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PERFORMANCE OF AN INTELLIGENT PROXIMITY DETECTION SYSTEM FOR CONTINUOUS MINING MACHINES

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ABSTRACT

Continuous mining machines are extensively used in the underground coal mining industry. These machines are typically remote-controlled, and severe injuries and fatalities occur every year when a miner is struck or pinned by the machine. Proximity detection systems offer a means to prevent these types of injuries and fatalities by sensing the presence of a miner and disabling machine motion. Researchers at the National Institute for Occupational Safety and Health (NIOSH)have developed the Intelligent Proximity Detection (iPD) system to provide enhanced protection while minimizing false alarms. The iPD system uses a set of pre-defined rules to determine which machine motions are safe and which would present a potential hazard, and automatically disables only the potentially hazardous motions. This system has been installed and tested on a Joy 14CM continuous mining machine at the NIOSH Office of Mine Safety and Health Research in Pittsburgh. Under laboratory conditions, the achievable accuracy and performance of the iPD system has been quantified with respect to a number of variables including position of the conveyor boom, presence of the machine's trailing cable, and orientation of the miner-wearable component.

INTRODUCTION AND PREVIOUS WORK

Underground coal mining operations use continuous mining machines (CMMs), such as the one shown in Fig. 1, to extract coal and other minerals from the ground. In the past, these machines were operated from an on-board operator's compartment that protected operators but severely restricted visibility and subjected them to machine vibration and high levels of dust and noise. With the advent of remote controls, the operators of these machines are now free to position themselves for best visibility for the task at hand and are no longer subjected to the rough motion of the CMM during mining operations. However, the removal of the operator from the protection afforded by the operator's compartmenthas exposed the operator to the hazard of being struck or pinned by the CMM or other large moving machines.

Figure 1. A continuous mining machine operating in an underground mine.

The National Institute for Occupational Safety and Health (NIOSH) has conducted studies on the positions operators take relative to the CMM and the reasoning behind those decisions [1,2,3]. These decisions are usually governed by visibility requirements and perceived safety concerns.

Since 1984 there have been 35fatalities involving striking and pinning of the operator and other workers by the CMM [4]. In August 2011, MSHA published a proposed regulation that would require proximity detection systems on all continuous mining machines except full-face machines [5]. Proximity detection systems are designed to cause machine shutdown to protect personnel from being crushed, struck, or pinned when they become positioned in a hazardous area in close proximity to the CMM. NIOSH researchers have developed the Intelligent Proximity Detection (iPD) system, which is designed to offer protection while minimizing the occurrence of false alarms.

Proximity detection systems consist of sensors that detect the presence of nearby objects, workers, or vehicles through either passive or active techniques. Proximity detection can result in warning alarms and automatic interdiction of machine controls. Passive detection systems include radar and sonar. A disadvantage of these types of systems is that the type of object detected cannot be determined. For example, they cannot distinguish between a rock and a person. For this reason, active systems are preferred in an underground environment, where false alarms would be common.

Active proximity detection systems require two-way communication between a device on the equipment and a separate device on any object or person to be detected. This type of system requires all vehicles and personnel that might be at risk to be outfitted with a detection device, sometimes referred to as a miner-wearable component. Distance between the equipment and the detected miner-wearable component is usually determined using a signal strength measurement.

Active proximity detection systems are available that are based on the generation and detection of magnetic fields. These fields are generated by running electrical current through a wire coil wrapped around a ferrite core. The strengths of the fields are measured by the miner-wearable component. This concept was originally developed at NIOSH in the 1990s as the Hazardous Area Signaling and Ranging Device (HASARD) and was tested on continuous mining machines, shuttle cars, belt conveyors, surface mining haul trucks, and a highwall launch vehicle [6]. The technology and methods developed with HASARD have since been adopted by a number of manufacturers. An example of the magnetic marker field used in the HASARD system is given in Fig. 2. This type of system is particularly applicable to underground mining because of its low false alarm rate in close proximity to ribs and its ruggedness with respect to water, dust, and vibration exposure. While the technology is applicable to all types of underground mining equipment, perhaps the greatest safety gains can be achieved with CMMs, which have a very high rate of pinning and striking accidents. CMM operators and their helpers often stand in close proximity to the machine in order to see visual cues needed to operate the machinery [1]. MSHA estimates that of the 35fatal striking and pinning accidents that have occurred since 1984 involving CMMs, the use of proximity detection could have been a preventative factor in at least 27 cases [4]. Further, MSHA estimates that proximity detection could prevent up to 20% of all deaths throughout the industry [7].

