, entanglement in conveyor components were the most common cause of fatal accidents (48 percent) (Ruff et al., 2011). The same study stated that one-third of these accidents involved improper lockout/tagout (LOTO) procedures as a contributing factor. The U.S. Mine Safety and Health Administration (MSHA) acknowledged this problem, stating in a recent request for information (MSHA, 2018): "Since 2007, there have been 17 fatalities related to working near or around belt conveyors, of which 76 percent were related to miners becoming entangled in belt drives, belt rollers and discharge points. Factors that contribute to entanglement hazards include inadequate or missing guards, inadequate or an insufficient number of crossovers in strategic locations; and/or inappropriate lock out/tag out procedures. Systems that can sense a miner's presence in hazardous locations; ensure that machine guards are properly secured in place; and/or ensure machines are properly locked out and tagged out during maintenance would reduce fatalities" (MSHA, 2018).

In response to this problem, NIOSH's Spokane Mining Research Division (SMRD) is exploring the potential application of Internet of Things (IoT) technologies to provide cost-effective intelligent machine monitoring systems for improved worker safety (Zhou et al., 2017; Reyes et al., 2014). SMRD partnered with Central Pre-Mix CRH Co. (Central Pre-Mix) to develop and install a proof-of-concept wireless IoT solution to monitor machinery and conveyors during operation and maintenance. The primary goals of the system were to provide real-time monitoring of access points and facilitate the planning and execution of LOTO procedures.

This article describes the design and field deployment of this system. Field demonstration is a first step toward widespread adoption of intelligent safety monitoring systems and holds promise to reduce accidents related to machine guarding and improper implementation of LOTO procedures.

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Monitoring of LOTO and confined-space requirements

Machinery monitoring requirements for this study were driven by Central Pre-Mix's concrete batch plant daily operational and maintenance practices. High-priority needs included monitoring access to the mixing area, measurement of concrete batch temperatures, measurement of the temperature of the concrete mixing drum main support bearings and, end-of-shift maintenance of the concrete mixer drum.

Access to mixing area. While access to the mixing area is not restricted, monitoring the access door allows batch-plant operators to be aware of any workers entering or leaving the vicinity.

Concrete batch temperature. Knowing the concrete batch temperature is critical to ensure quality and long-term integrity of the concrete. The batch temperature could be determined by a worker using a handheld infrared (IR) thermometer. However, this is hazardous as the worker could be entangled in the mixer drum while taking measurements.

Temperature of mixer drum main support bearings. The temperature of the concrete mixing drum main support bearings is checked regularly as a predictor of necessary maintenance or potential failure. A sudden bearing failure could be hazardous to workers and incur costly repairs, but this can be mitigated through routine monitoring for elevated bearing temperatures.

LOTO/confined space. Daily maintenance of the mixer drum requires a worker to crawl inside the drum and remove accumulations of hardened concrete using a pneumatic rotary hammer (mixer drum chipping), as shown in Fig. 1. Access to the mixer drum entry is through a gate labeled with a confined space warning sign. Prior to this, electrical power is isolated from the drum, charge belt, mixer feed conveyor and hydraulic pump motors using four disconnect switches. The daily cleaning procedure thus entails both LOTO and confined space protocols.

During daily mixer maintenance, the four disconnects are locked in the OFF position (lockout) using a long bar held in place by a single padlock (Fig. 2). A tag belonging to the worker(s) involved is placed on the lock (tagout), then verification of electrical isolation is performed by attempting to start each motor (try out), at which point the LOTO is complete and the worker may enter the drum.

Before entry, a confined space permit must be filled out. Both the worker who is performing the chipping and an attendant who will remain outside the drum sign the form. Once the mixer drum chipping is complete, the confined space entry permit is indicated as complete by writing the word "canceled" in big letters across the form. The last step is filing the completed permit onsite.

System design considerations and hardware selection

The system was designed as proof-of-concept and thus is exploratory in nature. The central aim was to determine the viability of IoT in providing intelligent machine monitoring and assisted LOTO. System design considerations included wired versus wireless technologies, sensor types, sensor node power requirements, sensor node network topology and data transport method.

Wired sensors were considered impractical for this work, since NIOSH's eventual goal is to demonstrate the technology for mine machinery and conveyor systems in a large surface operation such as an SSG facility. A wired solution would severely increase installation and maintenance costs, along with slowing deployment. Further, some sites would have limited access to ac power. It was with these factors in mind that battery-powered sensor nodes were selected. This requires that batteries be replaced on a yearly basis.

The mixer area presented a challenging environment for a wireless network since it contains large metal objects such as the mixer drum and its support structure, conveyors, conduits, and electrical panels, all of which will create signal interference. Also, only three of the proposed sensor node locations had a line-of-sight to the IoT node coordinator (gateway). Given the difficult environment, it was decided that a self-configuring, self-healing mesh network topology would offer the best chance for robust wireless links (Akyildiz and Wang, 2005; Bruno et al., 2005).

In order to process data independently of Central Pre-mix's information technology

Figure 1

Entering mixer drum to perform maintenance.

