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PROXIMITY DETECTION WITH SELECTIVE MACHINE SHUTDOWN

J. P. DuCarme, Office of Mine Safety and Health Research, Pittsburgh, PA
J. L. Carr, Office of Mine Safety and Health Research, Pittsburgh, PA
C. C. Jobes, Office of Mine Safety and Health Research, Pittsburgh, PA

ABSTRACT

An average of 1.2 fatalities occur per year in underground coal mines in the United States when a miner is struck or pinned by a remote-controlled continuous mining machine. Proximity detection technology provides a means to prevent these types of accidents by disabling all machine motion when a miner is in close proximity. Researchers at the National Institute for Occupational Safety and Health (NIOSH) have developed the intelligent Proximity Detection (iPD) system, which continuously tracks the position of miners near the machine and disables only those machine motions that could cause a pinning accident. This system, previously demonstrated using non-permissible proximity detection hardware, has now been shown to be effective when implemented using an MSHA-approved system as a platform. Performance tests have shown accuracy, repeatability, and stop zone identification to be comparable to or better than the system demonstrated with non-permissible hardware.

INTRODUCTION

Underground coal mining room-and-pillar operations typically use Continuous Mining Machines (CMMs), such as the one shown in Figure 1. When CMMs first became available, they were operated from an on-board operator's compartment that protected operators from roof falls and other hazards but severely restricted visibility and subjected them to machine vibration and high levels of dust and noise. To solve these problems, remote controls were developed to operate CMMs. Now CMM operators are free to position themselves for best visibility of each mining task and are no longer subjected to the rough motion of the CMM during mining operations or the dust and noise generated by the machine. However, this technological advance removed operators from the protection afforded by the operator's compartment and exposed them to the hazard of being struck or pinned by the CMM or other large moving machines.

Figure 1. Continuous mining machine during tramming.

Previous research conducted by the National Institute for Occupational Safety and Health (NIOSH) has revealed the positions that 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.

Remote controls began to be used on CMMs in 1984 and since then there have been 38 fatalities involving striking and pinning of the operator and other workers by the CMM [3]. In August 2011, the Mine Safety and Health Administration (MSHA) published a proposed regulation that would require proximity detection systems on all continuous mining machines except full-face machines [4]. Proximity detection systems are designed to activate a warning signal or stop machine movement 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 conducted a series of field tests on MSHA-approved proximity detection systems [5]. The tests were designed to quantify the performance of these systems in a mine environment. The results of the tests of proximity detection systems indicate that these systems should significantly improve safety. However, they also show opportunities for improvement. Notably, several of the systems include a "mining mode" in which the behavior of the system is changed when the cutter head is running. This is intended to allow the operator to be closer to the CMM during cutting operations for better visibility of cutting operations and to avoid other hazards such as being struck by haulage equipment.

The field tests showed that during mining mode it is possible for the operator to come into contact with the mining machine. Although no fatality has ever occurred while cutting coal, it is the opinion of the authors that the mining mode introduces the potential for a new hazard to be created if operators become dependent on the system and expect it to protect them while cutting. One solution to this concern is to implement intelligent proximity detection as described in this paper.

DEVELOPMENT OF INTELLIGENT PROXIMITY DETECTION

Magnetic Field Modeling

NIOSH researchers have been involved in the development and testing of proximity detection technology since creating the Hazardous Area Signaling and Ranging Device (HASARD) system in the 1990s [6] and have now developed the iPD (Intelligent Proximity Detection) system for continuous mining machines (CMM). As a foundation for the development of the iPD system, NIOSH researchers developed a sophisticated model of the magnetic fields used in proximity detection systems [7, 8]. This mathematical model is an equation describing the shapes of magnetic "shells," which are comprised of all points having equal magnetic field strength. The three-dimensional variation in shape and size of the shells described by this model is shown in Figure 2.

Determining Miner Position

Given this model of the magnetic fields, the research team then developed a novel method for determining the location of a miner-wearable component (Personal Wearable Device or PWD) relative to the magnetic field generators. The position of the PWD is determined by finding the intersection of two or more magnetic shells using a trilateration process. Due to the irregular shapes of these shells, an analytic solution could not be derived. While numerical method techniques might be sufficient for the two-dimensional case, they proved insufficient for finding a three-dimensional solution due to the high computation times required. Therefore, a novel geometric search method was developed which converges to the intersection of the shells through an iterative series of spherical approximations [9].