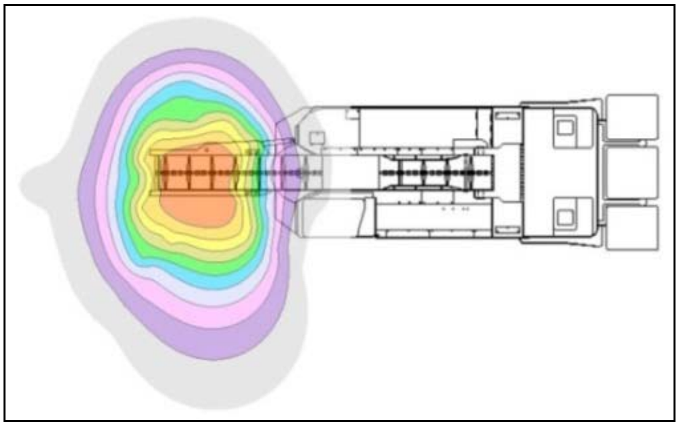

Figure 2. Example magnetic marker field used in the HASARD system.

NIOSH researchers have been involved in the development and testing of proximity detection technology since creating the HASARD system and have now developed the iPD system for continuous mining machines. As a foundation for the development of the iPDsystem, NIOSH researchers developed a sophisticated model of the magnetic fields used in proximity detection systems [8,9]. At the core of this model is an equation for the shapes of magnetic "shells," which are comprised of all points having the same magnetic field strength reading. The three-dimensional variation in shape and size of the shells described by this model is shown in Fig. 3.

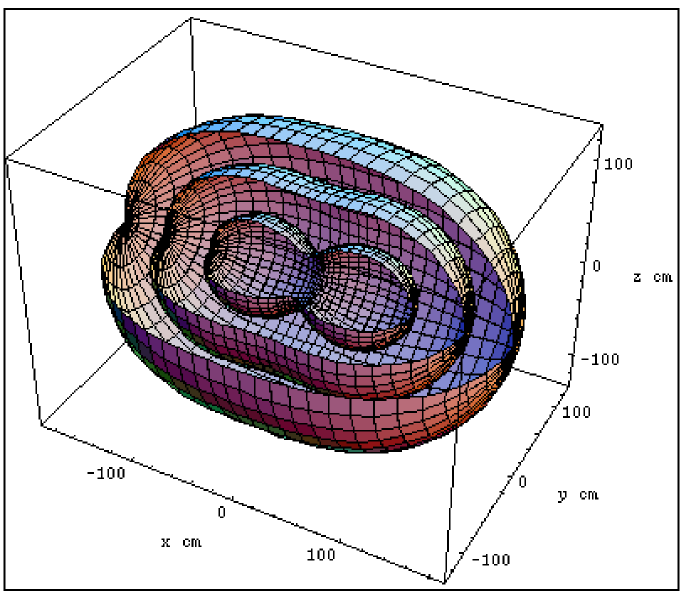

Figure 3. Example magnetic shell shapes as modeled by Li et al. [8,9].

Given this model of the magnetic fields, the research team then developed a novel method for determining the location of a miner-wearable component relative to the magnetic field generators. The position of the miner-wearable component is determined by finding the intersection of two or more magnetic shells. Due to the irregular shapes of these shells, an analytic solution cannot be determined. While numerical techniques may be sufficient for the two-dimensional case, they are not sufficient for finding a three-dimensional solution due to high computation time.Therefore, a novel geometric search method was developed which converges to the intersection of the shells through an iterative series of spherical approximations [10].

Using this method to continuously track the position of miners around a CMM, the iPDsystem was developed. Once the position of a miner is identified, the iPDsystem provides protection against striking and pinning accidents by acting to disable all machine motions that could cause a collision between the machine and a miner. To do this, a set of zones is defined around themining machine and each zone is associated with potentially dangerous machine functions. If a person is detected in a zone, the functions associated with that zone are disabled. This system was implemented in a laboratory setting and was provento provide good performance in identifying which machine functions should be disabled [11,12]. An example of how these zones could be configured is shown in Fig. 4. This example is one of many possible configurations and is not meant to be a recommendation.

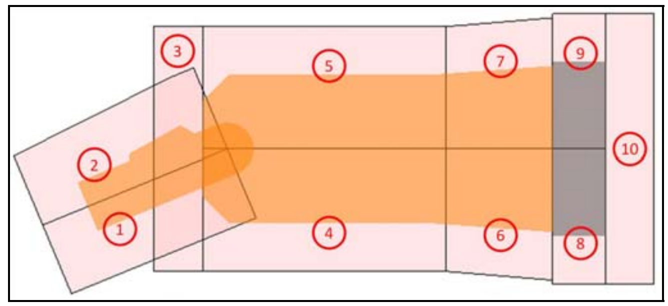

Figure 4. Example safety zone configuration used in the iPD system.