Figure 2

Locked out disconnect panel.

Figure 3

A SmartSwarm cellular gateway (left), industrial-grade Wzzard node (middle) and commercial-grade Wzzard node (right).

network, a cellular data transport (backhaul) was determined to be the best choice to transport sensor data to cloud storage (Zheng et al., 2012). This does not place a burden on the site's network infrastructure, and it avoids any concerns regarding confidential data.

With the system design criteria defined, a review of various wireless IoT technologies and manufacturers was conducted, seeking products that were commensurate with the requirements. It was found that the Wzzard platform by Advantech (Ottawa, IL) provides such a solution in the form of rugged IP67 rated nodes. Additionally, these nodes come configured with a variety of analog and digital sensors and create a self-forming and self-healing mesh network topology. This solution is scalable to hundreds of nodes and has available a cellular gateway for ease of data transport to cloud storage. Figure 3 shows a photo of a SmartSwarm cellular gateway (by Advantech) on the left and two Wzzard sensor nodes on the right. These sensors utilize the message queuing telemetry transport (MQTT) protocol, which is a publish/subscribe protocol requiring a publisher (the sensor), a broker (the gateway), and a subscriber (the webpages). This type of network is time synchronized, which helps to ensure low power by reducing the duty cycle. However, this also means that data is received, at most, every 10 seconds.

Cloud data storage

The sensor data is sent to the cloud from the local mesh network using a cellular gateway, creating an additional network parallel to the site's infrastructure. This provides additional security by segregating the collected data from sensitive material on the site's existing network. Additionally, the use of a cellular backhaul provides a quick installation, which can be easily upgraded, replaced or relocated at the site.

The monitoring system uses the cloud for data storage, which has become common for enterprise applications, as it offers many benefits over traditional local storage. Foremost, the monitoring data can be easily viewed remotely, providing personnel with real-time data off-site via a PC or mobile device. A safety officer, management or foreman will receive alerts concerning LOTO violations or impending equipment failure and can readily check current conditions in the plant. Cloud storage also offers scalability. Should the monitoring system expand, the local network and storage would be placed under a heavier load and would require upgrades and maintenance. Cloud storage removes this problem while keeping costs low.

One concern about cloud storage is security, namely data leaks. To help alleviate these concerns the data should encrypted during transport to the cloud and while it is stored on the cloud. Further, users of cloud services are able to effectively own their data by controlling their own encryption keys (Wall, 2016). These practices along with two-factor authentication will do a great deal for improving data security. It should be noted that many of the recent infamous data breached systems, for example Sony and Target, were not cloud based but rather internal data systems.

Installation, configuration and commissioning

The first step in field installation was to install sensors and connect them to the wireless nodes. For the access door and entry gate, magnetically activated reed switch sensors were selected. With this method, the opening of the gate/door is detected while vibrations do not cause false readings (Reyes et al., 2014). For temperature measurements on the bearings, contact thermocouples were installed under mounting bolts with thermal grease. Finally, the batch temperature was measured using a self-powered IR thermocouple.

Once sensors were in place, each was connected to its dedicated node. The roller temperature nodes were set to a publish rate of two minutes, whereas the door, gate and safety disconnects were set to publish every 10 seconds. Publishing every 10 seconds will greatly impact battery life but was deemed necessary to provide timely worker location data.

After installation, all of the nodes were configured to communicate with a gateway on which a scripting software (Node-RED) was used to parse the data and create local webpages (independent of Internet connectivity for redundancy), displaying the sensor data on a web browser. Additionally, the gateway collects the data from sensors and sends the data in the form of encrypted MQTT messages to the cloud where scripting software parses the data and relays it to webpages for remote viewing.

The redundant local viewing (store and forward configuration) provides a safeguard in the (yet to be encountered) case where the cellular network fails. The local display consisted of a 48-cm (19-in.) touchscreen and a Raspberry Pi, essentially acting as a thin client, modified to operate in kiosk mode. This does not ensure remote viewing capability in the event of cellular network failure but does provide those on site with accurate up-to-date safety-related information. Remote or local viewing is possible on any device with a current web browser, as shown in Figs. 4 and 5.

In addition to viewing data, the prototype system allows the worker to use a tablet or cell phone to populate forms that are required for LOTO or confined space procedures (typically done using paper and pencil). While this currently does not supplant paper forms, the digital submission and archiving of such forms provides useful data that can easily be referenced later. It is however hoped that in the future easy-to-use mobile forms or strategically located LOTO kiosks will replace the current paper and pencil method.

Currently the supplemental form data are compared with sensor data thereby confirming that the LOTO process is performed according to policy and providing alerts in the event that it is circumvented. For example, if there has not been a form submitted to plan the chipping of the mixer and the gate is opened, an alarm is sent via text message and email. Alarms are also sent in the event that the chipping of the mixer takes inordinately long.

Two key challenges to the implementation of the system were battery life of the nodes and configuration of the network to ensure all nodes had a robust connection. These two issues are closely related in that one of the main causes of reduced battery life occurs when nodes are repeatedly seeking and failing to connect with each other. This can be aided by using better antennas (e.g. larger, externally mounted) or by installing repeater nodes in cases where neighboring nodes are failing to connect properly.