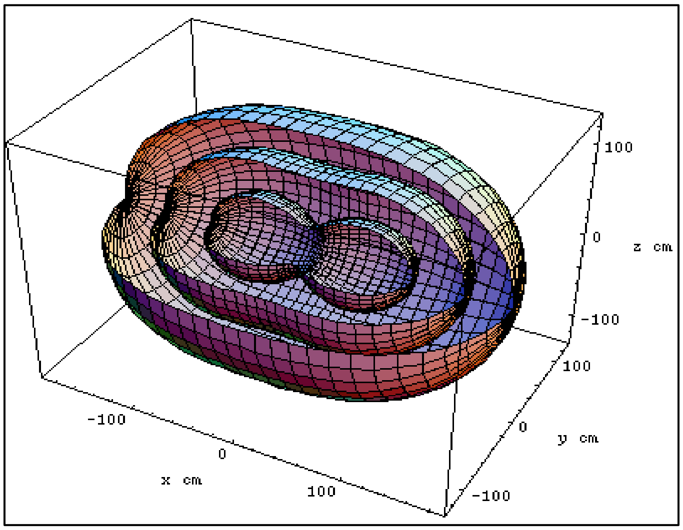

Figure 2. Example of the variation in the magnetic shell shape with increasing distance from the generator.

Initial Intelligent Proximity Detection Prototype

The trilateration algorithms that were developed made it possible to implement an intelligent proximity detection system in which an onboard controller issues alarms and disables specific machine functions based on situation-specific conditions. This innovation represented a significant advance in the technology of proximity detection.

These algorithms were implemented in a prototype iPD system on a Joy 14CM continuous mining machine platform at the NIOSH research facility in Pittsburgh. This prototype system utilized four non-permissible CMM-mounted generators, an onboard controller, and several PWDs worn by mining personnel around the CMM.

The iPD system utilized the developed trilateration method to continuously track the position of mining personnel around the CMM. Once the position of a miner was identified, the iPD system could provide protection against striking and pinning accidents by acting to disable any CMM motions that could cause a collision between the CMM and mining personnel in the vicinity.

In the prototype system, the actuator signals traveled through a set of relays that the onboard controller selectively opened or closed to effectively disable or enable the associated actuator. In this manner, individual controls could be selectively disabled, but the control software did not send active control signals to the actuators. Figure 3 shows one of the major components installed on the iPD CMM test platform, the magnetic field generator.

Figure 3. Field generator for non-permissible prototype system

To enact this level of control, a set of zones were defined around the CMM and each zone was associated with potentially hazardous CMM functions. If a PWD was detected in a zone, the functions associated with that zone were disabled. This system was implemented in a laboratory setting and was proven to provide good performance in identifying which machine functions should be disabled [10, 11].

Intelligent Proximity Detection with Permissible Hardware

Researchers at NIOSH determined that it would be advantageous to modify a commercially available permissible proximity detection system to demonstrate that iPD could be retrofitted to an existing installation of a similar type. The MSHA-approved (permissible) system consists of four generators, a controller, and four PWDs. These components are shown in Figure 4. Each of the new generators had an increased and adjustable range, but it was found that a large increase in range would saturate the sensors in the PWDs close to the generators. Once the generators were installed on the test platform they were calibrated for optimum range.

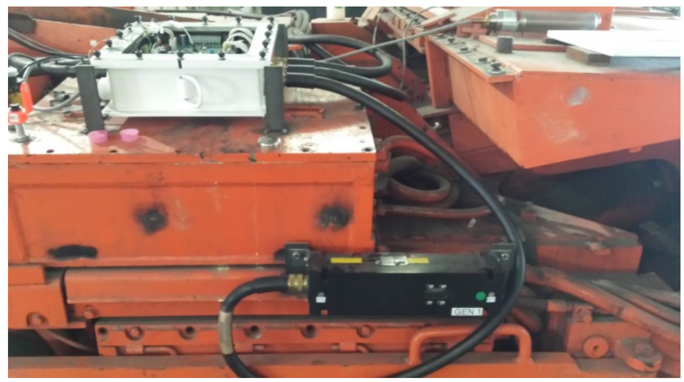

Figure 4. Permissible proximity detection system controller and magnetic field generator.