By only preventing the actions that could cause an injury, the iPD system allows miners more freedom to select where they position themselves. This allows miners to better avoid other hazards such as unsupported roof and ribs or collisions with other pieces of equipment in the area. Additionally, by minimizing the effect on the machine from operators' normal working procedures, acceptance of the system by operators should be enhanced. However, it is always the responsibility of the miner to position themselves in an area where they will be best protected from all potential hazards, and proximity detection should not be relied upon to provide fail-safe protection.

CURRENT WORK

The iPDsystem was successfully demonstrated under laboratory conditions using a first-generation prototype system [12]. However, this system had some limitations, the greatestof which was insufficient range to provide coverage around the entire machine. Therefore, a new six-generator, increased-range system was installed which is capable of providing complete protection around the machine. The locations of the generators in this system are shown in Fig. 5. It may be possible to provide similar performance with fewer generators or with the generators at different locations. The configuration shown is one possible configuration that was used to demonstrate the achievable accuracy of the iPD system and is not meant to be a recommendation.

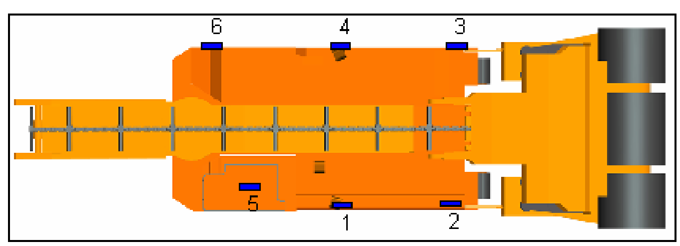

Figure 5. Magnetic field generator locations used in the current installation of the iPD system on a Joy14CM test bed.

A series of tests were conducted to determine the achievable accuracy of the position calculation. The accuracy of the system is affected by several variables that limit the maximum achievable performance due to the physics of the technology involved. This research investigates the influence of three of these variables that were considered likely to cause a significant change in performance. These variables are:

1) Conveyor boom position
2) Trailing cable position
3) Orientation of the miner-wearable component

DATA COLLECTION

To expedite the collection of a large dataset, a method of automatically moving the miner-wearable components around the machine was designed. A Parker HLE-C linear drive with approximately 20 feet (600 cm) of travel was used. One miner-wearable component was mounted on each side of this drive and was set at a height of 46 inches (117 cm) off the ground to approximate waist height.

The linear drive is shown in Fig. 6. The miner-wearable components are mounted on a nonmetallic structure that holds them at a distance from the metallic rail that was thought to minimize the effect on the readings. In addition, the miner-wearable components are mounted on 3-axis gimbals that allow the orientation of the miner-wearable component to be easily varied on all three axes.

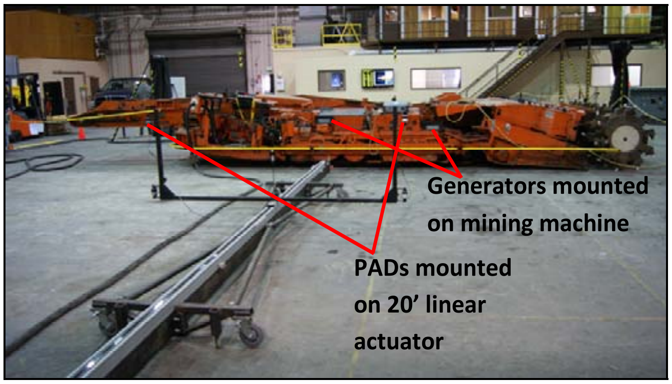

Figure 6. Automated data collection apparatus.

Using this apparatus, data was collected at a large number of locations around the mining machine. These locations are shown in Fig. 7. Each time the linear drive apparatus was set up at a new location, the position and orientation of both the machine and the linear drive were measured using land surveying equipment. This allowed the position of the miner-wearable components relative to the machine to be calculated. The miner-wearable components were moved automatically along the rail in 4-inch (10-cm) increments. At each position, the rail paused and approximately 20 readings were collected for each combination of miner-wearable components and magnetic field generators.

The readings generated by the miner-wearable component were recorded and converted to a normalized, unit-less value ranging from 0 to 100, where 100 corresponds to the maximum value that could theoretically be measured. In reality, readings near 100 are not observed.

RESULTS AND DISCUSSION

Once all data had been collected, the coordinates of the data locations relative to the machine were calculated. The origin of the coordinate system used is the nominal location of the pivot point of the mining machine. At each location there are readings for every combination of one of two miner-wearable components and six magnetic field generators. The actuator apparatus used to automatically move the miner-wearable components is suspected to have an impact on the magnetic fields used in the system. It is therefore not possible to consider all of the readings together. It is, however, possible to compare the readings collected with the actuator and CMM at a single setup location while the variables of interest such as conveyor boom position are varied. Since the influence of the test apparatus is a constant to all cases a direct comparison between cases can be made. For example, with the actuator and CMM in a constant position, repeated measurements with the miner-wearable component at a constant orientation can be compared to repeated measurements with the miner-wearable component at other various orientations. If there is a significant change in these measurements, it can be attributed to the change in orientation and not to the influence of the test apparatus.