To address these issues and troubleshoot connectivity problems, one may utilize the "network health reports." Using these reports, nodes that are having to repeatedly rejoin the network can be detected, and the signal strength among all of the nodes is detailed.

Figure 4

Web browser view of disconnect switches and gate/door statuses.

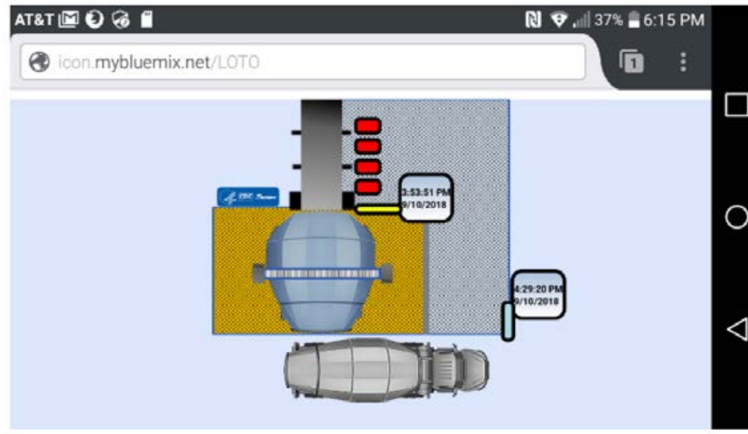
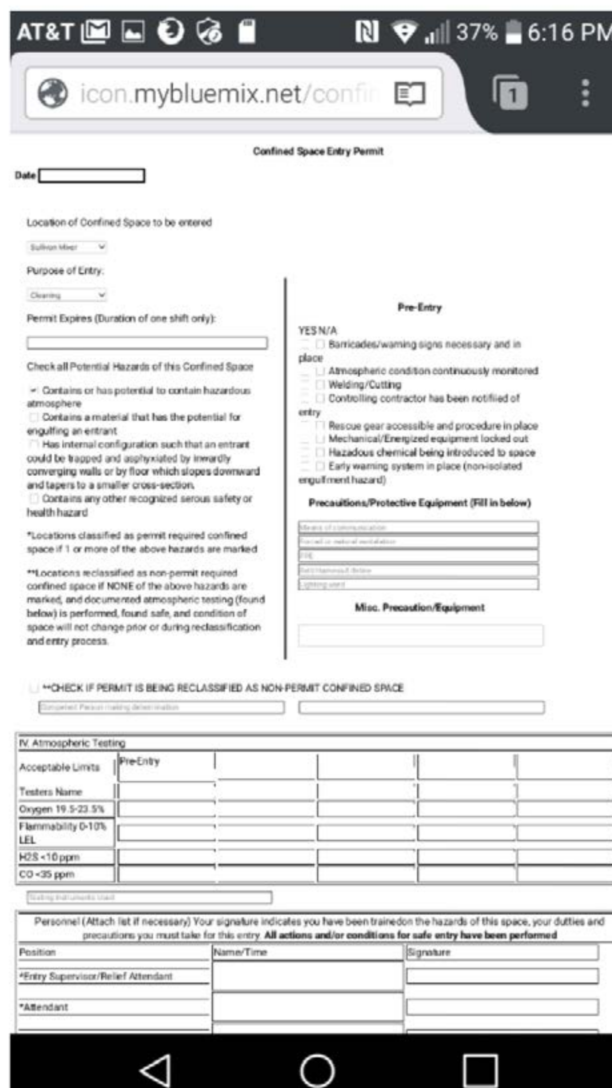


Figure 5

Web browser view of online confined space entry form.



Summary

A wireless IoT system was utilized to monitor a LOTO process and shows promise for both making LOTO less burdensome and providing additional accountability for following required safety practices. NIOSH researchers are currently expanding this system in terms of scope and functionality. The final system is expected to include predictive failure analysis as well as additional sensors to monitor worker proximity to hazards. Significant research will be conducted in the field of human factors in hopes of ensuring that the system is easy to use and effective, thereby encouraging widespread adoption throughout the mining industry.

The proliferation of IoT devices in the business and consumer spheres illustrates that the public is ready to adopt these new solutions. The mining sector in particular will benefit enormously from the ability to remotely view safety-related data in real time and to receive alarms when safeguards are potentially failing. There is a preponderance of evidence that conveyor operation and maintenance is hazardous to workers, and NIOSH will continue working to reduce these accidents through leveraging emerging technologies such as IoT.

Future opportunities

In the future, it is hoped that LOTO can be performed seamlessly without having to leave the machine and return to the office to fill out paperwork. This will first require mobile or strategically placed devices for planning the LOTO, and secondly, appropriately placed locks, which ideally will be networked as well. Such a lock will discern not only if it is open or closed, but also that it is being used on the appropriate piece of equipment, i.e. the piece of equipment for which maintenance has been planning to use the electronic forms.■

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Disclaimer

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement of NIOSH.

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