RESULTS OF LABORATORY TESTS ON IPD SYSTEM PERFORMANCE

Accuracy of Localization

A series of laboratory tests were conducted to determine the achievable accuracy of the position calculation. The accuracy of the system was affected by several variables that limit the maximum achievable performance due to the physics of the technology involved. These tests were designed to investigate the influence of three of these variables that were considered likely to cause a significant change in performance: conveyor boom position, trailing cable position, and orientation of the PWD.

Data was collected by moving PWDs around a test installation of the iPD system. These tests were designed to determine the upper limit of performance for the iPD system. Importantly, these experiments showed some possible limitations of the iPD system. Errors as large as ±30 cm were observed during the experiments. In addition, the measured reading at the PWD could vary by up to 15% [12].

Figure 5 depicts the trilateration accuracy achieved in tests with the prototype system. The dots represent the actual PWD position, circles represent the triangulated PWD position with uncertainty radius, and the red solid circle indicates a missed alarm. Due to the sampling locations and low sampling density in the prototype system test, the area outside three feet from the machine is somewhat under-represented in these results.

Excellent accuracy was achieved close (within 1.5m) to the CMM and the PWD position was generally known to within 20 to 50 cm. The errors predictably increased with distance from the generators and tended to be high in specific areas, especially in a tangential direction, due to the shape of the fields and generator pair selection for trilateration. The accuracy also depended strongly on accurate knowledge of the PWD elevation which is used as a constraint in the trilateration algorithm. At the limit of the system's detection (about 6 M) from the CMM, accuracy deteriorated – becoming slightly over 3 meters in the worst case. However, accuracy further from the machine was not deemed to be as critical since the miner operator would be in a safer location and identifying only the operator's general location was considered of importance.

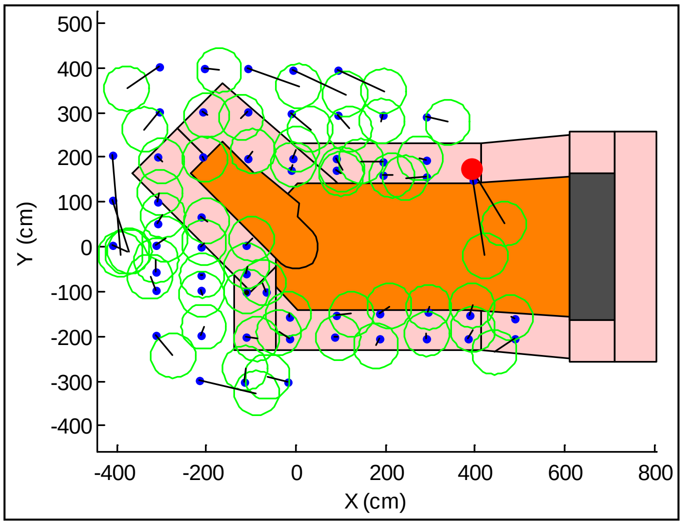

Figure 5. Example of triangulation accuracy results with prototype system.

Simulated Mining Experiments

In addition to the localization accuracy tests, simulated mining tasks were performed to collect data on the human/machine interaction aspects of implementing this advanced proximity detection system (see figure 6). These tests used volunteers from local mines who had CMM operation experience. The operators conducted typical tramming motions while the proximity system recorded their position relative to the CMM. A single test trial consisted of the operator performing a series of routine mining tasks consisting of moving the continuous mining machine from one location to another. The locations of the continuous mining machine are shown in figure 7 and the positioning tasks are described in Table 1. The operators completed three trials under each of the three separate treatments: with no proximity detection system in use, with a conventional proximity detection system in use and with the NIOSH-developed iPD system in use (nine trials in total). Researchers constructed a simulated underground mine setting consisted of 8 foot high curtains that provided the confined space and limited visibility of an actual mine setting. Conventional proximity system behavior was emulated in the iPD software by programming a mode where intrusion into any zone around the CMM disabled all machine motions. Preliminary results (Table 2) show the iPD system allowed the tasks to be completed about 10% quicker than using a conventional proximity mode. These tests are on-going and further results are expected.