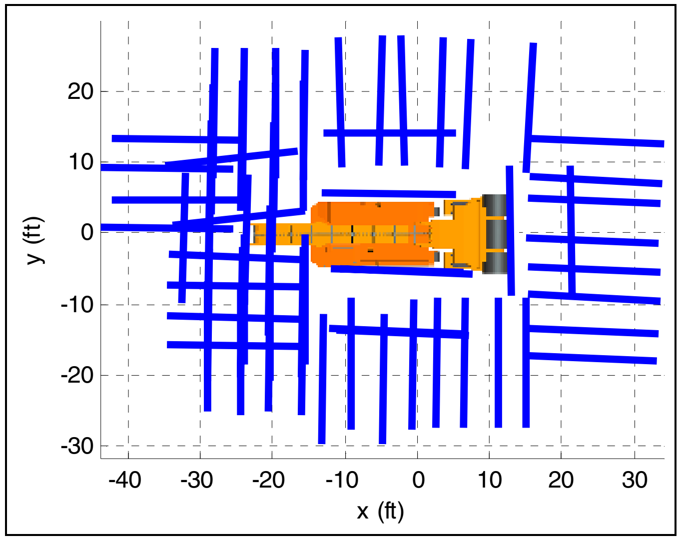

Figure 7. Data collection locations around the Joy14CM continuous mining machine: miner-wearable components were positioned in4-inch (10-cm) increments along each of the lines shown.

Conveyor Boom Position

The iPD system utilizes magnetic fields, which are affected by the presence of ferrous materials. With the magnetic field generators mounted on a steel mining machine, the shape and size of the fields used will change depending on the relative position of the generators to moving parts on the machine, such as the conveyor boom. The position of all moving parts of the machine including conveyor boomand cutter head is referred to as the “machine pose.” While the frequency used in the iPD system is known to be less susceptible than other frequencies, there is still an influence due to machine pose.

At several locations around the back half of the machine, readings were collected with the conveyor boom in the following positions at the extremes of the range of motion:

1) Down and center (Baseline)
2) Down and left
3) Down and right
4) Up and center
5) Up and left
6) Up and right

An example of the results obtained are shown in Fig. 8. In this figure, the position of the miner-wearable component changes from position A near the end of the conveyor boom to position A' approximately 20 feet (600 cm) further behind the machine. As with all of the data collected in these experiments, readings were obtained for each of the six generators mounted at various locations on the machine. The readings shown in this figure are for the generator mounted at the middle-left of the machine. With readings from this generator, the position of the conveyor boom apparently has a negligible influence on the readings.

An example of a worse case is shown in Fig. 9. In this figure, the miner-wearable component was moved along line A-A' to the rear of the conveyor. However, the generator used is much closer to the rear of the machine. The readings, therefore, seem to be more substantially affected by the position of the conveyor. Note that the iPD system has a minimum range inside of which the miner-wearable components do not return a reading. This results in the slightly shorter range of readings seen as compared to Fig. 8. Of particular interest is the range of distances over which a given reading could be observed. In the deployed system, this would correspond to the confidence interval that could be placed on the distance estimated from a reading. In this example, a reading of 30 could occur anywhere between about 3 feet

(91 cm) and 5 feet (152 cm) along the line A-A'. This means that, even for a perfectly calibrated system, a position error of ±1 foot(30 cm) could be expected.

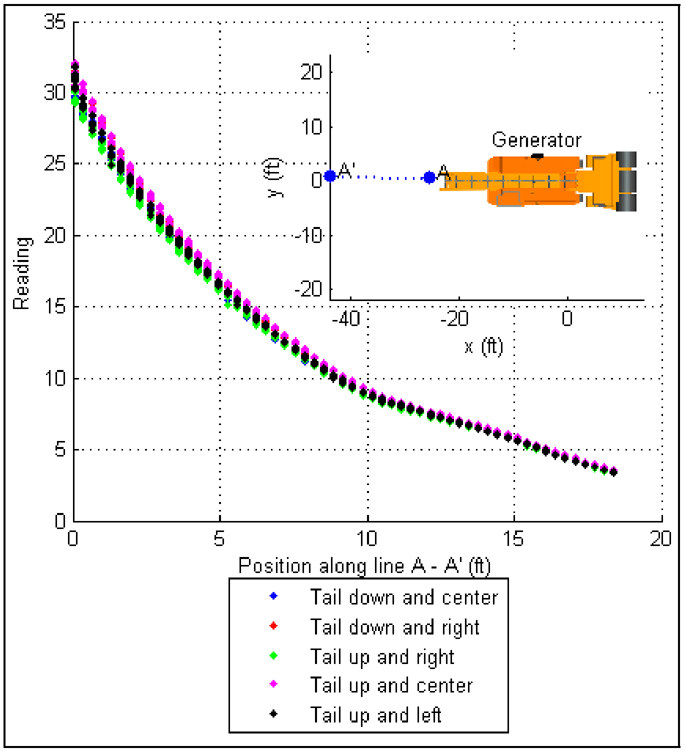

Figure 8. Example 1 of measured readings for various conveyor boom positions.

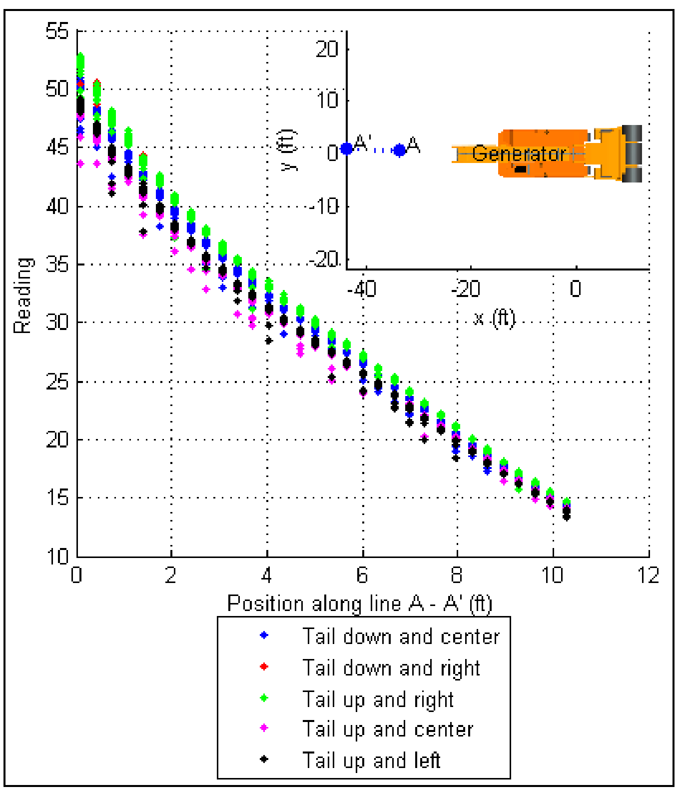

Figure 9. Example 2 of measured readings for various conveyor boom positions.

For points further away from the conveyor, the effect of conveyor position is smaller. However, the effect is still present. A third example is shown in Fig. 10. For all points where data was collected, the relative difference between each reading and a baseline reading was calculated. The baseline data set is with the conveyor boom down and in the center. At each data collection location, approximately 20 readings were collected. The average of these readings is used to normalize the measurements. For example, a normalized reading of 1.1 indicates that the measurement is 10% higher than the average of the baseline measurements at the same location. A histogram showing these normalized readings for a large number of locations around the back half of the mining machine is shown in Fig. 11. Ninety percent of all readings observed were within ±10% of the average baseline measurement.The correlation between this change in reading and a change in alarm distance or position accuracy will depend on several factors that influence the decay of the magnetic fields with distance. These factors include the power supplied to the generators, the design of the internal components of the miner-wearable components and signal processing that is performed internally on the miner-wearable component. However, since the strength of the magnetic fields decays in a non-linear fashion with respect to distance [8], it is reasonable to assume that a 10% change in reading could result in a difference of more than 10% in the distance at which an alarm would be issued.

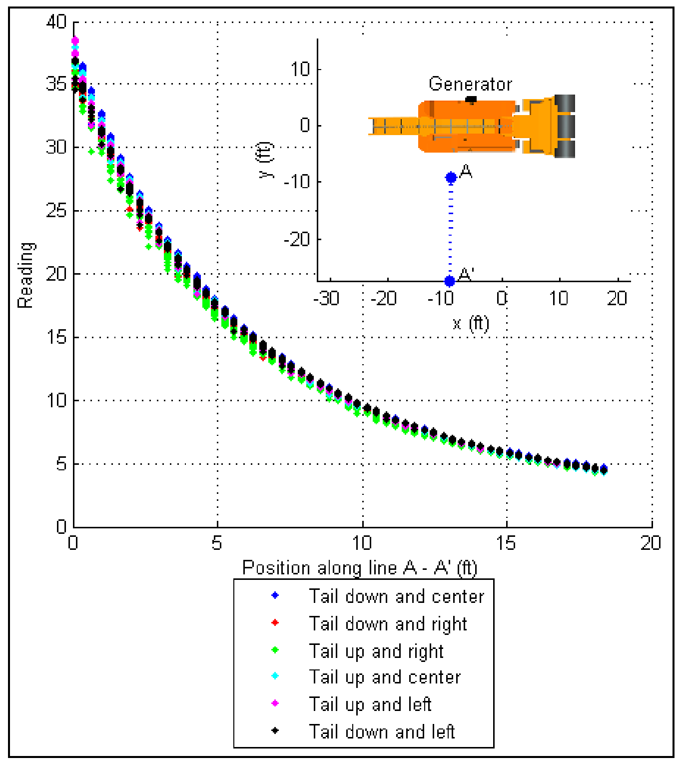

Figure 10. Example 3 of measured readings for various conveyor boom positions.