Figure 6. Tramming test of iPD in simulated mine.

DISCUSSION

Proximity detection technology should provide pronounced improvements in the safety of CMM operators and should prevent striking and pinning accidents. Proximity system vendors are beginning to provide systems for underground mobile equipment. Application of this technology to underground mobile equipment would also provide similar safety benefits.

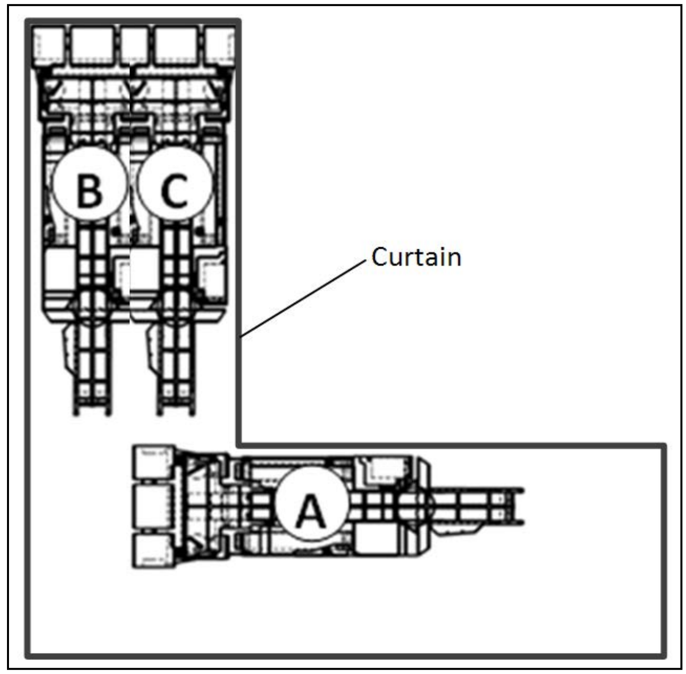

Figure 7. CMM positions used for simulated mining tests.

Table 1. Simulated mining tasks constituting a single test session.

Task	Description	Mining activity simulated	Referring to Figure 7, Continuous mining machine is moved
1	Right turn followed by tram forward	Turning a crosscut, then positioning at coal face for a cut	From A to B
2	Shifting machine to the right by backing away, turning and advancing	Repositioning at the coal face to continue cutting	From B to C
3	Returning machine to original position by backing out and turning	Moving machine away from coal face following a completed cut	From C to A

Table 2. Simulated mining tasks constituting a single test session.

Proximity	Average time to complete all three trials (seconds)
None	364 (baseline)
Conventional	406 (12% increase)
Intelligent	372 (2% increase)

NIOSH conducted field testing of MSHA-approved systems shows that repeatability and accuracy is adequate to provide protection [5]. However, some tests showed opportunity for improvements. While the current approved systems provide a relatively simple protection zone around the entire CMM, it is difficult for an operator to adequately and safely perform all the necessary operational tasks while continuously positioned far from the machine. To address this difficulty, several MSHA-approved proximity detection systems provide a mining mode which is activated when the cutter head motors are energized. While in this mode, CMM operators have the ability to stand closer. As with the advent of remote controls, the mining mode technology solves one problem while creating the potential for other problems.

The iPD technology developed during this research provides a better solution than the use of a mining mode. NIOSH has pioneered the research of electro-magnetic proximity detection technology, starting with the development of HASARD and through the current work developing a functional iPD system using off-the-shelf approved hardware. The primary difference between the iPD system and current approved systems is that the iPD system provides selective shutdown of machine functions depending on the worker's position relative to the CMM. Accuracy of this position determination has been measured at 30 to 50 cm. Simulated mining tests with the iPD system show the viability and performance during typical tramming procedures. As compared to the baseline of no proximity system, the operators were able to complete a series of tramming tasks with only a 2% increase in time. This is compared to a 12% increase without selective shutdown. NIOSH researchers are actively engaged in efforts to transfer this technology to industry.

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