These results apply to the iPD system as configured for these experiments and are meant to demonstrate some of the limitations of the technology. In the design and implementation of any proximity detection system, it is critical to correctly locate the generators on the CMM to limit the errors introduced by machine pose.

Trailing Cable Position

The CMM trailing cable is another potential cause of changes in the measured field strength at the miner-wearable component. A test was conducted at a single location near the mining machine in which the miner-wearable components were moved along line A-A' as shown in Fig. 12. First, data was collected without the trailing cable near the miner-wearable components. Then data was collected with the trailing cable running along line A-A' directly below the miner-wearable components (this data is labeled "Cable Parallel" in Fig. 12). Finally, data was collected with the cable running perpendicular to line A-A' along the side of the CMM (this data is labeled "Cable Perpendicular" in Fig. 12). As can be seen in Fig. 12, with the miner-wearable components at 46 inches (117 cm) from the ground, no significant difference was observed with the cable present in either the parallel or perpendicular configuration.

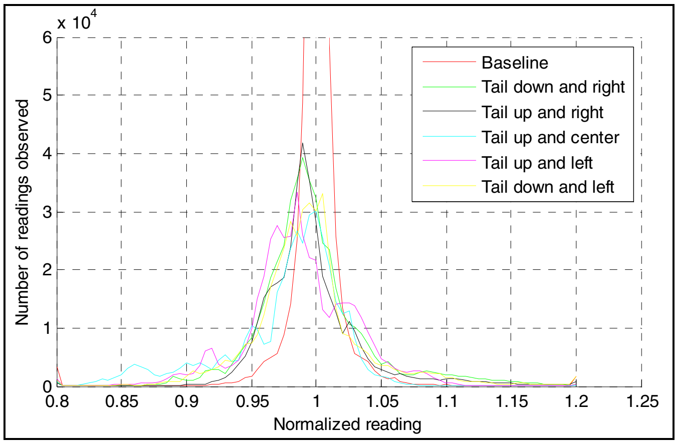

Figure 11. Histogram of normalized measured readings for various conveyor boom positions.

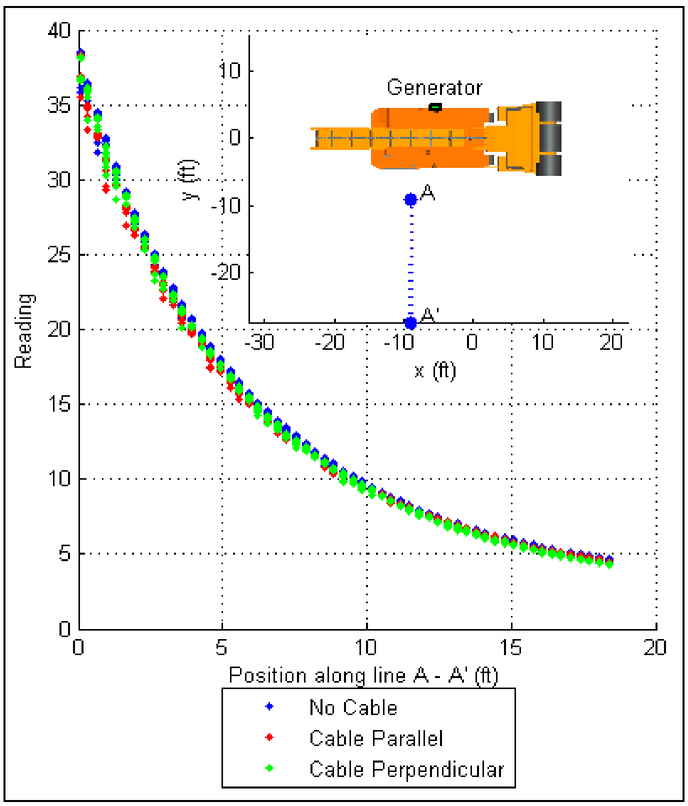

Figure 12. Example of measured readings for trailing cable positioned near the miner-wearable components.

Orientation of the Miner-Wearable Component

Design features within the miner-wearable component are meant to ensure that a consistent measurement is returned regardless of orientation. This is accomplished by using three receivers mounted orthogonally within the miner-wearable component. The signals from the three receivers are combined using a vector norm, which varies much less with variations in orientation. This is especially important since the miner-wearable component may be mounted on a miner's belt and is constantly changing orientation relative to the magnetic field generator as the person moves. The size of the receivers and the spacing between the receivers within the miner-wearable component limit the degree to which the effect of orientation can be mitigated using a vector norm calculation. Since it is physically impossible to manufacture a miner-wearable component with receivers of zero size and with zero spacing between the receivers, it is impossible to fully counteract the impact of miner-wearable component orientation.

To quantify this impact, a test was conducted in which the miner-wearable components were moved along the same line with 21 different orientations. These orientations are shown in Table 1 and are meant to cover a range of orientations that might be possible as a miner is moving with the device on his belt. Of particular interest is yaw (rotation about the vertical axis), since this will change most frequently as the miner turns. Roll and pitch will change less frequently only when the miner is bending or changing posture.

Table 1. Orientations evaluated.

Data Set Number	Roll (degrees)	Pitch (Degrees)	Yaw (Degrees)
1 (Baseline)	0	0	0
2	0	0	15
3	0	0	30
4	0	0	45
5	0	0	60
6	0	0	75
7	0	0	90
8	30	0	0
9	45	0	0
10	60	0	0
11	90	0	0
12	0	30	0
13	0	45	0
14	0	60	0
15	0	90	0
16	30	0	30
17	45	0	45
18	0	30	30
19	0	45	45
20	30	30	0
21	45	45	0

Example results from this experiment are shown in Fig. 13. In this figure, the baseline readings are shown in red while all other readings are shown in black. Similar to the results with the conveyor position, it is possible to see that a single value of the reading could occur over a range of approximately 2 feet (61 cm). This indicates that at best a ±1-foot (30-cm) error would be expected in this example.

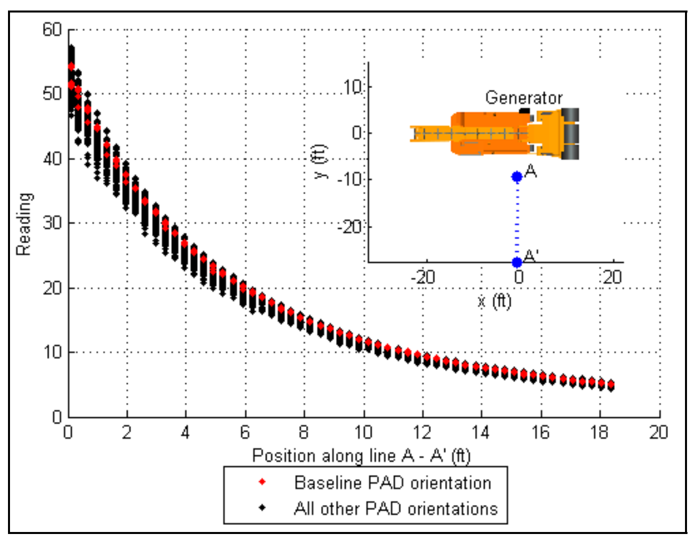

Figure 13. Example of measured readings for various orientations of the miner-wearable component.

Data was collected at the 21 orientations of the miner-wearable component and for each of the six magnetic field generators.

Approximately 20 readings were collected at each 4-inch (10-cm) step along the actuator. A histogram of all of these readings is shown in Fig. 14. Similar to the results shown for the conveyor position, these readings have been normalized to the average of the baseline readings at each 4-inch (10-cm) step. From all of the measurements taken, 90% were within ±10% of the average baseline reading and 95% were within ±15%.Again, the correlation between the accuracy of the field strength and the accuracy of alarm distance is not direct. However, for example, at a distance of 10 feet (305 cm) from the magnetic field generator, one would expect that at best an accuracy of ±1.5 feet (46 cm) could be expected.

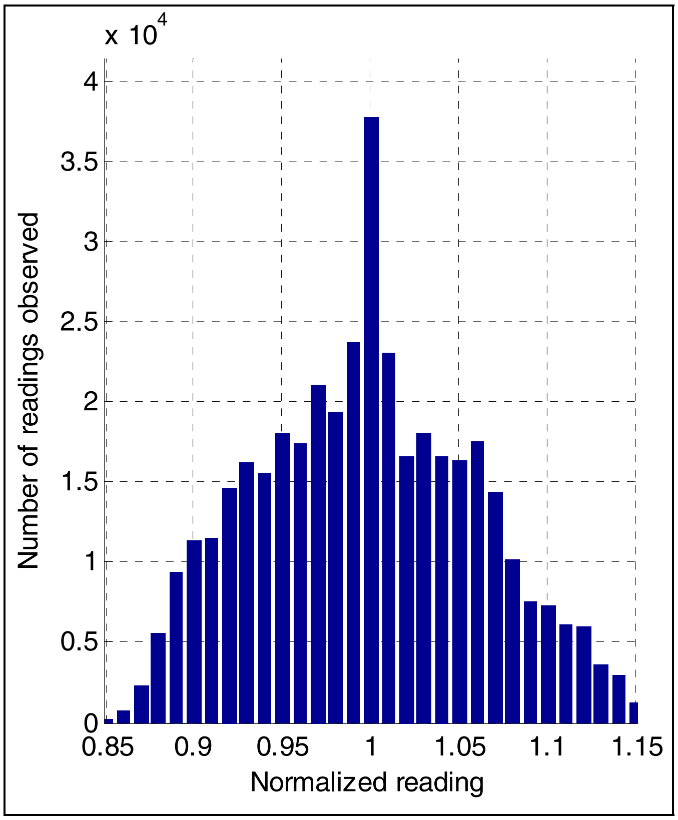

Figure 14. Histogram of normalized measured readings for various orientations of the miner-wearable component.

CONCLUSIONS

Data was collected by moving miner-wearable components around a test installation of the Intelligent Proximity Detection system installed on a Joy 14CM continuous mining machine. These tests quantified the potential influence that conveyor boom position, trailing cable position, and orientation of the miner-wearable component could have on the accuracy of the system. These tests were designed to determine the upper limit of performance for the iPD system. The actual performance of a proximity detection system using this technology will also depend on other factors not considered in these experiments.

These experiments have shown some possiblelimitations of the iPD system. Errors as large as ±1 foot (30 cm) were observed during the experiments. In addition, the measured reading at the miner-wearable component could be off by up to 15%.These results should be considered by proximity detection manufacturers in the design and implementation of future systems. By considering the limitations of the technology, the accuracy, repeatability and reliability of systems can be optimized to help ensure the safety of all miners working near heavy equipment underground.

REFERENCES

1. Bartels, J., Gallagher, S., Ambrose, D. “Continuous Mining: A pilot study of the role of visual attention locations and work position in underground coal mines.” *Professional Safety*. pp 28–35. 2005.
2. Bartels, J., Ambrose, D., Gallagher, S. “Analyzing Factors Influencing Struck-by Accidents of a Moving Mining Machine by Using Motion Capture and DHM Simulations.” Digital Human Modeling for Design and Engineering Conference and Exhibition. June 17–19, 2008. Pittsburgh, PA.
3. Kingsley-Westerman, C. “Behavioral Considerations for Proximity Warning Implementation.” Presented at the Proximity Warning Systems for Mining Equipment NIOSH Workshop. September 15, 2010. Charleston, WV.
4. Huntsley, C. “Remote Controlled Continuous Mining Machine Fatal Accident Analysis Report of Victim’s Physical Location with Respect to the Machine.” December 23, 2011. Retrieved from http://www.msha.gov/webcasts/Coal2005/Fatal%20Accident%20 Summary.pdf on 5/17/2012.
5. Mine Safety and Health Administration. “Proximity Detection Systems for Continuous Mining Machines in Underground Coal Mines.” Notice of Proposed Rule Making. Federal Register Volume 76, Number 169. August 31, 2011. pp 54163–54179.
6. Schiffbauer, W. “Active Proximity Warning System for Surface and Underground Mining Applications.” *Mining Engineering*. 2002.
7. Chirdon, D. “MSHA Proximity Detection.” February 2, 2009. Retrieved from http://www.msha.gov/Accident_Prevention/NewTechnologies/ProximityDetection/Proximity%20Detection%20Paper.pdf on 5/17/2012.
8. Li, J., Carr, J.L., Jobes, C.C. “A shell-based magnetic field model for magnetic proximity detection systems.” *Safety Science*. Vol. 50, Issue 3. March, 2012. pp 463–471.
9. Li, J., Jobes, C.C., Carr, J.L. “Comparison of magnetic field distribution models for a magnetic proximity detection system.” 2011 IEEE Industry Applications Society Annual Meeting (IAS). October 9–13, 2012. Orlando, FL.
10. Carr, J.L., Jobes, C.C., Li, J. “Development of a method to determine operator location using electromagnetic proximity detection.” 2010 IEEE International Workshop on Robotic and Sensors Environments (ROSE). October 15–16, 2010. Phoenix, AZ.
11. Jobes, C.C., Carr, J.L., DuCarme, J.P., Patts, J. “Determining proximity warning and action zones for a magnetic proximity detection system.” 2011 IEEE Industry Applications Society Annual Meeting (IAS). October 9–13, 2012. Orlando, FL.
12. Jobes, C.C., Carr, J.L., DuCarme, J.P. “Evaluation of an Advanced Proximity Detection System for Continuous Mining Machines.” *International Journal of Applied Engineering Research*. Vol. 7, No. 6. 2012. pp 463–471.